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Sources of uncertainty in the closed-loop supply chain of lithium-ion batteries for electric vehicles

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ABSTRACT

Due to increasing demand for electric vehicles and short innovation circles of battery, production, and recycling technology, different uncertainties need to be faced at different stages of the supply chain. However, a qualitative analysis of the uncertainties and their sources is missing. Therefore, in this paper the authors propose an empirical approach to the identification of uncertainty occurring in the closed-loop supply chain of lithium-ion batteries from electric vehicles (uncertainty in supply, process, demand, control, and environmental uncertainty). The investigation methodology consists of a content analysis of press media documents related to electric vehicles and the automotive industry. The final content analysis comprises 102 evidences of uncertainty. Consequently, the evidences of uncertainty found are classified in a spectrum between statistical uncertainty and total ignorance (levels of uncertainty). Graphs and data are described to provide detailed information. The results signal predominant environmental uncertainty besides the uncertainty within control and supply of the closed-loop. A conclusion on the investigation shows cobalt as a raw material responsible for increasing uncertainty (boomerang effect). Additionally, the content analysis evidences uncertainty with the availability, quantity, stock control policies, government regulations, and political instability with cobalt, lithium, and nickel.

1. Introduction

Europe is in a long-term strategy to achieve a climate-neutral economy. The agreement of Paris approved on 12 December 2015 sets a global consensus of international cooperation between countries to reduce carbon emissions. Thus, the future of electrification in the automotive industry is a target to reduce the carbon footprint. In this context, car manufacturers rely on lithium-ion (Li-ion) batteries for energy storage in electric vehicles (EVs). The reason is that Li-ion batteries offer good efficiency, long cycle life, high power, and energy densities (Kwade & Diekmann, 2018). Even though EVs slowly penetrate the market, competition will arise to secure the availability and a steady supply of batteries and critical raw materials. In this context, car manufacturers currently face the challenge of dealing with the battery manufacturers, which have a high influence on the EV market due to the scarcity of batteries. Statements from prominent car manufacturers show the new trend. In 2019, Volvo announced the ambition to become one of the world's leading electric car manufacturers while revealing a partnership with CATL and LG Chem, both Li-ion battery manufacturers in the automotive industry (Volvo Group, 2019). The transition to electromobility causes uncertainties in the automotive supply chain due to the massive technology shifts, changes in the structural design of batteries, supply chain, and production process, as well as network relationships. As described by Ortiz et al. (2019), changes in technology, product, and processes contribute to an escalation in the uncertainty level of the supply chain. For example, Daimler (owner of the Mercedes-Benz brand) disclosed in their 2017 report future supply chain risks due to the new industry pattern that will create changes in sales, volumes, and production capacity (Daimler, 2017). In the same manner, the '2018 Sustainability Report' from Daimler draws attention to the 'many risks and uncertainties' from the company's statements reflecting their view of the future (Daimler, 2018, p. 120).

In this context, it is important to emphasize a rapidly increasing demand for batteries and consequently critical materials such as cobalt, lithium, and nickel. For that reason, challenges to master are the availability of raw materials, an unbalanced demand and supply, potential price spikes, environmental impacts, human rights abuse, as well as political conflicts (Mitchell et al., 2017; IEA, 2019). Other factors contributing to the uncertainty are the limited availability

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and spatial concentration of lithium, the early stage of recycling, the gap between demand caused by production and lithium availability, the demand for competing applications, and production capacities (Egbue & Long, 2012). Furthermore, lithium comes with a special challenge in recycling due to the high costs of its recovery (Rosendahl & Rubiano, 2019). Therefore, car companies will have to manage and anticipate challenges in their supply chain, while managers need to make decisions based on incorrect or imperfect information. Usually, this leads to non-optimal decisions based on imperfect information and consequently to opportunity costs. At the same time, the uncertainty occurs in different sources, with different levels and categories in the management of the forward and reverse supply chain.

First, the identification of sources of uncertainties may improve the performance of supply chains. Second, practitioners recognize the identification of uncertainty as an effective procedure to improve supply chain performance through redesign strategies (van der Vorst and Beulens, 2002; Simangunsong et al., 2012). For instance, Sanchez Rodrigues et al. (2008) defined improvements to the performance of logistics operations within supply chains after identifying sources of uncertainty affecting transportation in the logistics triad. Rohr et al. (2017) identify the source of uncertainties in the lifetime prediction of batteries to estimate cell failure. The same article highlights the importance of the identification of uncertainties for evaluating the possible economic benefit during the decision-making process considering the value chain of end-of-life batteries. Besides, regulations from European and other governments concerning carbon dioxide emissions have pressured the automotive industry to build technologies with fewer emissions, which lead to the development and production of EVs. In order to fully leverage the benefits of EVs, the traditional supply chain must be extended by the after use-phase (Spengler et al., 2010). Furthermore, when considering Li-ion batteries, recycling processes are expected to have an essential role in feeding back the production systems with valuable materials by closing the loop for battery materials (Kwade & Diekmann, 2018). Thus, closed-loop supply chains (CLSC) arise which focus on sustainability. In this context, closing the material loop is regarded as an environmentally friendly initiative in the literature (Quariguasi Frota Netoet al., 2010). Our premise is that identifying uncertainty enables the development of advanced planning approaches in the management of CLSCs of the automotive sector.

Hence, this paper's objective is to identify the uncertainties (sources, categories, and uncertainty levels) in the management of the automotive CLSC of Li-ion batteries. As a result of the identification of uncertainties, this paper will provide information that can be accessed by practitioners and managers to develop strategies to improve the management of CLSCs for Li-ion batteries of EVs.

2. Conceptual background

2.1. The lithium-ion battery and the electric vehicle

In this paper, the term of EV - ‘electric vehicle’ - is used as a broader term. Richardson (2013) uses the EV denomination to refer to an automobile that is powered by an electric motor. Thus, EVs can be of three types: battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs). Although manufacturers use different battery chemistries, the overall functionality remains Li-ion. An example is the cell chemistry based on a graphite anode and a lithium iron phosphate cathode (Peterson, Whitacre, & Apt, 2010).

Meanwhile, addressing the reverse flows in the supply chain for the automotive Li-ion battery seems to be challenging. The first reason is that the quantity of spent Li-ion batteries is still small. The reason is the still increasing sales in combination with the time delay between sales and returns. On the other side, if the sales take off presumably faster than expected, the reverse supply chain might not be prepared to take back such an amount of spent batteries. According to the European Commission (European Commission, 2017), only 900 end-of-life EV batteries were expected to reach recycling in 2018 in the European market. However, the forecast for 2025 is significantly higher with 147,000 end-of-life EV batteries. Another study from the Nordic Council of Ministers (Dahllöfet al., 2019) concerning the fate of automotive Li-ion batteries in the Nordic countries presented the ‘assumptions’ and schemes of ‘the probable fates of the car Li-ion batteries’. This indicates that the industry does not know what the trend is going to be and there are many future scenarios and assumptions. Therefore, how the loop will be closed is still under research and subject to future changes. This fact gives further strength to address the supply chain uncertainty of automotive Li-ion batteries. Yet, it may be challenging to identify uncertainty on the operational level of the reverse flow. The operations that will occur in the reverse flow of automotive Li-ion batteries are still dependent on modern scientific research and progress in better waste management processes to handle used Li-ion batteries. Li et al. (2018) argue that the uncertainty surrounding the production capacity, Li-ion battery demand and supply, as well as the automotive market is still emerging. This makes stakeholders reluctant to participate in the EV market and consequently holds back automotive Li-ion battery remanufacturing. This could be related to the different scenarios that can be displayed while designing a network for the recycling of Li-ion batteries (e.g. Hoyer et al., 2011). In support of this argument is the statement of Chen et al. (2019), who note that the research in Li-ion battery recycling is still in the lab-scale phase although different recycling approaches and methods have been proposed and studied. According to Ordoñez et al. (2016), the recycling for Li-ion batteries comprises a physical process (such as the mechanical preparation which separates the battery into different fractions) and chemical processes (e.g. solvent extraction). The chemical processes are described to involve acid or base leaching, solvent extraction, chemical precipitation, bioprocesses, and electrochemical processes. Also, combinations of these processes exist (hydrometallurgical methods). The problem found with battery recycling is that is expensive and research regarding the recycling technologies of spent Li-ion batteries is considered to be on a pilot or laboratory scale (Zeng, Li, & Singh, 2014). In conclusion, further research on recycling and recovery technologies for Li-ion batteries is necessary. This is also argued by Xu et al. (2008). Still, the possibilities for the spent batteries are open to different recovery options and do not solely rely upon recycling, allowing other options to close the loop.

To provide a vision of the EV battery CLSC, we describe a comprehensive closed-loop based on models or descriptions given in the literature. Thies et al. (2019) describe the closed-loop material flow as we move downstream in the supply chain: first, the different raw materials such as copper, cobalt, lithium, nickel, manganese, aluminum, and silicon are extracted from different locations; afterward, those raw materials are used in the production of the battery cell components (anode, separator, cathode, electrolyte); then, battery cell production takes place; finally, the assembly of the battery can be executed by the car manufacturer. After its use, the batteries should be returned to the manufacturer (who has the legal responsibility to take the spent batteries back). However, manufacturers often transfer the obligations to companies of the reverse supply chain. In this context, three possible value chains can occur after removing the battery pack from the EV (Rohr et al., 2017): i) the recycling of the battery; ii) the remanufacturing of the battery; iii) the reuse of battery modules or the complete battery pack (this is called the second life/use application). Those value chains are the ‘return loops’ in the context of CLSCs. Currently, recycling is the predominant return loop due to its comparable higher maturity. The recycling of the Li-ion batteries is of high importance to recover valuable raw materials such as lithium and cobalt but also environmentally necessary due to the toxicity of some battery components. Thus, recycling needs to consider the different cell chemistries and configurations.

2.2. Supply chain uncertainty

One of the first pieces of evidence of uncertainty that affects the management of supply chains is found in the work of Davis (1993). Davis points out three sources of uncertainty that 'plague' supply chains: demand, process, and supply uncertainty. Later on, Mason-Jones and Towill (1998) developed the 'uncertainty cycle model' and added a new source of uncertainty: the control uncertainty. How uncertainty affects the supply chain is that it causes additional costs within the supply chain. The issue of supply chain uncertainty is often found associated with risk management. Risk management deals with the way that companies react to uncertainties (Hoffmannet al., 2013; Vilkoet al., 2014; Oliveira et al., 2013) and this association often leads to confusion between the concept of 'uncertainty' and 'risk' (Sanchez Rodrigues et al., 2008). According to Simangunsong et al. (2012, p. 4494), both the uncertainty and risk literature are relevant to the study of supply chain uncertainty. Therefore, the literature regarding 'risk' often considers the definition of elder papers, such as Lowrance (1980) and Chiles & McMackin (1996), which define risk as to the probability of adverse effects; the possibility of a negative outcome. According to Rowe, 'Risk is the potential for realization of unwanted, negative consequences of an event or combination of events' (Rowe, 1975, p. 1). Another formulation often found in research considers risk as the result between the product of the 'probability of the risk occurring and the 'degree of impact of the risk' (Zhi, 1995; Jaafari, 2001). An event is said to be certain if the probability of its occurrence is 100% or totally uncertain if the probability of occurrence is 0% (Jaafari, 2001).

The concepts of 'uncertainty' and 'risk' are inseparable and different, although it is possible to follow a research approach that does not consider a separate trait between both concepts when referring to the concept of 'supply chain uncertainty'. Therefore, by considering the relationship between risk and uncertainty this paper addresses a definition of 'supply chain uncertainty' together with the concept of 'risk' similar to the review proceeded by Simangunsong et al. (2012). That is to incorporate risk in the study of uncertainty in the context of supply chains. The same research approach is found in literature concerning the supply chain context (van der Vorst 2000; Sanchez Rodrigues et al., 2008; Hollmann 2011; Simangunsong et al., 2012; Wang et al., 2014). Therefore, we address a view of 'supply chain uncertainty' in the same logic as Davis (1993), Zimmermann (2000), van der Vorst and Beulens (2002), and Ben Amor et al. (2017): supply chain uncertainty is a state of lack of information that restrains the ability of decision-makers to accurately predict the right outcome of scenarios and the impact of control actions in the supply chain. The uncertainty appears in the form of late deliveries, machine breakdowns, order cancellations, and variances that have a significant negative impact on performance.

The concept of supply chain uncertainty is indisputably connected with a lack of information in the course of decision-making processes. Managers need to analyze information to predict future case scenarios such as demand for a product to decide accordingly and determine planning strategies (e.g., allocate resources to meet the demand scenario). When the information is imperfect, this can lead to high costs for a company. In an article from Kubota et al. (2018) published by The Wall Street Journal, the authors report Apple Inc suppliers' to be suffering from demand uncertainty based on Apple's decision to stop reporting its unit sales. In this situation, the lack of information (about Apple's unit sales) was affecting the capabilities of the suppliers to forecast Apple's demand, causing uncertainty in their supply chain. Afterward, the relationship between the lack of information and uncertainty is well addressed in the literature. Ben Amor et al. (2017) refer that information used to assess alternatives in discrete multicriteria decision-making can be imperfect, creating a situation that attempts to find additional information to reduce imperfections. They refer to 'information imperfections' as a general term that comprehends all kinds of 'deficiencies' (uncertainty, imprecision, ambiguity, incompleteness). Zimmermann (2000) defined uncertainty in a decision logic context as the case where a decision-maker does not have any information about which of the possible states of nature will occur.

To identify supply chain uncertainty, many approaches have been taken in the literature (Towill et al., 2000; Gosling et al., 2013; Sanchez Rodrigues et al., 2008; Angkiriwang et al., 2014; Böhme et al., 2014; Ortiz et al., 2019). For instance, Towill et al. (2000) diagnose the health of value streams in the automotive sector based on the 'uncertainty circle model'. They perceive uncertainty introduced within the supply chain arising from the significant sources conceptualized in the uncertainty circle. According to Simangunsong et al. (2012), the identification of uncertainty sources is made considering models of uncertainty. Towill et al. (2000) point out that the uncertainty circle provides the necessary focus to identify uncertainty. This can be sustained with research works in which the uncertainty circle proves to be a reliable tool to identify uncertainty in the supply chain scope (Towill et al., 2000; Sanchez Rodrigues et al., 2008; Gosling et al., 2013; Böhme et al., 2014). The uncertainty circle (Fig. 1) frames in a generic form the uncertainty that companies face in four fundamental constituent segments; due to manufacturing (i.e. process-side), demand-side, supply-side, and control-side (Mason-Jones & Towill, 1998). Those four fundamental segments are the uncertainty sources that affect supply chains.

2.3. Sources of uncertainty

In the literature, many authors describe supply, process, demand, and control uncertainty sources (Hobbs, 2021; Lima et al., 2021; Pishvaee et al., 2021; Rahimi et al., 2019). Besides these definitions, several categories of uncertainties began to be identified, especially with the current COVID-19 pandemic (Hobbs, 2021). The sources of uncertainty are experienced in both open-loop and closed-loop supply chain. To expand the uncertainty analysis, an additional source of uncertainty is introduced to this study: environmental uncertainty which is related to the unpredictability of the business environment. The reason to address environmental uncertainty is that it is a major determinant of business performance (Simangunsong et al., 2012; Wang et al., 2014). For example, if governments introduce new legislation in the Li-ion batteries marketplace, uncertainty will be generated and propagated to supply chain members' activities. Furthermore, some of the raw materials that constitute a Li-ion battery come from countries facing political instability such as the Democratic Republic of Congo. Moreover, the automotive industry is undergoing tremendous changes in structure, network, and technology while transitioning to electrification. Thus, environmental uncertainty should include technology innovation and EVs are no exception to that. A study carried out by Ettlie and Bridges (1982) highlights that meeting technology requirements is one of the most mentioned facts that contribute to uncertainty. Other authors considering technology in environmental uncertainty are Karagozoglu (1993), Bstieler (2005), and

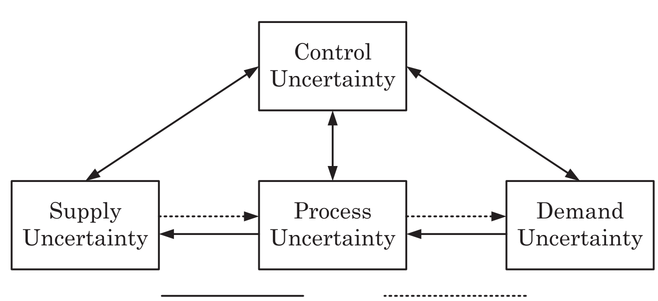

Fig. 1. The uncertainty circle (adapted from Mason-Jones and Towill 1998).

Table 1
Sources of supply chain uncertainty.

Source of uncertainty	Definition
Supply uncertainty	It results from poor supplier performance by not meeting the requirements: the uncertainty of materials' supply (Childerhouse, Disney, & Towill, 2000); (Angkiriwang et al., 2014).
Process uncertainty	The uncertainty inherent in the production systems; affects the internal ability of a company to meet production targets (Childerhouse et al., 2000); (Angkiriwang et al., 2014); (Ortiz et al., 2019).
Demand uncertainty	It is associated with customers' orders and transparency of the information flow. It can be perceived as the difference between the orders placed by customers and the end marketplace demand, costumers' product specification, and life-cycle stages (Childerhouse et al., 2000); (Gosling et al., 2013). It is related to the probabilistic nature of demand quantity, timing, and locations. (Angkiriwang et al., 2014).
Control uncertainty	It is introduced from the mechanisms employed to control supply, process, and demand uncertainty (Goltsos et al., 2018) and concerns the ability to transform customer orders into production targets and supplier raw materials requests (Childerhouse et al., 2000).
Environmental uncertainty	It is characterized by any factors (outside of the supply chain) in a particular context affecting the choice of management strategy (Simangunsong et al., 2012). It is considered the uncertainty introduced by external conditions to the supply chain: governmental and political, macroeconomic, natural disaster conditions, and technological factors that affect supply chains, and create uncertainty within them. Changes occurring externally, that might result in an inability of an organization to understand, estimate, and respond to such changes (Jangga, Ali, Ismail, & Sahari, 2015)

Table 2
Sources and categories of uncertainty in a generic closed-loop supply chain. Adapted from Goltsos et al. (2018) and Tibben-Lembke and Rogers (2002).

Source of uncertainty	Categories of uncertainty	
	Forward flow	Reverse flow
Supply uncertainty	Raw material availability Supply lead time	Cores availability Quality of cores Collection procedure Transportation lead time Packing Speed
Process uncertainty	Yield and quality Processing times Machine availability	Yield and quality Processing times Machine availability
Demand uncertainty	Quantity Timing Locations Product specification Life-cycle stage	Product cannibalization Product substitution Negotiation
Control uncertainty	Serviceable stock control policy Raw material stock control policy Demand forecasting method Batching rules Capacity planning decisions Policies and methods interactions	Recoverable stock control policy Returns forecasting method Inventory management

Chen (2013). The uncertainty sources and the definition that concern them are synthesized in Table 1.

2.4. Application of the uncertainty circle to the closed-loop supply chain

Uncertainty in supply chains can be managed considering the ongoing decision processes that occur within supply chains. Decisions are the result of processing and analyzing information, when the information is imperfect, uncertainty can result in inefficient decision making. To identify the uncertainty in the CLSC of Li-ion batteries from EVs, this paper considers Goltsos et al. (2018) framework of the uncertainty circle (Table 2). It also considers the forward logistics information flow and the reverse logistics information flow proposed by Tibben-Lembke and Rogers (2002). The framework represents in the generic form the uncertainty that is experienced by decision-makers in the operational scope of a CLSC.

The categories of uncertainty are retrieved from Goltsos et al. (2018), nevertheless the definition of each category is retrieved from the literature in which specialists describe or defined the uncertainty that is being discussed. Table 3 defines the categories of each uncertainty source.

2.5. Levels of uncertainty

This paper includes another layer considering the different levels of uncertainty - the uncertainty identification that is related to the qualitative expressions. Walker et al. (2003) provided a theoretical framework for systematic uncertainty analysis that supports the identification, articulation, and prioritization of critical uncertainties, considering a spectrum of four levels of uncertainty: 'statistical uncertainty', 'scenario uncertainty', 'recognized ignorance' and, 'total ignorance'. In addition to these levels, Brown (2004) refers to the 'unbounded uncertainties'. That is when not all possible outcomes are known, or quantitative probabilities cannot be determined and rely on 'qualitative expressions of likelihood' or 'scenario analysis' (Brown, 2004; Reibnitz, 1988). This judgment can be linked to the concept of 'qualitative uncertainty'. Qualitative uncertainty is 'uncertainty that cannot be expressed in terms of nominally measurable values. This level of uncertainty comprises opinions of experts, linguistic probabilities, and ambiguities between people (Warmink, Janssen, Booij, & Krol, 2010, p. 1521). Considering the existence of this level of uncertainty, Warmink et al. (2010) expanded the framework proposed by Walker et al. (2003) adding the 'qualitative uncertainty', situated between 'scenario uncertainty' and 'recognized ignorance'. The objective of Waemink's work is to enhance the objectivity in the uncertainty identification process. Furthermore, according to the authors, their framework can be applied to different model studies. The various levels of uncertainty, according to Walker et al. (2003) and Warmink et al. (2010), are defined in Table 4.

3. Research methodology

The objective is to identify the uncertainties that decisions makers face upon the management of the CLSC of Li-ion batteries for EVs. The uncertainties sources are described using the 'uncertainty circle' and from those sources, different categories of uncertainty emerge in the operational framework of the CLSC. To enhance the identification of uncertainty, the sources of uncertainty are classified in different levels. Fig. 2 provides the conceptual framework used to characterize the analyzed uncertainties in the CLSC of Li-ion batteries from EVs (sources of uncertainty, categories, and levels of uncertainty).

Fig. 3 displays the various stages of the research methodology. The analysis of the secondary data follows a method similar to Carvalho et al. (2012) and Carvalho et al. (2011). First, it is necessary to understand the phenomenon of uncertainty in CLSC management. Second, the secondary data is collected from press news (the database for this

Table 3
Categories of uncertainty in the Closed-loop supply chain (cont.)

Source of uncertainty	Categories of uncertainty
Supply uncertainty	*Raw material availability*: 'uncertainty regarding material availability/supply capacity' (a); 'The availability of supply may be uncertain' (b) *Supply lead time (schedule adherence):* 'Long and variable lead times' (d); 'variance of material supply lead-time usually disrupts regular production schedules.' (p) *Cores availability:* 'uncertainties in quantities (…) of used products' (i); 'rate of returns' (d) *Quality of cores:* 'uncertain quality or supply standards'(j); 'quality of returned products is the major source of uncertainty and thus a major determinant of value in CLSCs'(k); 'uncertainty deriving from returns quality'(l); 'condition of the received products'(d) *Collection procedure:* 'collection channel selection' (d); 'collection process can strongly influence both the rate and the quality of the items returned by the customer.'(d) *Transportation lead time:* 'uncertainty in reference to (…) timing of the collected discarded products leads to an increased system complexity'(m)
Process uncertainty	*Yield and quality:* 'nature of machine performance, mainly in terms of yield and quality' (c); the percentage of processed product units passing inspection(p) 'uncertainty concerns equipment performance and factory conditions (quality issues), which could lead to uncertainty in the yield rate.'(s) *Processing times:* 'lead-time estimates of operations for each work process' (e) 'lead time variability for the remanufacturing process' (l) *Machine availability:* 'internal ability to meet a production target' (e); 'uncertainty of machine availability (machine breakdown), which leads to uncertainties in the flow time, and hence to uncertainties in the cumulative number of output lots at a particular future time.' (s)
Demand uncertainty	*Quantity:* 'the difference between the end marketplace demand and orders placed on us by our customer' (e); 'uncertainty related to demand quantity' (c); 'Demand signal processing that leads to unusually high stock levels in the upper regions of the supply chain' (b); *Timing:* probabilistic nature of time *Locations:* probabilistic nature of locations *Product specification:* 'uncertainty about the product specification/mix that the customers will order' (e); 'customers' product specifications' (c) 'Unexplained and late changes to orders and project specification' (c) *Life-cycle stage:* 'facing shrinkage in the product life cycle and increasing competition in the market.' (e) *Product substitution:* 'fulfilling customer demand when the main product is unavailable.'(v)
Control uncertainty	*Serviceable stock control policy*: Serviceable stock/inventory consists of manufactured products and remanufactured products (g); 'to the difficulties to know accurately inventory levels' (f). Difficulties to know manufactured and remanufactured products inventory levels. *Raw material stock control policy:* 'to the difficulties to know accurately inventory levels' (f). *Demand forecasting method:* 'speculation relies on forecasts of coming demand' (h); Speculative purchases may also be precautionary in that they reflect increased uncertainty about future demand and supply'(t); 'to the difficulties (…) to make a right forecasting' (f). *Batching rules:* Different batching rules *Capacity planning decisions:* 'calculations are done to determine what capacity is needed for a resource or an application.'(r) 'Uncertainty future demands and competition among producers to satisfy them, increase the complexity of the capacity planning problem.' (q). That is the divergence between production and demand and the difficulties in determining the capacity that is needed. *Policies and methods interaction:* 'understanding of the interdependencies between the relevant parts of the system' (d); 'partners' approach to supply chain management' (d). *Recoverable stock control policy:* 'to the difficulties to know accurately inventory levels' (f); inventory level of cores. *Returns forecasting method:* know when the product will re-enter the production facilities (d) 'speculation relies on forecasts of coming demand' (h); 'to the difficulties (…) to make a right forecasting' (f)
Environmental uncertainty	*Government regulation:* when it is often changed, it may disrupt company plans, e.g. a new trade barrier for imported raw material'(b) *Political instability:* Political stability, i.e. political instability in a country that has a serious impact on supply-chain processes'(b) *Macroeconomic issues:* price inflation, fluctuations in exchange and interest rates, may press a company to change its plan, e.g.' switch to local suppliers in case of an unfavorable exchange rate (b) *Natural disasters:* Weather, natural disasters/accident(o) *Technology:* 'uncertainty inherent in long-range traditional strategic planning e.g. technology innovations' (b); 'Environmental uncertainty also makes the identification, evaluation, and adoption of technological innovations a critical determinant of organizational performance' (u)

Notes: (a) Angkiriwang et al. (2014); (b) Simangunsong et al. (2012); (c) Gosling et al. (2013); (d) Goltsos et al. (2018); (e) Childerhouse et al. (2000); (f) Ortiz et al. (2019); (g) Vlachos et al. (2007); (h) Yang and Burns (2003); (i) Thierry et al. (1995); (j) King et al. (2006); (k) Nikolaidis (2013); (l) Difrancesco and Huchzermeier (2016); (m) Spengler et al. (2010); (n) Zhang and Zhang (2019); (o) Wang et al. (2014); (p) Ho et al. (2005), (q) Kandiraju et al. (2016); (r) Bourne (2014) (s); Hung and Chang (1999); (t) Kilian and Murphy (2014); (u) Karagozoglu (1993); (z) Widodo (2017).

Table 4
The levels of uncertainty.

Levels of uncertainty	Definition
Statistical uncertainty	The uncertainty can be described in statistical terms such as probabilities or numbers. It is possible to formulate the probability of any particular outcome.
Scenario Uncertainty	A plausible description of how the system and/or its driving forces may develop in the future; set of assumptions about key relationships and driving forces (e.g., technology changes, prices). It is not a forecast of what will happen in the future but rather a forecast of what might happen, a range of possible outcomes.
Qualitative uncertainty	Any uncertainty that cannot be expressed in terms of nominally measurable values. It comprises the opinions of experts, linguistic probabilities, and ambiguities between people.
Recognized ignorance	Neither the functional relationships are known nor the statistical properties, and the scientific basis for developing scenarios is weak. The uncertainty exists, but it is not possible to outline different possibilities
Total ignorance	Implies a deep level of uncertainty, to the extent of do not even know the existence of uncertainty.

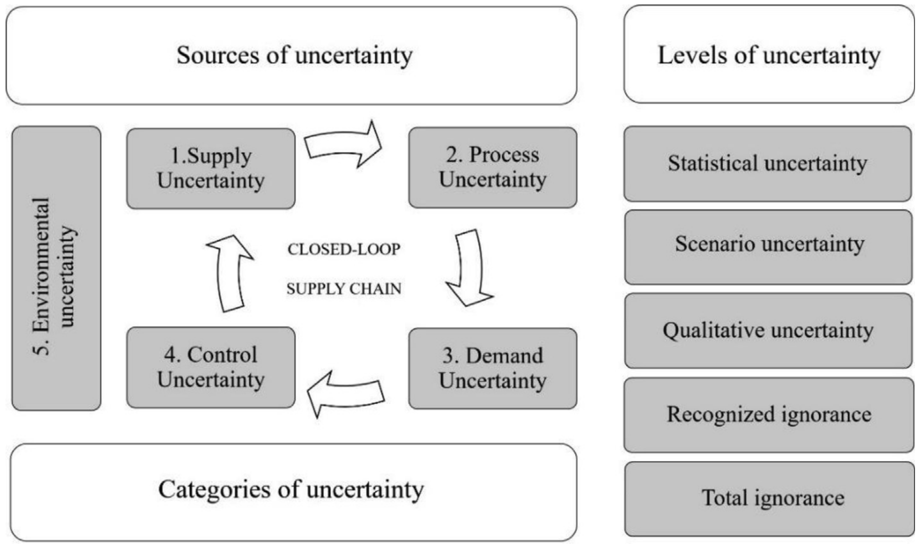

Fig. 2. Conceptual framework. The sources, categories, and levels of uncertainty in the closed-loop supply chain of Li-ion batteries for electric vehicles.

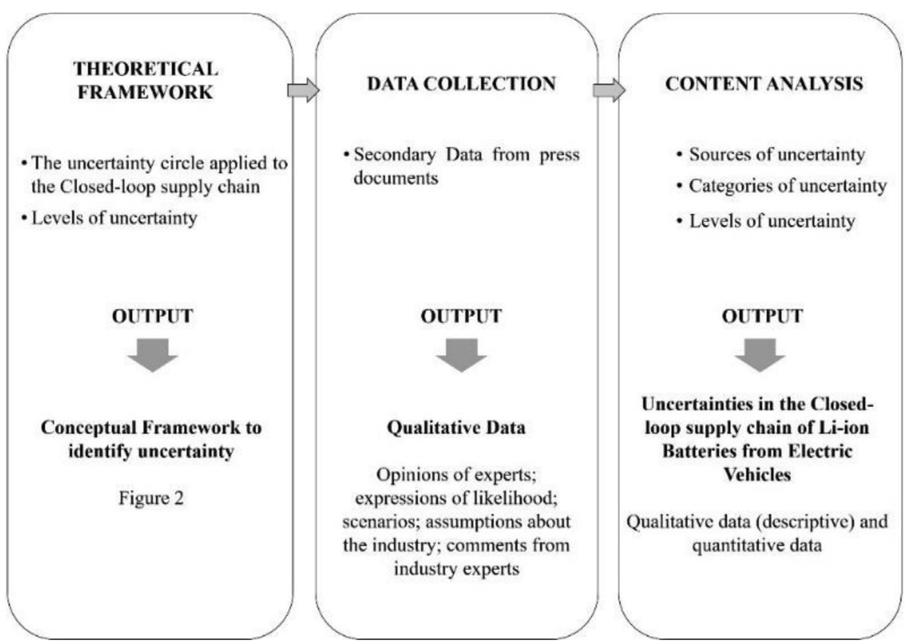

Fig. 3. Research procedure to identify uncertainty in the closed-loop supply chain of Li-ion batteries for electric vehicles.

was Thomas Reuters News Agency). Third, a sample data set is created containing all information from the viewpoint of the informants (industry experts that express their opinions directly or indirectly and describe the phenomenon of uncertainty they experience). The final sample containing the qualitative data is computed and analyzed in detail using content analysis. From the descriptive data, the variables and relationships are identified. Therefore, the uncertainties in the CLSC of Li-ion batteries from EVs are presented in qualitative and quantitative forms.

3.1. Data collection

The data that constitutes the sample was obtained from Reuters News Agency (Reuters.com). The choice of a single news agency to collect data and the exclusion of other secondary sources, such as industry reports, was made to ensure the study to be as consistent as possible. It should be noted that different media sources, for example, news or industry reports, can display a diversity of contents (e.g., interviews, images, and documents with different nature) making it difficult to assure the data reliability and validity. A reason for the use of the Reuters press media documents is the reliability of the agency that is often figuring in the references of academic and scientific literature. For instance, Williard et al. (2013) make references to Reuters' news articles concerning issues on Li-ion battery reliability on Boeing' 787 Dreamliners. To cite other examples: Baek and Elbeck (2015); Lagi et al. (2011). Another reason is that researchers use press media articles as secondary data sources to display reliable results and new insights about the phenomena they are studying. For instance,

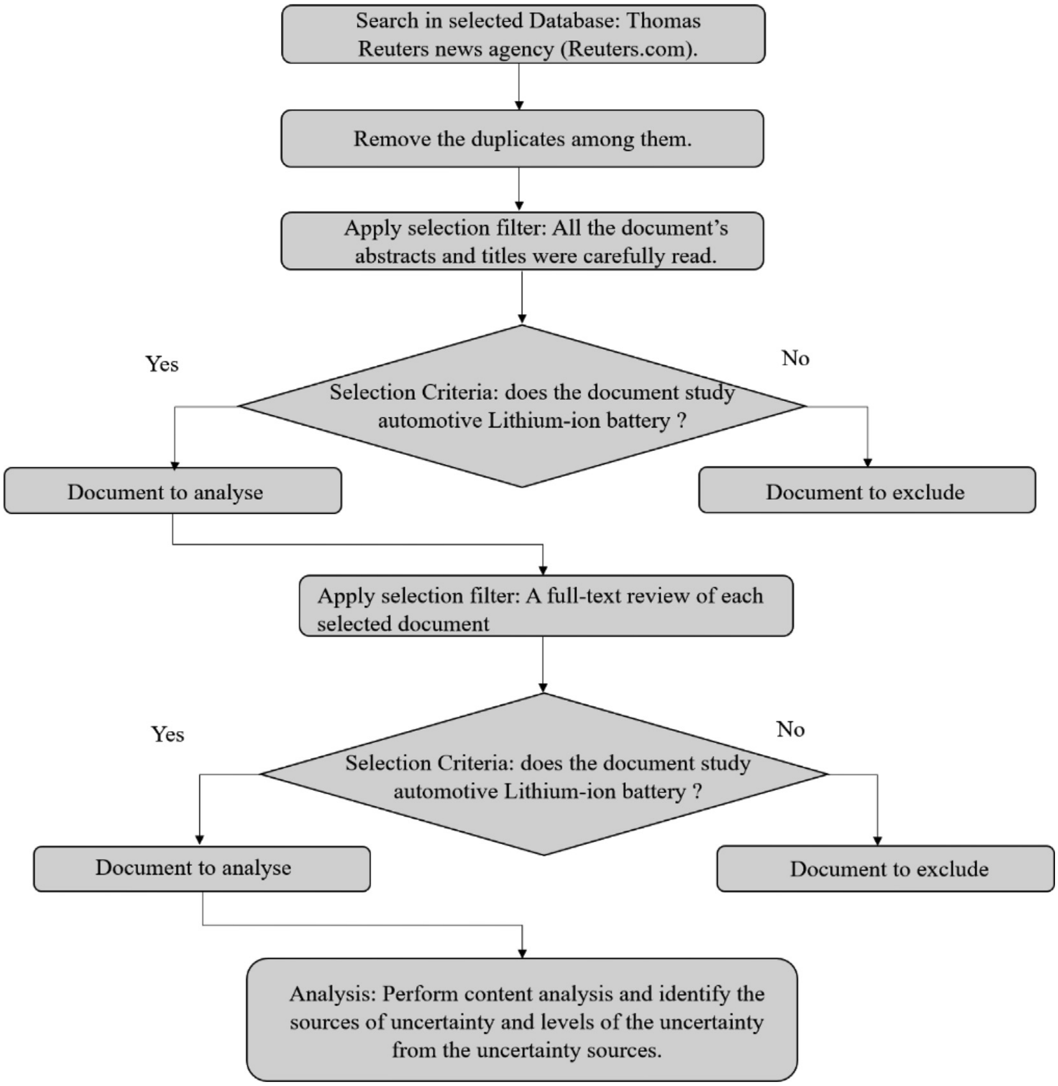

Fig. 4. Data collection and selection procedure. Adapted from Braz et al. (2018) to the context of this research.

Carvalho et al. (2012), collected empirical data from media news to show the links between supply chain disturbances, problems, and resilience strategies. On the other hand, Gosling et al. (2013) and van der Vorst and Beulens (2002) work also show that it is possible to address qualitative research methodologies to find uncertainty in the supply chain.

3.2. Sampling

Two searches at the time were performed using Reuters (Thomas Reuters) News Agency search engine (Reuters.com) with two different search strings (A and B).

String A: "lithium ion battery" AND uncertain* ***String B:*** "lithium ion battery" AND recycl*

Using the asterisk wildcard (*) is useful to leave a placeholder that is automatically filled by the search engine, this attains documents referring the terms: uncertainty, uncertainties, or uncertain, as well as recycling, recycler, recycle, or recyclers. The search engine was set to display each article entry in chronological order. The final count, considering the mentioned specifications, resulted in 119 documents for string A and 64 documents with string B. The sample is initially composed of 183 pieces of evidence (A + B) in which duplicates had to be eliminated. The timeline for the selection of the articles was set considering the latest article in the database till the earliest issue released in December 2019. The timeline of articles was: i) string A from July/09/2012 to November/08/2019; ii) string B from March/21/2012 to August /28/2019.

3.3. Data selection and collection procedure

Fig. 4 displays the data selection and collection procedure. The selection criteria for the documents to be included in the sample was whether they studied the supply chain of Li-ion batteries from EVs (that comprises statements, quotes, and comments from companies, experts, and supply chain members). Therefore, documents outside of the automotive Li-ion battery scope (e.g., documents about portable gadgets powered by Li-ion batteries or related to Li-ion batteries for the aeronautic industry) were discarded from the sample. In the end, from the 183 articles obtained, 32 met the selection criteria and comprised the selection to be part of this study. Appendix A provides the full list of the documents in the sample; an identification number (id. n.) was assigned for each document. Our data output is in the form of a document combining transcripts, notes, and observations from managers and experts from the automotive sector (e.g. Gosling et al. 2013).

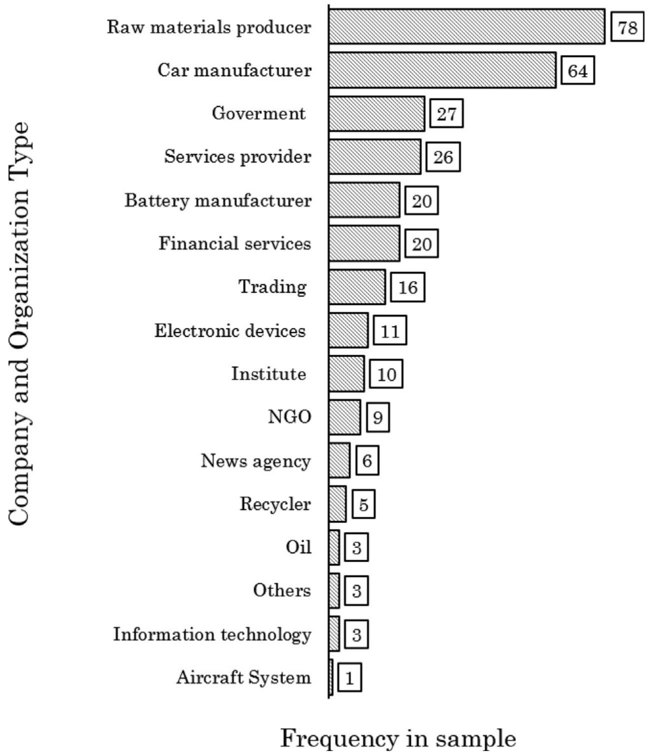

Fig. 5. Companies and organizations in the sample by type.

3.4. Content analysis

The content analysis follows Carvalho et al. (2012) approach: first, the variables are identified; second, the variables are defined according to the literature (the categories of each uncertainty source); third, the categories are described. The identification of the uncertainties is made using the sources of uncertainty from the uncertainty circle (supply, process, demand, and control). Furthermore, environmental uncertainty is also identified. The different categories emerge from Goltsos et al. (2018) work and are defined in Table 3. Subsequently, the sources of uncertainty are classified in different levels (statistical uncertainty, scenario uncertainty, qualitative uncertainty, and recognized ignorance) considering Table 4. To attain the viability of the content analysis, recommendations from experts that performed similar methods in previous research are taken into consideration. Dooley (2016) recommends that to be objective and complete, single-source should be considered. Second, multiple text documents should be treated independently rather than as a single text. Appendix B provides the sample characterization and Appendix C the data set obtained after the coding.

4. Content analysis

4.1. Sample characteristics

The data was collected from a sample of 32 press media documents. In the sample, 102 uncertainties from the CLSC of Li-ion batteries for EVs were identified. Some documents contained multiple uncertainties, others just one. On the one hand, 80 uncertainties came from documents obtained using string A and 22 uncertainties were retrieved from the documents obtained with string B. In the sample, different companies are referred. The frequency of companies and organizations in the sample by industry type is displayed in Fig. 5. This displays the number of times different companies appear in each document according to their characteristics and product.

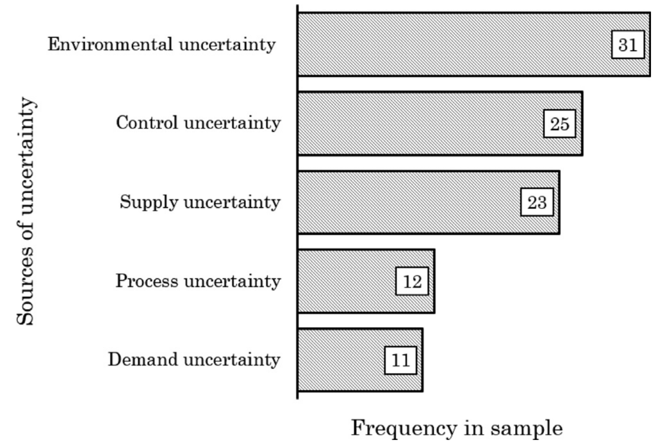

Fig. 6. Number of environmental, control, supply, process, and demand uncertainty evidence in the sample.

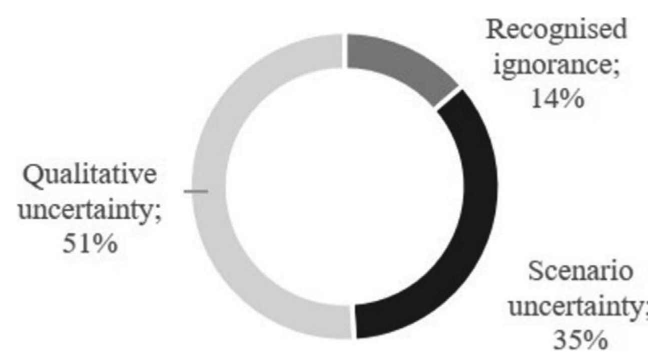

Fig. 7. Frequency of qualitative uncertainty, scenario uncertainty, and recognized ignorance in the sample.

Fig. 6 displays the number of uncertainties evidence in the sample by the source of uncertainty. Environmental, supply, and control uncertainty are the sources of uncertainty with the highest frequency in the sample. Environmental uncertainty is a broader variable that crosses companies' boundaries nationally and internationally. Therefore, the same uncertainty could affect many supply chain members. One evidence of this in the sample is '*Around half of global cobalt reserves is held by Democratic Republic of Congo (DRC), presenting a volatile cocktail of political, operational and ethical risk*' [id. n. 11]. To this end, environmental uncertainty regarding the Democratic Republic of Congo will affect every company that extracts cobalt in the country (i.e., the raw material producers). At the same time, this uncertainty will affect other companies (the battery manufacturers) that rely on the supply of cobalt from the Democratic Republic of Congo (this is also because cobalt is geographically concentrated).

The sample contains 52 uncertainties that fall under the qualitative level, 36 under scenario, and 14 recognized ignorance. Therefore, 51% of the found uncertainty falls under the qualitative level (Fig. 7). Qualitative uncertainty appears when the uncertainty is described. Scenario uncertainty occurs when there is a description of supply chain performance in the future. Recognized ignorance is when the uncertainty is simply acknowledged (this was considered to be when the informant referred to the word 'uncertainty' explicitly). Total ignorance is not possible to identify for its intrinsic nature. Additionally, to be

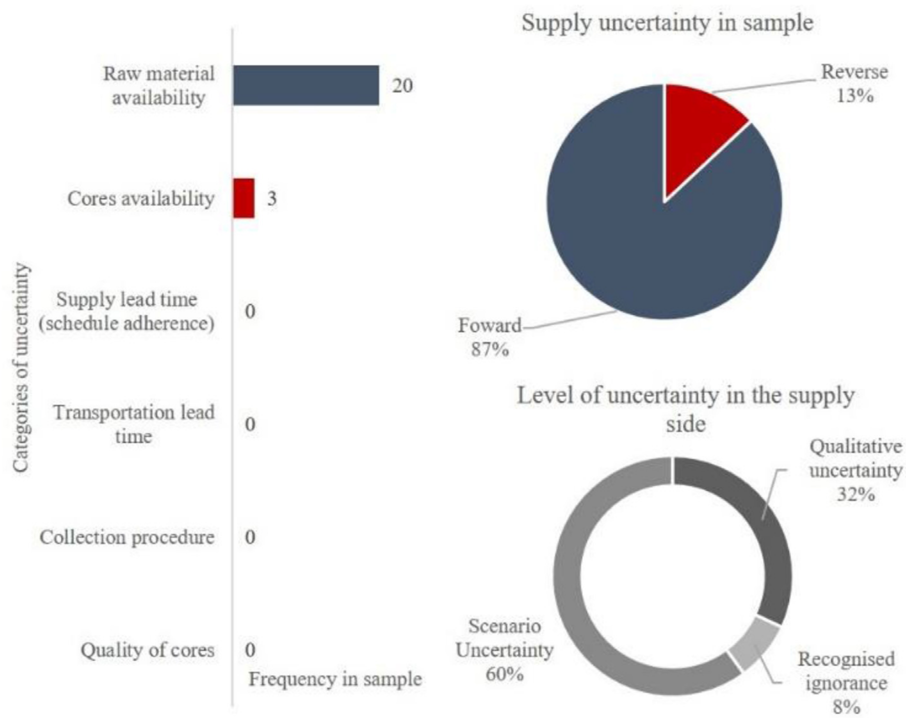

Fig. 8. Dashboard: Supply uncertainty.

considered within statistical uncertainty the data needs to be sufficiently descriptive to provide probabilities of an outcome. Therefore, the sample does not contain any uncertainty that is related to the statistical level.

4.2. Results and discussion

4.2.1. Uncertainty sources in the closed-loop supply chain of lithium-ion batteries from electric vehicles

In this section, the findings from the content analysis are examined in detail. A dashboard of each uncertainty source is presented from Fig. 8 to Fig. 12 which containing data regarding the distribution of the uncertainty pieces of evidence in the reverse and forward flow of the closed-loop, as well as the levels of uncertainty from that source in the sample. Table 5 contains part of the content analysis. The first 7 entries are all the evidence of uncertainties from the reverse flow found in the sample.

- ***Evidence of supply uncertainty***

The content analysis shows that 87% of the supply uncertainty is in the forward supply chain. All the supply uncertainty described by companies and organizations in the sample concern 'raw materials availability' in the forward flow and 'cores availability' in the reverse flow. The way the reverse and forward flow are related is that the cores that appear in the reverse flow are dependent on the number of batteries, which the forward supply chain puts in the market. In the same way, the batteries that are processed after the end-of-life will supply the forward flow with secondary raw materials, remanufactured batteries, or second-life batteries.

The pieces of evidence for uncertainty concerning the reverse flow are related to 'cores availability' as '*The main obstacle recyclers face now is a shortage of spent batteries to recycle to make their technology cost-effective*' [id. n. 32]. Accordingly, remanufacturers experience uncertainty with the availability of spare battery components for remanufacturing as well. Later this uncertainty will show a clear connection between both flows. For instance, in the sample is evidenced uncertainty regarding 'raw materials availability' of secondary cobalt that is expected to reach the aftermarket and incorporate new or remanufactured batteries '*extensive recycling of used batteries is likely to still leave a shortfall of cobalt*' [id. n. 31]. This uncertainty is described in the forward flow by the companies that consume secondary cobalt produced by recycling companies. Therefore, the supply uncertainty experienced in the reverse flow will be delivered to the forward flow. Hence, those results evidence what Goltsos et al. (2018) described as the 'boomerang' (the effect between the products going into the market and returning and augmented uncertainty in the CLSC).

Fig. 8 displays that 60% of the supply uncertainty in the sample falls under scenario level, 32% under qualitative and 8% are recognized ignorance. According to Mansoornejad et al. (2013), scenarios are generated in terms of feedstock supply and product demand. Managers often project scenarios that will help base their decisions on the best possible outcome. Therefore, much of the uncertainty in the sample related to supply and demand-side sources are scenarios.

- *Evidence of process uncertainty*

Process uncertainty is the uncertainty that occurs at the manufacturing level, related to the machinery. This uncertainty was found in a descriptive way, related to quality, yield, and processing times. All pieces of evidence of uncertainty found in the sample regarding the process side refer to the qualitative level (Fig. 9). Although statistical uncertainty could be expected, the sample did not reflect a quantitative description of probability. In the forward flow, 10 uncertainties are related to 'yield and quality'. In a qualitative outlook, this is described in the sample '*industry grapples with declining ore quality*'[id. n 5] and '*Fisker halted production of the Karma last July when A123 had trouble supplying batteries because of quality issues*' [id. n. 19]. Both describe qualitative uncertainty related to concerns with equipment performance and factory conditions; they unite passing inspection, which could lead to uncertainty with 'yield and quality'. One piece of evidence describing this situation is '*challenges extracting lithium in*

Table 5
Excerpt from the content analysis.

Id. n	Source of uncertainty	Category of uncertainty (Forward flow)	Category of uncertainty (Reverse flow)	Example of text found in the sample	Level of uncertainty
14	Supply uncertainty	N/A*	Cores availability	'And that's going to draw a lot of unwelcome attention from a physical supply chain desperately seeking spare units.'	Qualitative uncertainty
25	Environmental uncertainty	N/A	Technology	'There are very few working, economically viable technologies for recycling the majority of materials in lithium-ion batteries'	Qualitative uncertainty
28	Environmental uncertainty	N/A	Technology	'The plant can process 2,250 battery packs a year, and initially plans to refabricate 'a few hundred' units annually, Makino said, adding that 4R would see whether the process could also be used for batteries from the latest Leaf model, which uses a different battery chemistry.'	Scenario uncertainty
32	Supply uncertainty	N/A	Cores availability	'The main obstacle recyclers face now is a shortage of spent batteries to recycle to make their technology cost-effective'	Qualitative uncertainty
32	Process uncertainty	N/A	Yield and quality	'challenges extracting lithium in a reusable form.'	Qualitative uncertainty
32	Process uncertainty	N/A	Yield and quality	'The cost of recycling varies widely,'	Qualitative uncertainty
32	Supply uncertainty	N/A	Cores availability	'commercial development for recyclers is tough without the economies of scale that will come with a greater supply of spent batteries.'	Scenario uncertainty
13	Environmental uncertainty	Government regulation	N/A	' political, legal and ethical uncertainties surrounding the DRC's mining sector.'	Recognized ignorance
26	Environmental uncertainty	Technology	N/A	'The project, which has proven resources of 3.1 million tonnes of lithium, requires a new extraction technique because no lithium-from-clay operations currently exist anywhere around the world.'	Recognized ignorance
2	Supply uncertainty	Raw material availability	N/A	'It's also highly uncertain how much nickel ore Indonesia will be exporting in 2022 anyway.'	Recognized ignorance
14	Demand uncertainty	Quantity	N/A	'what the demand for cobalt as a constituent for future batteries will be is open to question.'	Qualitative uncertainty
10	Environmental uncertainty	Government regulations	N/A	'new restrictions could impact current supply and add uncertainty to future development'	Scenario uncertainty

Note: N/A – Not Applicable.

a reusable form' [id. n 32]. The way this is related to 'yield and quality' is that production targets must be met and raw materials should be extracted most efficiently and economically. Therefore, challenges to perform the extraction procedure will hamper those objectives and targets. The other evidence in 'yield and quality' concerning the reverse flow is described as '*The cost of recycling varies widely*' [id. n. 32]. Variations in recycling costs can occur due to the quality of the cores. Furthermore, many secondary battery raw materials retrieved in recycling will incorporate in new battery cells. Consequently, the quality level of secondary raw materials will affect the efficiency of manufacturing of new batteries. Therefore, quality and yield are considered jointly. These findings are close to what can be found in the literature. For instance, Egbue & Long, 2012 state that it '*is unknown if secondary lithium has a high enough quality for reuse*'. At the same time, Fisker comments ([id. n 19]) referring production of Karma EVs to be affected due to battery quality issues from the supplier.

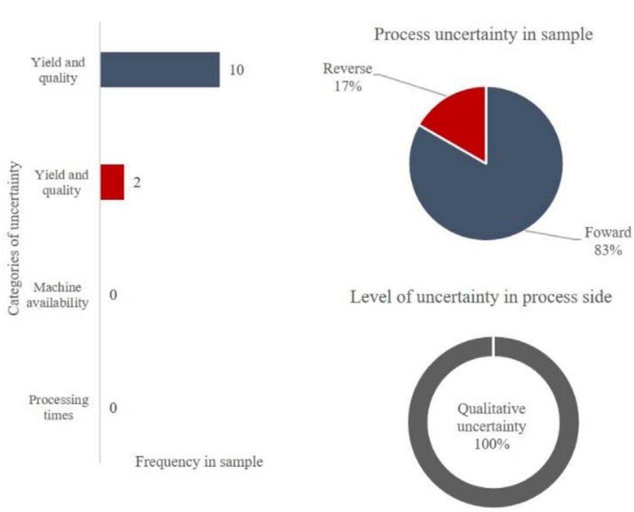

Fig. 9. Dashboard: Process uncertainty.

- **Evidence *of* demand uncertainty**

In the sample, demand uncertainty is found exclusively in the forward flow. 36% of the demand uncertainty found is in the form of a scenario (Fig. 10). That was already discussed when addressing the analysis of the sample in the supply uncertainty source. No evidence of demand uncertainty in the sample related to the reverse flow was found in the sample. On the one hand, this can be due to the chosen database not containing data reflecting demand uncertainty within the reverse flow. On the other, 'product cannibalization' might not be happening in the supply chain of Li-ion batteries because there are not enough batteries reaching the end-of-life that could reduce the sales of new ones. The forecast of Li-ion batteries reaching the end-of-life is about 17,000 for 2020 in Europe (European Commission, 2017) – by far a low number to create cannibalization of new batteries. The same can be considered, while there is no evidence of uncertainty regarding product substitution in the reverse flow. Demand uncertainty with 'quantity' is well described by the '*uncertainty about Japan imports*' [id. n 1]. In the 'life-cycle stage', it is noticeable that current raw materials could be replaced by others as evidenced in the sample '*Still, some copper executives are concerned that aluminum may try to supplant copper's role in electronic equipment in the near future*' [id. n 5] (this was not coded as 'product substitution' since 'product substitution' is a category from the reverse flow). Although, it fits perfectly 'life-cycle stage'. A sudden change in orders of raw materials could happen when the battery producer changes their cell chemistry. Considering a hypothetical situation in which aluminum supplants copper, the cycle stage of copper in the battery supply chain changes (for instances from growth to sudden decline without going under the other phases such as maturity). Concerning demand uncertainty regarding the 'quantity', it is referred to a scenario

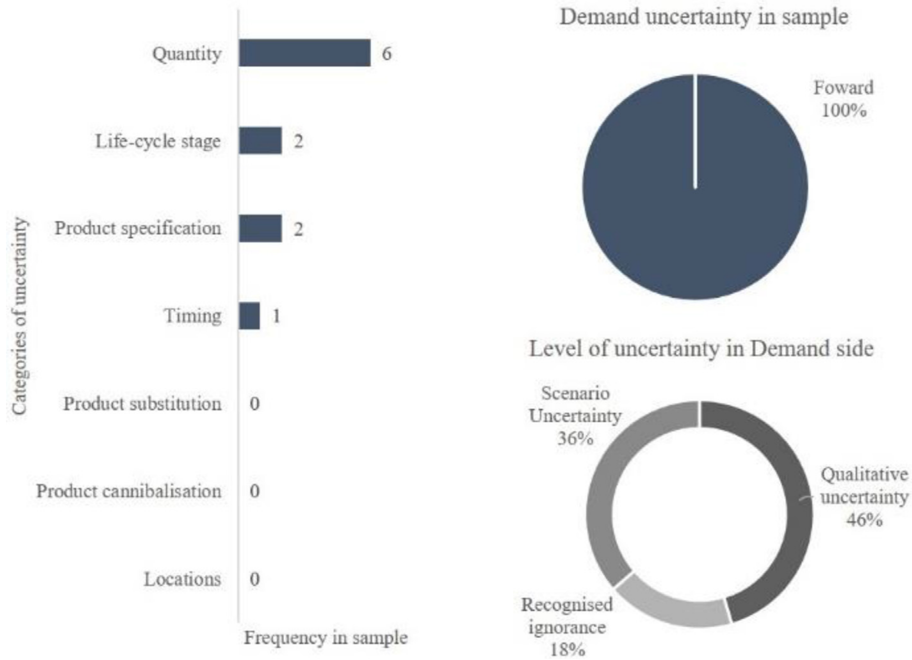

Fig. 10. Dashboard: Demand uncertainty.

prospect that is very inconclusive and uncertain since '*cobalt demand in the year 2021 could be anything from marginally lower to 80 percent higher than today*' [id. n 14] and another evidence statement revealing recognized ignorance '*what the demand for cobalt as a constituent for future batteries will be is open to question.*'[id. n 14]. Those two last pieces of evidence (id. n 14) support the 'boomerang effect'. The findings of this study are consistent with current academic literature. For example, Olivetti et al. (2017) also conclude within their scenario analysis that cobalt demand shows high uncertainties regarding 'quantity' (source). The same authors estimate that the cobalt demand will fluctuate between 136 and 330 kt in 2025.

- **Evidence of control uncertainty**

In the sample, 52% of the control uncertainty belong to the qualitative level. Furthermore, there is no evidence of control uncertainty in the reverse flow (Fig. 11). Control uncertainty is the uncertainty introduced from the mechanisms employed to control supply, process, and

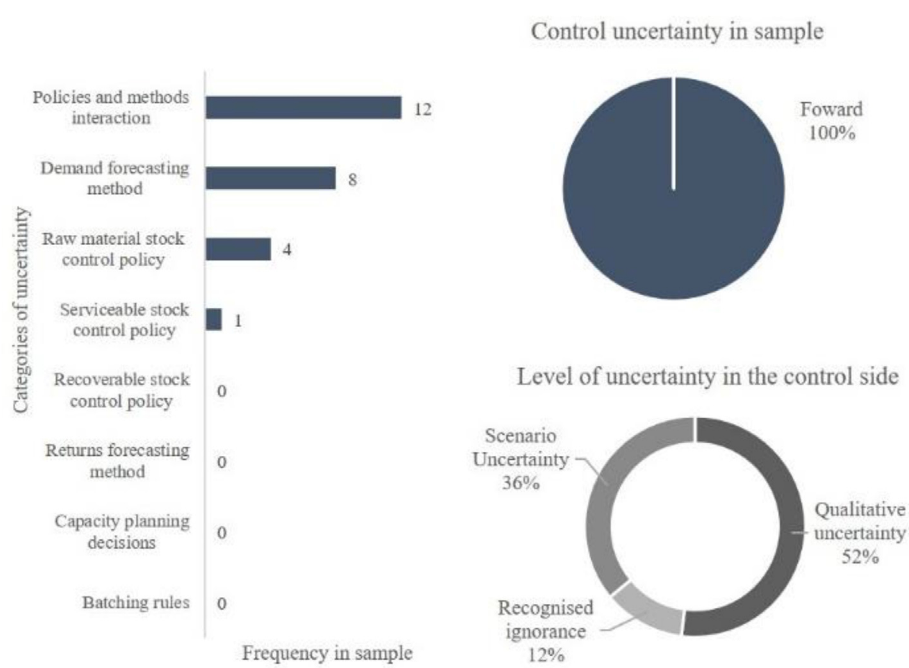

Fig. 110. Dashboard: Control uncertainty.

demand uncertainty (Goltsos et al., 2018). In the sample, a quote refers to uncertainty regarding the 'demand forecasting method' as *'Nickel's 'hope' premium, as it were, is being reinforced by physical stock building on the part of both the battery supply chain and speculators.'* [id. n. 3]. This is a speculative stock building with no evidence of nickel's actual demand, rather a belief that it will increase. Therefore, the battery supply chain and speculators increase their material stocks (a control action) with the hope to profit from later nickel demand by battery producers. Thus, uncertainty in control is introduced while trying to cope with demand uncertainty. One evidence of cobalt's influence on the 'boomerang effect' is '*growth rate of cobalt's demand is still uncertain*' [id. n 11]. This control uncertainty is delivered by the struggle to forecast cobalt demand (uncertainty regarding 'demand forecasting method'). There is evidence in existing studies that support this uncertainty. As mention concerning 'demand uncertainty', (Olivetti et al., 2017) forecast demand for cobalt in 2025 between 136 and 330 kt while the Öko-Institut forecast demand for cobalt between 60 and 260 kt in 2030 (Meyer et al., 2018). It becomes evident that there are significant uncertainties regarding the demand for cobalt both within and between the studies which can be justified with the 'control uncertainty'. Another uncertainty in the control side related to 'policies and methods interaction' is described in sample as '*Changing suppliers will not be easy, however, as it will take quite some time for LG Chem to run a series of tests and discuss the matter with clients*' [id. n. 1]. This concerns the 'partners' approach to supply chain management and the lack of information to decide in the short term. In the 'raw material stock control policy' one evidence is '*uncertainty over how much lithium the company had already mined.*' [id. n. 7]. This is uncertainty over how much lithium left the stockpile. At the same time, this creates uncertainty in the 'raw material availability' on the supply side. Evidence for uncertainty regarding the reserves of lithium can be found in (Zubi et al., 2018, p.304) who state that 'improvements in extraction technologies and higher lithium prices will result overtime in an increase in the global reserves'. In 2016, total global lithium reserves were estimated to be 16 million metric tons (Igogo et al., 2019). Hence, the exact forecast of global or regional lithium reserves remains uncertain due to 'environmental uncertainties'. Additionally, the sample only contains 5 recyclers (Fig. 5) and this could reflect why there are no evidences of uncertainty in the reverse flow affecting control operations.

- Evidence of environmental uncertainty

In the sample, we found that 94% of the pieces of evidence related to the 'environmental uncertainty' are associated with the forward flow with the uncertainty with 'government regulation' standing out (Fig. 12). This was expected since the EV market is going under new regulations. For instance, regulation (EU) No 540/2014 of the European Parliament and of the Council on the sound level of motor vehicles that will apply on 2019 vehicles. At the same time, government regulations affect every supply chain and the activity of companies that operate in a country. This makes many companies vulnerable to the same regulations and policies present in the countries they operate. In the sample, some uncertainty relates to China, the Democratic Republic of Congo, Japan, and the USA *'Around half of the global cobalt reserves is held by Democratic Republic of Congo (DRC), presenting a volatile cocktail of political, operational and ethical risk.'* [id. n. 11] and *'Political friction between China and Japan has delayed by one year a Nissan plan to gain 10 percent market share in China'* [id. n. 18] (Igogo et al., 2019). A clear statement in the sample that shows the implications of environmental uncertainty in terms of 'government regulation' is '*U.S-China trade war may hit long-term demand*' [id. n 5] described in the classification of scenario level. While the environmental uncertainty regarding cobalt from the Democratic Republic of Congo is widely discussed in the literature (Mayyas et al., 2019; Olivetti et al., 2017), few to non studies can be found dealing with the political difficulties regarding China.

Uncertainty with 'technology' is evidenced in the sample in both flows of the supply chain and described in the reverse flow *'There are very few working, economically viable technologies for recycling the majority of materials in lithium-ion batteries'* [id. 25] and in the forward flow '*The project, which has proven resources of 3.1 million tonnes of lithium, requires a new extraction technique because no lithium-from-clay operations currently exist anywhere around the world*' [id. n 26]. This demonstrates the uncertainty delivered by a lack of technology that was also expected given the early stage of EV production and battery

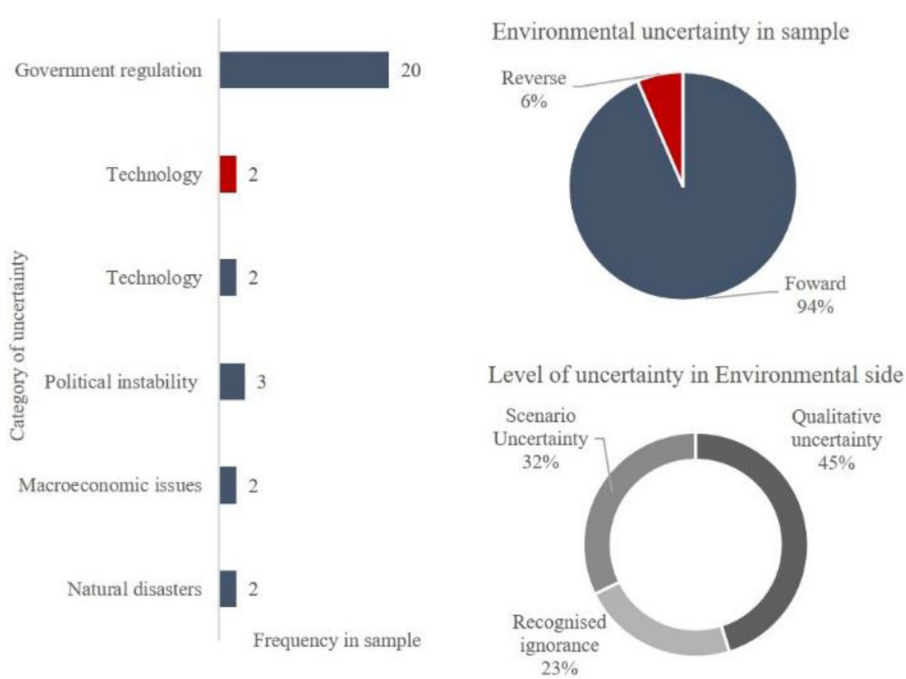

Fig. 12. Dashboard: Environmental uncertainty.

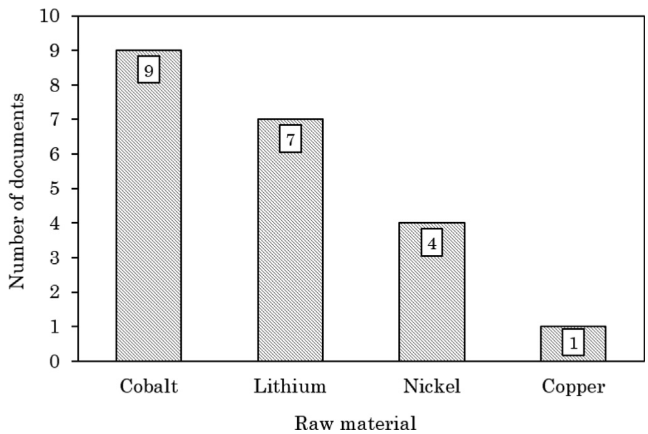

Fig. 13. Number of documents in sample referring uncertainty with cobalt, lithium, nickel, and copper.

recycling. For instance, Harper et al. (2019) refer to how the variety of battery cells, compositions, and architectures will impose challenges for battery recycling.

4.2.2. The impact of raw material availability and the 'boomerang effect' in the closed-loop supply chain

The sample under study highlights the uncertainty engendered by 'raw materials availability' in the CLSC. Fig. 13 accounts for the number of documents referring to uncertainty with Li-ion battery raw materials. In total, 16 documents containing pieces of evidence of uncertainty related to cobalt, lithium, nickel, and copper. The sample contains 9 documents [id. n. 11, 12, 13, 14, 27, 29, 30, 31, 32] referring to uncertainty regarding cobalt; 7 references to lithium [id. n. 4, 7, 9, 10, 14, 24, 26]; 4 documents evidence uncertainty regarding nickel [id. n. 2, 3, 6, 8] and 1 to copper [id. n 5]. The higher frequency of evidence in cobalt can be linked to the issues in the Democratic Republic of Congo; this is a region where cobalt reserves are concentrated, thus, a worldwide supply source for many companies. Cobalt, lithium, nickel, and copper are also considered as potential critical raw materials by the EU (Directorate-General for Internal Market et al., 2020). While all four materials meet the criteria for economic impact, only cobalt and lithium are considered with a high supply risk and are, therefore, considered to be critical raw materials.

The analysis of the qualitative data allows us to make conclusions about the uncertainty surrounding cobalt: 'raw materials availability' (*'strong cobalt demand, coupled with challenged supply due to a lack of primary cobalt mines)'* [id. n. 13]; 'political instability' (*'political instability in the Democratic Republic of Congo')* [id. n. 14]; 'government regulation' (*'political, legal and ethical uncertainties surrounding the DRC's mining sector.'* [id. n. 13]; demand uncertainty with 'quantity' (*'cobalt demand in the year 2021 could be anything from marginally lower to 80 percent higher than today)*' [id. n. 14]. These findings are consistent with the study of Olivetti et al. (2017) who analyzed the supply and demand of battery materials. The study also concludes that cobalt is the material within the Li-ion battery with the highest supply risk.

Regarding lithium, the analysis of the qualitative data evidences uncertainty regarding 'raw materials availability' [id. n 24] and 'raw material stock control policy' [id. n 7]. Regarding nickel the content analysis evidence uncertainty with 'raw materials availability' *'It's also highly uncertain how much nickel ore Indonesia will be exporting in 2022 anyway.'*[id. n 2]. The uncertainty in the sample concerning copper refers to its 'life-cycle stage'. Also, those results can be sustained with the European Commission's 2020 report of critical raw materials. The report identifies the raw materials with a higher risk of supply shortage and pointed out cobalt and lithium as critical raw materials due to their economic importance and supply risk (Directorate-General for Internal Market et al., 2020). This is particularly interesting considering the fact cobalt is the raw material with the highest number of evidence of uncertainty in the content analysis. The European Commission's report also points out that 68% of cobalt production is held by the Democratic Republic of Congo. This information sustains the relationship between the environmental and supply uncertainty demonstrated by the content analysis.

Table 6
Evidence of the augmented supply chain uncertainty related to cobalt.

Evidence	Extract from content analysis
Demand uncertainty 'quantity'	'what the demand for cobalt as a constituent for future batteries will be is open to question.'[id. n 14]
Supply uncertainty 'raw material availability'	'extensive recycling of used batteries is likely to still leave a shortfall of cobalt' [id. n 32]
Supply uncertainty 'cores availability'	'The main obstacle recyclers face now is a shortage of spent batteries to recycle to make their technology cost-effective' [id. n 32]
Control uncertainty 'Demand forecasting method'	'growth rate of cobalt's demand is still uncertain,' [id. n 11]

The evidence of uncertainty found in the supply and process sides of the reverse flow coupled with the evidence of demand uncertainty in the forward flow, demonstrate what Goltsos et al. (2018) described as the 'boomerang effect'. According to Goltsos et al. (2018, p.27) 'together with the demand uncertainty, the boomerang is accompanied by temporal, quantitative, and qualitative supply uncertainty and if not controlled would result in a high process uncertainty'. The uncertainty in the CLSC is augmented with uncertainty in demand, plus supply uncertainty concerning the quantity and quality of the returned product. That is the uncertainty with the 'yield and quality' (process), 'quantity' (demand), and 'cores availability'(supply) of the products that reach the end-of-life and enter back into the supply chain towards the reverse flow. Table 6 attains a proportion of the pieces of evidence in the sample that support augmented uncertainty in the CLSC related to cobalt.

5. Managerial and academic implications

The data and the uncertainties found in this study can be used by researchers in models for supply chain network redesign. Furthermore, the identification of the uncertainty is the preliminary step to identify and address effective strategies to improve supply chains. In practice, the pieces of evidence provided by this paper can give managers and researchers the ability to recognize where and which uncertainty is occurring in the electric automotive sector. Thus, practitioners can benefit from the detailed analysis provided in this paper to develop approaches for the design and management of the CLSC of Li-ion batteries for electric vehicles. In the following, some key managerial and academic implications of this study are given.

For managers, the key task to secure an economical and environmental viable electomobility is the design of a robust and resilient supply chain for raw materials and battery cells. Althaf and Babbitt (2021) describe two pathways to reduce supply risk within the supply chain of electronics and batteries. The first pathway is the increased use of recycling and, hence, secondary materials. However, they find that recycling is not feasible to reduce supply risk in the short term because of a lack of infrastructure and economically beneficial business models. Hence, building up a recycling infrastructure for critical raw materials, such as cobalt and lithium, is a promising policy to reduce risk and uncertainty in the long term. The second pathway is supply chain diversification. The key idea of this pathway is to spread the mining and production globally which leads to reduced impacts when locally concentrated disruptions occur. While this is a viable policy for materials and products with a noticeable global distribution, e.g., lithium and manganese, it remains infeasible for regional concentrated materials, e.g., the mining of cobalt. However, such concepts can be adapted for further production steps, e.g., building refineries for cobalt in Europe. Although this still not solves all challenges regarding cobalt mining from the Democratic Republic of Congo, it reduces the dependence on China and, hence, reduces the supply risk and uncertainty. Furthermore, the ongoing technological advancement of batteries may also contribute to reduced supply risk (Olivetti et al., 2017). New or improved cell chemistries, such as low cobalt cathode materials, e.g., NMC-811, decrease the generation of supply uncertainty. However, it must be noted, that such technological advances are likely to increase demand uncertainty regarding raw materials as well as technological uncertainties.

According to the managerial implications, new strategies for managing the identified uncertainties are needed. First, the study of Althaf and Babbitt (2021) gives some possible pathways to build a robust and resilient supply chain for Li-ion batteries. However, the high uncertainties regarding 'demand´ and 'quantity´ of cobalt necessitate further research. Regarding an extension of this study, future research should be conducted to answer a question delivered by Angkiriwang et al. (2014), inquiring if a relationship exists between uncertainty typologies (the categories of uncertainty) and the flexibility strategies adopted by manufacturing companies. The suggestion is to identify supply chain uncertainty together with the strategies employed by managers to overcome those uncertainties using a similar empirical approach. Furthermore, the identified uncertainties need to be tackled. For 'process' and 'environmental' uncertainty, multiple new research tasks occur.

Second, raw supply uncertainties regarding 'raw material availability' are the key challenge within the CLSC. In this context, control uncertainties regarding 'raw material stock control policy' and supply uncertainties regarding 'core availability' have a significant influence. Therefore, developing reliable forecasting methods for the availability of cores for recycling, upscale of mining capacities, and materials reserves seem to be a promising research task. The results influence the strategic supply chain design as well as the operational planning within existing supply chains.

Third, there is evidence for a lack of economic feasibility of recycling technologies. Two main reasons can be found. On the one hand, it must be noted that different sources of the study indicate challenges regarding 'quality and yield' in recycling. This results in a low value of the secondary materials. On the other hand, the small amounts of spent Li-ion batteries result in missing economies of scale. Therefore, different research tasks should be tackled in the future. A critical review of existing recycling technologies containing an extensive analysis of technological, environmental, and ecological feasibility is needed. The expected outcomes are the quantification of the influence of economies of scale for different recycling routes and the identification of challenges of existing recycling technologies. Based on the expected findings, existing recycling technologies can be improved or new recycling technologies be developed.

Last, as observed by the variety of different uncertainties, the currently emerging supply chain shows a high level of innovation. Especially, the combination of rapidly evolving production, recycling, and product technologies brings new challenges and opportunities. In this context, analyzing the market diffusion of innovative products considering the effects of evolving production and recycling technologies, as well as, the effect on CLSC and the different strategies used seems promising. Furthermore, developing strategic pathways to structure and plan the product innovations seems necessary to achieve an economical and ecological electromobility.

6. Conclusion

In this paper, the research question we propose to answer can be addressed as follows: what uncertainty occurs in the management of the closed-loop supply chain of Li-ion batteries from EVs? Thus, data were collected from 32 press documents and 102 pieces of evidence of uncertainty were found in the CLSC of Li-ion batteries for EVs. The content analysis identifies uncertainties regarding 'raw material availability', 'government regulations', 'yield and quality' 'policies and methods interaction', 'demand forecasting method', 'quantity', 'raw material stock control policy', 'technology', 'cores availability', 'political instability', 'life-cycle stage', 'macroeconomic issues', 'natural disasters', 'product specification', 'serviceable stock control policy', and 'timing'. We found evidence of uncertainty concerning the different battery raw materials, such as cobalt, lithium, nickel, and copper, in different degrees. Furthermore, the paper contains pieces of evidence that support the allegory of the boomerang effect (Goltsos et al. 2018). That is the augmented uncertainty in the CLSCs is based on the expectations that products sent to the market will return after the end of the use phase. The boomerang effect is described by the evidence of uncertainty regarding cobalt availability. The results show cobalt demand uncertainty concerning 'quantity' and supply uncertainty in the forward flow regarding 'raw material availability'. Additionally, there is evidence of control uncertainty regarding the 'demand forecasting method' of cobalt. Consequently, cobalt is leading to increased uncertainty in the supply chain structure that will further hit the reverse flow whereas recyclers anticipate the return of the boomerang (i.e., a battery that eventually will contain cobalt). In the reverse flow, the 'supply uncertainty' concerns the availability of spent batteries ('cores availability'). Regarding the reverse flow, the content analysis shows less evidence of uncertainty. This can be justified with the methodology focusing on the operational side of the CLSC. Also, the industry did not fully embrace reverse flow operations coupled with the low number of end-of-life automotive Li-ion batteries reaching the recycling phase.

Overall, the pieces of evidence show that most of the uncertainty found is in the qualitative form (50%), followed by scenario uncertainty (36%) and recognized ignorance (14%). Those results reveal that most of the uncertainty identified can be described or that managers can at least deliver a plausible description of how the supply chain of Li-ion batteries might evolve. The evidence of recognized ignorance revel that in some cases developing scenarios about the industry is still weak. To overcome limitations of content analysis (such as the subjectivity of the text and interpretation), this study had attention to the recommendations given by experts and past similar studies. Although restricting the diversity of results, the provided solution limits the data source and the timeline of the analysis. On one hand, the potential of the data analysis process is limited to the selected data source and the quality of the data that is found there. Nevertheless, the study identifies important uncertainties and presents managerial and academic implications to cope with the identified challenges.

Several studies regarding the uncertainty in the Li-ion supply chain can be further performed. Namely, the impact of the COVID-19 pandemic on this crucial supply chain. Moreover, battery minerals are set to become the most demanded resources, with Li-ion battery supply chains turning out to be the main ones. China is currently the main country that produces Li-ion batteries for battery production — meaning a significant shift in the supply chain. All these factors have an impact on uncertainty and have to be addressed in future studies.

Funding

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Appendix A. References of the documents in the sample

Table A- Documents in the sample (cont.)

Id. n.	Search string	Reference
1	A	Reuters (2019). South Korean battery maker LG Chem aims to rely less on Japanese parts amid trade row - Reuters. Retrieved December 07, 2019, from Reuters: https://www.reuters.com/article/us-southkorea-japan-labourers-lg-chem/south-korean-battery-maker-lg-chem-aims-to-rely-less-on-japanese-parts-amid-trade-row-idUSKCN1VI0XH.
2	A	Home, A. (2019). RPT-COLUMN-Nickel jumps but fear of Indonesia export ban is unfounded: Andy Home - Reuters: Retrieved December 07, 2019, from Reuters: https://www.reuters.com/article/metals-nickel/rpt-column-nickel-jumps-but-fear-of-indonesia-export-ban-is-unfounded-andy-home-idUSL8N24I468
3	A	Home, A. (2019). RPT-COLUMN-Why Goldman thinks nickel is trading like a biotech start-up: Andy Home - Reuters. Retrieved December 08, 2019, from Reuters: https://www.reuters.com/article/metals-nickel-ahome/rpt-column-why-goldman-thinks-nickel-is-trading-like-a-biotech-start-up-andy-home-idUSL8N23X4OP.
4	A	Reuters (2019). UPDATE 1-Livent cuts 2019 forecast on weak demand; shares tumble: A4. Retrieved November 27, 2019, from Reuters: https://fr.reuters.com/article/energySector/idUKL3N22J5EE.
5	A	Shabalala, Z. & Scheyder, E. (2019). Copper producers gather; electric cars seen driving demand growth. Retrieved December 08, 2019, from Reuters: https://www.reuters.com/article/us-chile-mining-preview/copper-producers-gather-electric-cars-seen-driving-demand-growth-idUSKCN1RJ0DY.
6	A	Home, A. (2019). Nickel rally fades, electric vehicle buzz doesn't: Andy Home: A6. Retrieved December 08, 2019, from Reuters: https://www.reuters.com/article/us-metals-nickel-ahome/nickel-rally-fades-electric-vehicle-buzz-doesnt-andy-home-idUSKCN1Q2045.
7	A	Sherwood, D. (2019). Exclusive: Chile nuclear watchdog weighs probe into fraud over lithium exports - documents - Reuters. Retrieved December 08, 2019, from Reuters: https://www.reuters.com/article/us-chile-lithium-exclusive/exclusive-chile-nuclear-watchdog-weighs-probe-into-fraud-over-lithium-exports-documents-idUSKCN1P91YG.
8	A	Home, A. (2018). China's Tsingshan rains on nickel bulls' party: Andy Home. Retrieved December 08, 2019, from Reuters: https://www.reuters.com/article/us-batteries-nickel-ahome/chinas-tsingshan-rains-on-nickel-bulls-party-andy-home-idUSKCN1N426Y.
9	A	Sherwood, D. (2018). A water fight in Chile's Atacama raises questions over lithium mining. Retrieved December 08, 2019, from Reuters: https://www.reuters.com/article/us-chile-lithium-insight/a-water-fight-in-chiles-atacama-raises-questions-over-lithium-mining-idUSKCN1MS1L8.
10	A	Sherwood, D. & Cambero, F. (2018). Exclusive: Chile says to clamp down on water rights in lithium-rich Salar de Atacama. Retrieved December 08, 2019, from Reuters: https://www.reuters.com/article/us-chile-lithium-water-exclusive/exclusive-chile-says-to-clamp-down-on-water-rights-in-lithium-rich-salar-de-atacama-idUSKCN1L827G.
11	A	Obayashi, Y. (2018). Japan takes steps to ensure stable cobalt supply for automakers. Retrieved December 08, 2019, from Reuters: https://www.reuters.com/article/us-japan-metals-cobalt/japan-takes-steps-to-ensure-stable-cobalt-supply-for-automakers-idUSKBN1KE1ZF.
12	A	Shabalala, Z. (2018). Glencore's Congo woes throw spotlight on country's cobalt dominance. Retrieved December 08, 2019, from Reuters: https://www.reuters.com/article/us-glencore-congo/glencores-congo-woes-throw-spotlight-on-countrys-cobalt-dominance-idUSKBN1I91TB.
13	A	Home, A. (2017). Cobalt, the heart of darkness in the shiny electric vehicle story: Andy Home. Retrieved December 09, 2019, from Reuters: https://www.reuters.com/article/us-cobalt-supply-ahome/cobalt-the-heart-of-darkness-in-the-shiny-electric-vehicle-story-andy-home-idUSKBN1DS316.
14	A	Home, A. (2017). RPT-COLUMN-Psst…wanna buy some cobalt? Just don't tell the auto guys!: Andy Home. Retrieved December 09, 2019, from Reuters: https://www.reuters.com/article/cobalt27-ipo-ahome/rpt-column-psst-wanna-buy-some-cobalt-just-dont-tell-the-auto-guys-andy-home-idUSL8N1JW4E7.
15	A	Jin, H. (2016). SK Innovation to delay China battery factory on regulatory uncertainty. Retrieved December 09, 2019, from Reuters: https://www.reuters.com/article/sk-innovation-china/sk-innovation-to-delay-china-battery-factory-on-regulatory-uncertainty-idUSL4N1DQ1F1.
16	A	Sage, ,Alexandria (2016). Electric Jaguar SUV highlights auto industry's cross currents. Retrieved December 09, 2019, from Reuters: https://www.reuters.com/article/us-autoshow-la-jaguar/electric-jaguar-suv-highlights-auto-industrys-cross-currents-idUSKBN13A0C4.
17	A	Reuters (2013). Nikkei falls 1.3 pct as profit-taking hits exporters; GS Yuasa tumbles. Retrieved December 10, 2019, from Reuters: https://www.reuters.com/article/markets-japan-stocks/nikkei-falls-1–3-pct-as-profit-taking-hits-exporters-gs-yuasa-tumbles-idUSL3N0CK7HD20130328.
18	A	Reuters (2013). Nikkei set to edge down, weakness in euro to weigh: A19. Retrieved December 10, 2019, from Reuters: https://www.reuters.com/article/markets-japan-stocks/nikkei-set-to-edge-down-weakness-in-euro-to-weigh-idUSL3N0CJQ4J20130327.
19	A	Shirouzu, N. (2013). "'Green-car" maker Fisker seeks salvation in China: sources. Retrieved December 10, 2019, from Reuters: https://www.reuters.com/article/us-autoshow-fisker/green-car-maker-fisker-seeks-salvation-in-china-sources-idUSBRE90C00H20130113.
20	A	Reuters (2012). Fisker: Karma battery did not cause Houston fire. Retrieved December 10, 2019, from Reuters: https://www.reuters.com/article/us-karma-houston/fisker-karma-battery-did-not-cause-houston-fire-idUSBRE8471FI20120508.

(*continued on next page*)

References of the documents in the sample (*continued*)

Table A- Documents in the sample (cont.)

Id. n.	Search string	Reference
21	A	Klayman, B. (2012). Electric car revolution faces increasing headwinds. Retrieved December 10, 2019, from Reuters: https://www.reuters.com/article/uk-electriccars/electric-car-revolution-faces-increasing-headwinds-idUSLNE82K05U20120321.
22	B	Home, A. (2019). COLUMN-The battery metal no one wants to talk about: Andy Home. Retrieved December 11, 2019, from Reuters: https://wwwhttps://www.reuters.com/article/metals-lead-ahome/column-the-battery-metal-no-one-wants-to-talk-about-andy-home-idUSL5N2712YE.
23	B	Ross, A. & Lewis, B. (2019). Congo mine deploys digital weapons in fight against conflict minerals. Retrieved December 11, 2019, from Reuters: https://www.reuters.com/article/us-congo-mining-insight/congo-mine-deploys-digital-weapons-in-fight-against-conflict-minerals-idUSKBN1WG2W1.
24	B	Scheyder, E. (2019). Exclusive: United States sets sights on China in new electric vehicle push. Retrieved December 12, 2019, from Reuters: https://www.reuters.com/article/us-usa-lithium-exclusive/exclusive-united-states-sets-sights-on-china-in-new-electric-vehicle-push-idUSKCN1RH1TU.
25	B	Reuters (2019). Finnish utility Fortum joins battery recycling market. Retrieved December 12, 2019, from Reuters: https://www.reuters.com/article/us-fortum-batteries/finnish-utility-fortum-joins-battery-recycling-market-idUSKCN1R61RW.
26	B	Taylor, S. (2018). Lithium Americas sees rapid development of major U.S. lithium project. Retrieved December 12, 2019, from Reuters: https://www.reuters.com/article/us-lithium-americas-mine/lithium-americas-sees-rapid-development-of-major-u-s-lithium-project-idUSKBN1JH3C3.
27	B	Daly, T. (2018). Chinese battery firms join Responsible Cobalt Initiative - Reuters. Retrieved December 12, 2019, from Reuters: https://www.reuters.com/article/us-china-electricvehicles-cobalt/chinese-battery-firms-join-responsible-cobalt-initiative-idUSKCN1IT04P.
28	B	Reuters (2018). Nissan spins up new plant to give second life to EV batteries. Retrieved December 12, 2019, from Reuters: https://www.reuters.com/article/us-nissan-battery/nissan-spins-up-new-plant-to-give-second-life-to-ev-batteries-idUSKBN1H30DD.
29	B	Burton, M. & Mordant, N. (2018). RPT-Battery makers descend on Australia, Canada cobalt developers. Retrieved December 12, 2019, from Reuters: https://www.reuters.com/article/mining-cobalt/rpt-battery-makers-descend-on-australia-canada-cobalt-developers-idUSL3N1R216F.
30	B	Reuters (2018). Glencore signs massive cobalt sale deal with China's GEM. Retrieved December 12, 2019, from Reuters: https://www.reuters.com/article/us-gem-glencore-cobalt/glencore-signs-massive-cobalt-sale-deal-with-chinas-gem-idUSKCN1GQ3B3.
31	B	Russell, C. (2018). RPT-COLUMN-Congo's cobalt hopes risk the same ruinous road as Thai rice: Russell. Retrieved December 12, 2019, from https://www.reuters.com/article/column-russell-cobalt-congo/rpt-column-congos-cobalt-hopes-risk-the-same-ruinous-road-as-thai-rice-russell-idUSL4N1Q912K.
32	B	Harvey, J. (2017). Metal recyclers prepare for electric car revolution. Retrieved December 13, 2019, from Reuters: https://www.reuters.com/article/us-batteries-recycling-analysis/metal-recyclers-prepare-for-electric-car-revolution-idUSKBN1DH1DS.

Appendix B - sample characterization

Table B Sample characterization (cont.)

Id. n.	No. evidences uncertainty in document	No. of companies/ organizations in the document	Companies7organizations in sample
1	3	7	LG Chem; Apple Inc; General Motors; YoulChon Chemical Co Ltd; Dai Nippon Printing Co Ltd; Showa Denko KK; South Korean government
2	2	5	London Metal Exchange; Indonesian government; Goldman Sachs; Tsingshan Group; Indonesian Energy and Minerals Resources
3	4	8	London Metal Exchange; International Nickel Study Group (INSG); Goldman Sachs; Adamas Intelligence; Contemporary Amperex Technology Co; Automotive Energy Supply Corp; Tsingshan;
4	3	2	Livent Corp; Refinitiv
5	7	12	London Metal Exchange; Comex; Shanghai Futures Exchange; Freeport-McMoRan Inc; Antofagasta Plc; BHP; Anglo American Plc; Jefferies; Nevada Copper Corp; Quantum Minerals Ltd; Glencore; Roskill
6	6	7	London Metal Exchange; Vale; Tsingshan Group; Anglo American; Benchmark Mineral Intelligence; Brazil's National Mining Agency; Marex Spectron.
7	5	4	CCHEN; Albemarle Cor; SQM; Nomura
8	4	12	London Metal Exchange; Tsingshan Holding Group; Vale; Contemporary Amperex Technology; GEM Co Ltd; Morowali industrial park; CRU; WoodMac; Citi; Huayou; International Nickel Study Group; Indonesia government
9	6	3	Albermarle Corp; SQM; Corfo
10	3	5	Albemarle; SQM; BHP; Zaldivar; Stormcrow Capital
11	3	5	Toyota Motor Corp; Nissan Motor Co Ltd; Honda Motor Co Ltd; Roskill; Japan's Ministry of Economy, Trade and Industry;
12	6	8	Glencore; Mutanda Mining; CRU; Kamoto Copper Co; Gecamines; RBC; Benchmark Mineral Intelligence; London Metal Exchange
13	5	16	Royal Dutch Shell; Eurasian Resources Group; London Metal Exchange (LME); Yantai Cash Industrial; Financial Times; The Carter Center; Gecamines; Glencore; Groupe Forrest; Tesla; Apple; DRC government; S&P Global Market Intelligence; iTSCi; Volkswagen; CRU
14	10	15	London Metal Exchange; Canada's Venture Exchange; Cobalt 27 Capital Corp; Glencore; United States Geological Survey (USGS); C. Steinweg; Vollers Group; Palisade Resources Corp; Asian Mineral Resources; Pala Investments; Green Energy Metals Fund; Portal Capital investment group; JPMorgan; BlackRock; RFC Ambrian
15	1	10	SK Innovation Co Ltd; China's Ministry of Industry and Information Technology; SNE Research; Samsung SDI; LG Chem; BYD Co; Amperex Technology Ltd; Beijing Automotive Group; Beijing Electronics; South Korea's trade ministry
16	2	13	Jaguar; BMW AG; SUVs; General Motors Co; Ford Motor Co; Fiat Chrysler Automobiles NV; Alfa Romeo; Volkswagen AG; Tesla; Audi; BMW; Mercedes-Benz; Tata Motors.
17	1	6	GS Yuasa Corp; Nikkei; Mitsubishi Motors Corp; Kawasaki Kisen Kaisha; Tachibana Securities; Bank of Japan (BOJ);
18	3	9	Nikkei; Bank Of Japan; Nissan Motor Co; Mazda Motor Co; Nikon Corp; Renault-Nissan; Nomura Holdings; Toyota Motor Corp; Mitsubishi Motors Corp
19	2	10	Fisker Automotive Inc; U.S. government; China Grand Automotive Services Co; Wanxiang Group; A123 Systems; U.S. Department of Energy; Tesla Motors Inc; Daimler AG ; Toyota Motor Corp; Evercore Partners
20	3	6	Fisker; A123 Systems; General Motors Co; Consumer Reports magazine; AutoWeek magazine; National Highway Traffic Safety Administration;
21	1	30	Consumer Reports magazine; General Motors Co; Fisker; Edmunds.com; U.S administration; Lux Research; Nissan; Toyota; Ford; Honda; BMW; Fiat; Tesla; A123 Systems; University of Rochester; Fiat-Chrysler; Lundberg Survey; Daimler; GM; U.S. Department of Energy; Ener1 Inc; Aptera Motors; AeroVironment; Mitsubishi; Kohl's; Walgreen WAG.N; PricewaterhouseCoopers; Chrysler; The CarLab; Kool-Aid (não tem nada haver com baterias… marca de sumos)

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Appendix B - sample characterization (*continued*)

Table B Sample characterization (cont.)

Id. n.	No. evidences uncertainty in document	No. of companies/ organizations in the document	Companies7organizations in sample
22	1	11	Wood Mackenzie; The Consortium for Battery Innovation (CBI); Advanced Lead Acid Battery Consortium; U.S. city authorities; International Lead Association (ILA); Battery Council International; EUROBAT; Association of Battery Recyclers; BEST Battery Briefing; European Union; European Chemicals Agency
23	2	18	RCS Global; Societe Miniere de Bisunzu (SMB); Apple; Samsung; IBM; Ford; GM; International Peace Information Service (IPIS); Danish Institute for International Studies; Circulor; Volvo; U.N; London Metal Exchange; U.S. Geological Survey; Tesla; U.S. Securities and Exchange Commission; Danish Institute for International Studies; International Tin Association initiative (ITSCI)
24	1	21	U.S. government; Volkswagen AG; Tesla Inc; Benchmark Minerals Intelligence; SK Innovation Co; U.S. Department of State; U.S. Department of Energy; U.S. Department of the Interior; U.S. Geological Survey; Energy and Natural Resources; Ford Motor Co; General Motros Co; Albemarle Corp; Livent Corp; ioneer Ltd; Standard Lithium Ltd; Lanxess AG; Lithium Americas Motors Co Committee; Lithium Americas Corp; U.S. Critical Minerals; GM;
25	1	2	Fortum; Fortum Recycling and Waste
26	1	4	Lithium Americas Corp; Ganfeng Lithium; U.S Commerce Department;
27	1	13	Contemporary Amperex Technology Co Ltd (CATL); GEM Co Ltd; Responsible Cobalt Initiative (RCI); Apple Inc; HP Inc; Huawei; Zhejiang Huayou Cobalt Co; Samsung SDI; Volvo; BMW; Daimler; GEM; London Metal Exchange
28	1	5	Nissan Motor Co; 4R Energy Corporation; Sumitomo Corp; Toyota Motor Corporation; U.S. Argonne National Laboratory
29	2	21	Cobalt Blue; SK Innovation Co Ltd; Australian Mines; Aeon Metals; Northern Cobalt; Canada's Ecobalt; Fortune Minerals; Beijing Easpring Material Technology Co; Clean Teq; Glencore Plc; ERG; Darton Commodities; GEM Co Ltd; Ardea Resources; Fortune Minerals; Panasonic; Tesla Inc; Canaccord Genuity; Samsung SDI; LG Chem; Tribeca Global Natural Resources Fund
30	1	2	Glencore Plc; GEM Co Ltd
31	4	6	Thai government; DRC government; Ivanhoe Mines; Gecamines; African Mining Indaba; Kinshasa government
32	7	10	Benchmark Mineral Intelligence; CRU; American Manganese; Umicore; Pury Pictet Turrettini & Cie; NSF Wealth Management's Global New Mobility fund; Retriev Technologies; Accurec; Australia Neometals; BMW;

Appendix c – Data set

Table C. Data set (cont.)

Id. n	Source of uncertainty	Category of uncertainty (Forward flow)	Category of uncertainty (Reverse Flow)	Example of text found in the sample	Level of uncertainty
14	Supply uncertainty	N/A	Cores availability	"And that's going to draw a lot of unwelcome attention from a physical supply chain desperately seeking spare units."	Qualitative uncertainty
32	Supply uncertainty	N/A	Cores availability	"The main obstacle recyclers face now is a shortage of spent batteries to recycle to make their technology cost-effective"	Qualitative uncertainty
32	Supply uncertainty	N/A	Cores availability	"commercial development for recyclers is tough without the economies of scale that will come with a greater supply of spent batteries"	Scenario uncertainty
2	Supply uncertainty	Raw material availability	N/A	"It's also highly uncertain how much nickel ore Indonesia will be exporting in 2022 anyway."	Recognised ignorance
5	Supply uncertainty	Raw material availability	N/A	"From a numbers perspective we have a deficit in copper, and it's expected to be a tighter market in 2019 relative to last year"	Scenario uncertainty
5	Supply uncertainty	Raw material availability	N/A	"lack of new supply and steady demand"	Qualitative uncertainty
9	Supply uncertainty	Raw material availability	N/A	"Chile's water regulator was preparing restrictions on new water rights in the Salar in part because of uncertainty over how much extraction it can support"	Recognised ignorance
9	Supply uncertainty	Raw material availability	N/A	"concerns over just how much brine is left and how long it will last (…) the filings had potential implications for the global production of lithium"	Qualitative uncertainty
9	Supply uncertainty	Raw material availability	N/A	"If SQM is extracting more brine than it is permitted from the Salar, that can have repercussions on the availability of reserves in the basin for other projects,""	Scenario uncertainty
9	Supply uncertainty	Raw material availability	N/A	"SQM has accused Albemarle of overdrawing brine at its mine and questioned in a filing whether its rival's actions could have repercussions on the availability of brine reserves in the Salar."	Scenario uncertainty
10	Supply uncertainty	Raw material availability	N/A	"future lithium supply anticipates a big chunk of growth from SQM and Albermarle on Atacama, so if that's in any way endangered that changes the supply picture dramatically"	Scenario uncertainty
12	Supply uncertainty	Raw material availability	N/A	"If (Katanga's mine ramp-up) is disrupted then this could lead to significant shortages in the short term, and the market would most likely return to a deficit next year as a result,""	Scenario uncertainty
13	Supply uncertainty	Raw material availability	N/A	"This concentration of supply risk, both in terms of physical units and ethical sourcing, isn't going away any time soon and could even worsen."	Scenario uncertainty
14	Supply uncertainty	Raw material availability	N/A	"strong cobalt demand, coupled with challenged supply due to a lack of primary cobalt mines"	Qualitative uncertainty
14	Supply uncertainty	Raw material availability	N/A	"a market that is widely viewed by analysts as being in transition from a state of supply surplus to one of shortfall."	Qualitative uncertainty
14	Supply uncertainty	Raw material availability	N/A	"The irony is that if they're right and the cobalt price does go stratospheric, it will be because there's not enough of it around to meet burgeoning demand from the battery sector."	Scenario uncertainty
24	Supply uncertainty	Raw material availability	N/A	"Lithium development projects have historically faced numerous obstacles, so that production number is far from guaranteed."	Qualitative uncertainty
29	Supply uncertainty	Raw material availability	N/A	"cobalt projects in Australia and Canada to lock in supplies of the critical battery ingredient ahead of expected shortages as demand for electric vehicles revs up"	Scenario uncertainty
30	Supply uncertainty	Raw material availability	N/A	"Expectations of supply shortages have fueled a cobalt rally"	Scenario uncertainty
31	Supply uncertainty	Raw material availability	N/A	"extensive recycling of used batteries is likely to still leave a shortfall of cobalt"	Scenario uncertainty
31	Supply uncertainty	Raw material availability	N/A	"cobalt supply crunch on the horizon,"	Scenario uncertainty
32	Supply uncertainty	Raw material availability	N/A	"expected shortfall in materials such as cobalt and lithium when sales of electric cars take off."	Scenario uncertainty
32	Supply uncertainty	Raw material availability	N/A	"Mining enough cobalt to meet demand is a particular concern as most of the world's supplies come from Democratic Republic of Congo, where mining areas areprone to conflict. The price of cobalt COB-CATH-LON has more than doubled so far this year."	Qualitative uncertainty
5	Process uncertainty	Yield and quality	N/A	" industry grapples with declining ore quality"	Qualitative uncertainty
8	Process uncertainty	Yield and quality	N/A	"High-pressure-acid-leaching (HPAL) technology has a troubled history of operational problems and slow ramp-ups. Brazil's Vale is still struggling with its Goro plant after six years of operation."	Qualitative uncertainty
17	Process uncertainty	Yield and quality	N/A	"GS Yuasa Corp, which tumbled 11.1 percent after Mitsubishi Motors Corp said a lithium-ion battery in its plug-in hybrid Outlander overheated last week. The automaker sunk 3.9 percent."	Qualitative uncertainty
18	Process uncertainty	Yield and quality	N/A	"A lithium-ion battery on a single Mitsubishi Motors Outlander plug-in hybrid overheated last week, the Japanese carmaker said on Wednesday"	Qualitative uncertainty
19	Process uncertainty	Yield and quality	N/A	"Fisker halted production of the Karma last July when A123 had trouble supplying batteries because of quality issues."	Qualitative uncertainty
20	Process uncertainty	Yield and quality	N/A	" regulators opened an investigation into General Motors Co's Chevrolet Volt after some battery packs caught fire during testing."	Qualitative uncertainty
20	Process uncertainty	Yield and quality	N/A	"Fisker has fielded tough questions about the reliability of the Karma after a spate of highprofile battery problems"	Qualitative uncertainty

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(*continued*)

Table C. Data set (cont.)

Id. n	Source of uncertainty	Category of uncertainty (Forward flow)	Category of uncertainty (Reverse Flow)	Example of text found in the sample	Level of uncertainty
20	Process uncertainty	Yield and quality	N/A	"In March, a Karma battery failed during a test conducted by Consumer Reports magazine. Fisker recalled 239 Karma cars in December to fix a battery defect that raised the risk of a fire."	Qualitative uncertainty
21	Process uncertainty	Yield and quality	N/A	"The Karma that died during testing by Consumer Reports magazine was another blow following a recall of more than 200 of the cars last year and the halting of sales in January for a software issue"	Qualitative uncertainty
29	Process uncertainty	Yield and quality	N/A	"cobalt developers, analysts warn the projects are not without risk, given fickle technology and the high cost of processing out contaminants"	Qualitative uncertainty
32	Process uncertainty	N/A	Yield and quality	"challenges extracting lithium in a reusable form (…)Most recyclers heat old batteries to high temperatures to retrieve metals, a process known as pyrometallurgy. But this generally only yields cobalt, and sometimes nickel, while lithium is more difficult and expensive to extract."	Qualitative uncertainty
32	Process uncertainty	N/A	Yield and quality	"The cost of recycling varies widely,"	Qualitative uncertainty
5	Demand uncertainty	Life-cycle stage	N/A	"Still, some copper executives are concerned that aluminum may try to supplant copper's role in electronic equipment in the near future"	Scenario uncertainty
11	Demand uncertainty	Life-cycle stage	N/A	"Japanese trading houses and mining companies, in general, are hesitant to make major investments in cobalt projects due also to risks that the mineral may not be needed if battery technology develops to provide alternatives"	Scenario uncertainty
6	Demand uncertainty	Product specification	N/A	"This is the core of nickel's electric bull narrative, one of a supply chain that is unprepared for a fundamental usage shift away from stainless steel to batteries. A shift that will be compounded by the need for the "right sort" of high-grade nickel to meet battery-makers' strict chemical requirements."	Scenario uncertainty
14	Demand uncertainty	Product specification	N/A	"Everyone agrees that the electric vehicle revolution has arrived but beyond that there is no consensus as to how fast it might evolve.And what sort of batteries will those vehicles use?"	Qualitative uncertainty
1	Demand uncertainty	Quantity	N/A	"uncertainty about Japan imports"	Recognised ignorance
4	Demand uncertainty	Quantity	N/A	"We are seeing weaker near-term demand for our highperformance lithium hydroxide"	Qualitative uncertainty
5	Demand uncertainty	Quantity	N/A	"lack of new supply and steady demand"	Qualitative uncertainty
14	Demand uncertainty	Quantity	N/A	"cobalt demand in the year 2021 could be anything from marginally lower to 80 percent higher than today."	Scenario uncertainty
14	Demand uncertainty	Quantity	N/A	"what the demand for cobalt as a constituent for future batteries will be is open to question.""	Qualitative uncertainty
16	Demand uncertainty	Quantity	N/A	"With a mandate that zero-emission vehicles make up 15 percent of automakers' California sales by 2025, the state is driving carmakers to roll out carbon-free vehicles in an environment of uncertain future demand. "	Recognised ignorance
14	Demand uncertainty	Timing	N/A	"Everyone agrees that the electric vehicle revolution has arrived but beyond that there is no consensus as to how fast it might evolve."	Qualitative uncertainty
2	Control uncertainty	Demand forecasting method	N/A	"speculative buying, both in the paper and physical market"	Qualitative uncertainty
3	Control uncertainty	Demand forecasting method	N/A	"Nickel bulls are undeterred, keeping faith with the metal's future prospects as a key raw material in the coming electric vehicle (EV) revolution."	Scenario uncertainty
3	Control uncertainty	Demand forecasting method	N/A	"Nickel's "hope" premium, as it were, is being reinforced by physical stock building on the part of both the battery supply chain and speculators. "Nickel - the 'hope stock' ofmetals""	Scenario uncertainty
3	Control uncertainty	Demand forecasting method	N/A	"forecasting nickel difficult"	Qualitative uncertainty
6	Control uncertainty	Demand forecasting method	N/A	"Nickel has the largest speculative long positioning of any of the core LME-traded metals."	Qualitative uncertainty
6	Control uncertainty	Demand forecasting method	N/A	"interest in the metal's potential demand boost from the electric vehicle (EV) revolution."	Scenario uncertainty
11	Control uncertainty	Demand forecasting method	N/A	"growth rate of cobalt's demand is still uncertain," "	Recognised ignorance
31	Control uncertainty	Demand forecasting method	N/A	"extensive recycling of used batteries is likely to still leave a shortfall of cobalt, assuming the forecasts for electric cars and powerstorage batteries are accurate"	Scenario uncertainty
1	Control uncertainty	Policies and methods interaction	N/A	"Changing suppliers will not be easy, however, as it will take quite some time for LG Chem to run a series of tests and discuss the matter with clients,"	Qualitative uncertainty
6	Control uncertainty	Policies and methods interaction	N/A	"Lacking any confirmation as to which dams may have to be removed or when, it's impossible to say what the potential impact might be on other operators"	Qualitative uncertainty
6	Control uncertainty	Policies and methods interaction	N/A	"Lacking any concrete news about what if any impact the Brumadinho dam collapse might have on Onca Puma, the Vale effect on the nickel price has almost completely dissipated."	Qualitative uncertainty
7	Control uncertainty	Policies and methods interaction	N/A	"lack of diligence in the office of control"	Qualitative uncertainty
8	Control uncertainty	Policies and methods interaction	N/A	"Assumptions as to how both nickel's price and supply chain would need to adapt to the new electric demand driver have just been upended."	Scenario uncertainty
12	Control uncertainty	Policies and methods interaction	N/A	"A tussle between Glencore (GLEN.L) and its former partner over Congo cobalt royalties highlights the nascent electric vehicle sector's vulnerability, with an escalation seen crippling supplies of the key battery metal."	Scenario uncertainty

(*continued*)

Table C. Data set (cont.)

Id. n	Source of uncertainty	Category of uncertainty (Forward flow)	Category of uncertainty (Reverse Flow)	Example of text found in the sample	Level of uncertainty
13	Control uncertainty	Policies and methods interaction	N/A	“This concentration of supply risk, both in terms of physical units and ethical sourcing, isn’t going away any time soon and could even worsen.”	Scenario uncertainty
13	Control uncertainty	Policies and methods interaction	N/A	“how much cobalt this gray sector generates is the main “known unknown” in any analysis of world production.”	Recognised ignorance
16	Control uncertainty	Policies and methods interaction	N/A	“Recent company research indicated one quarter of Jaguar drivers would consider a battery-powered vehicle. “There are differing views of how rapidly that shift is happening and to what degree. We want to be prepared.”	Qualitative uncertainty
23	Control uncertainty	Policies and methods interaction	N/A	“Car companies (…) are all under pressure to show metals used in products such as (…) vehicle batteries are sourced responsibly.”	Qualitative uncertainty
23	Control uncertainty	Policies and methods interaction	N/A	“Experts say measures adopted since 2010 have helped clean up supply chains. But gaps persist.”	Qualitative uncertainty
27	Control uncertainty	Policies and methods interaction	N/A	“how seriously cobalt users are taking the traceability of their material after allegations of sourcing via child labor in the Democratic Republic of Congo, the country that supplies about 60 percent of the world’s cobalt.”	Qualitative uncertainty
7	Control uncertainty	Raw material stock control policy	N/A	“CCHEN’s accounting of the sales of the world’s top lithium producers Albemarle Corp and SQM SQM_pb (….) lost track of how much lithium was being exported and where it was going.”	Qualitative uncertainty
7	Control uncertainty	Raw material stock control policy	N/A	“CCHEN’s discovery that its records of lithium exports are far from accurate could complicate the agency’s efforts to determine just how much lithium SQM and Albemarle have mined and when their quotas of the metal will be exhausted.	Scenario uncertainty
7	Control uncertainty	Raw material stock control policy	N/A	“CCHEN in September denied a request to triple production from Albemarle, the world’s top producer of lithium, citing, in part, uncertainty over how much lithium the company had already mined.”	Recognised ignorance
9	Control uncertainty	Raw material stock control policy	N/A	“concerns about the amount of brine SQM had been drawing ”	Qualitative uncertainty
13	Control uncertainty	Serviceable stock control policy	N/A	“Whether there would be sufficient inventory of cobalt to buffer the market against serious disruption in the DRC is a very moot point.”	Scenario uncertainty
1	Environmental uncertainty	Government regulation	N/A	“I expect we wouldn’t have any issues with those Japanese suppliers if they follow the compliance rules, but we are in the situation where the Japanese government could say different things if they wanted,””	Scenario uncertainty
3	Environmental uncertainty	Government regulation	N/A	“trade stand-off between China and the United States.”	Qualitative uncertainty
4	Environmental uncertainty	Government regulation	N/A	“Livent, which has been hit by uncertainty around China’s electric vehicle subsidies”	Recognised ignorance
4	Environmental uncertainty	Natural disasters	N/A	“Livent also said its lithium carbonate operations in Argentina were back at normal levels, following almost three weeks of lost production due to the heavy rains in late January.”	Qualitative uncertainty
5	Environmental uncertainty	Government regulation	N/A	“U.S-China trade war may hit long-term demand.”	Scenario uncertainty
5	Environmental uncertainty	Government regulation	N/A	“geo-political uncertainty.”	Recognised ignorance
6	Environmental uncertainty	Macroeconomic issues	N/A	“nickel’s ability to rally at all in the current gloomy macroeconomic environment”	Qualitative uncertainty
7	Environmental uncertainty	Government regulation	N/A	“Chile’s lithium industry has recently come under increasing scrutiny by various government agencies, including the country’s environmental and water authorities”	Qualitative uncertainty
8	Environmental uncertainty	Technology	N/A	”Whether Tsingshan can deliver its HPAL plant on time and on budget remains to be seen”	Qualitative uncertainty
8	Environmental uncertainty	Government regulation	N/A	”Tsingshan is in the curious position of facing an anti-dumping investigation by the Chinese authorities”	Scenario uncertainty
9	Environmental uncertainty	Natural disasters	N/A	”Bitran wrote that SQM's actions pose a “severe risk” to the ecosystem of the Salar and its brine reserves. ”	Qualitative uncertainty
10	Environmental uncertainty	Government regulation	N/A	”It was not immediately clear what impact, if any, the new restrictions will have on the two miners’ operations.”	Scenario uncertainty
10	Environmental uncertainty	Government regulation	N/A	”new restrictions could impact current supply and add uncertainty to future development”	Scenario uncertainty
11	Environmental uncertainty	Government regulation	N/A	”Around half of global cobalt reserves is held by Democratic Republic of Congo (DRC), presenting a volatile cocktail of political, operational and ethical risk.“”	Qualitative uncertainty
12	Environmental uncertainty	Government regulation	N/A	”If (Katanga's mine ramp-up) is disrupted then this could lead to significant shortages in the short term, and the market would most likely return to a deficit next year as a result,“”	Scenario uncertainty
12	Environmental uncertainty	Government regulation	N/A	”risks to global supplies created by a controversial mining code signed into law by President Joseph Kabila in March”	Scenario uncertainty
12	Environmental uncertainty	Government regulation	N/A	”The DRC’s dominance of cobalt supply does bring with it a significant amount of political risk,” CRU analyst George Heppel said”	Qualitative uncertainty
12	Environmental uncertainty	Government regulation	N/A	”additional risk of uncertainty around the Congo’s mining code”	Recognised ignorance
13	Environmental uncertainty	Government regulation	N/A	”political, legal and ethical uncertainties surrounding the DRC’s mining sector.“”	Recognised ignorance
14	Environmental uncertainty	Macroeconomic issues	N/A	”There are any number of uncertainties in trying to forecast the price in such a fast-evolving market as cobalt, or lithium for that matter.”	Recognised ignorance

(*continued on next page*)

(*continued*)

Table C. Data set (cont.)

Id. n	Source of uncertainty	Category of uncertainty (Forward flow)	Category of uncertainty (Reverse Flow)	Example of text found in the sample	Level of uncertainty
14	Environmental uncertainty	Political instability	N/A	”political instability in the Democratic Republic of Congo”	Qualitative uncertainty
15	Environmental uncertainty	Government regulation	N/A	”South Korea’s SK Innovation Co Ltd will delay building an electric vehicle battery factory in China because of regulatory uncertainty in the world’s top auto market, two company officials told Reuters on Friday”	Recognised ignorance
18	Environmental uncertainty	Government regulation	N/A	”Exporters with high exposure to the euro zone such as Mazda Motor Co and Nikon Corp may underperform after political uncertainty in Italy drove its borrowing costs to five-month highs. ”	Scenario uncertainty
18	Environmental uncertainty	Political instability	N/A	”Political friction between China and Japan has delayed by one year a Nissan plan to gain 10 percent market share in China,”	Qualitative uncertainty
19	Environmental uncertainty	Government regulation	N/A	”Fisker is preoccupied with a more pressing task - courting investors after a tough year (…) and an election season that turned the U.S. government-backed company into a political punching bag.”	Qualitative uncertainty
22	Environmental uncertainty	Government regulation	N/A	”European Union, which is scrambling to formulate a comprehensive policy for building out its own battery supply chains.”	Qualitative uncertainty
25	Environmental uncertainty	N/A	Technology	”There are very few working, economically viable technologies for recycling the majority of materials in lithium-ion batteries”	Qualitative uncertainty
26	Environmental uncertainty	Technology	N/A	”The project, which has proven resources of 3.1 million tonnes of lithium, requires a new extraction technique because no lithium-from-clay operations currently exist anywhere around the world.”	Recognised ignorance
28	Environmental uncertainty	N/A	Technology	“The plant can process 2,250 battery packs a year, and initially plans to refabricate “a few hundred” units annually, Makino said, adding that 4R would see whether the process could also be used for batteries from the latest Leaf model, which uses a different battery chemistry.”	Scenario uncertainty
31	Environmental uncertainty	Government regulation	N/A	”DRC is in pole position to benefit from the expected surge in demand for cobalt, but only if it decides to pursue polices that don’t alienate mining companies and encourage the rapid development of alternatives.”	Scenario uncertainty
32	Environmental uncertainty	Political instability	N/A	”most of the world’s supplies come from Democratic Republic of Congo, where mining areas are prone to conflict”	Qualitative uncertainty

Note: N/A - not applicable

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