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Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries

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Abstract

Lithium-ion batteries are considered a key component in mobile and stationary energy storage applications. However, the current technology is based on several critical materials, such as lithium, cobalt, nickel, manganese, and graphite, which are associated with various environmental and social impacts in their supply chain. While the environmental impacts of lithium-ion batteries have been investigated in numerous studies, little attention has been given to the potential social impacts. Therefore, an assessment of the social sustainability hotspots of lithium-ion batteries is carried out. The assessment is based on a spatially differentiated resource flow model of the supply chain. Data on social risks with respect to child labor, corruption, occupational toxics and hazards, and poverty are extracted from the Social Hotspots Database in openLCA. The results of the social assessment are discussed along with environmental and economic considerations to generate recommendations for improving supply chain sustainability.

Keywords: Social life cycle assessment; Social Hotspots Database; Lithium-ion batteries; Supply chain

1. Introduction

Lithium-ion batteries are considered a key component in mobile and stationary energy storage systems. As an enabler for electric mobility, they contribute to the reduction of harmful emissions from the transport sector. As stationary storage, they enable the transition to smart energy systems by compensating for the variability of supply and demand. For electric mobility applications alone, the global annual demand for lithium-ion batteries is expected to increase from 10 GWh in 2015 to almost 1,300 GWh in 2030 [1].

Despite the considerable benefits that are related to the use phase of lithium-ion batteries, there are significant impacts related to their production. The current technology is based on critical raw materials such as lithium, cobalt, nickel, manganese, and graphite, which are associated with various environmental and social impacts in their supply chains. While the environmental impacts have been investigated in various studies [2–5], little attention has been given to the social implications [6].

It is therefore the objective of this paper to analyze the social hotspots in the supply chain of lithium-ion batteries. We carry out a Social Life Cycle Assessment (S-LCA) of a state-of-the art battery system using an implementation of the Social Hotspots Database (SHDB) in openLCA to find out which parts of the supply chain and which social issues present a high risk.

The contribution of this paper is threefold. First, we complement the existing environmental life cycle assessments of lithium-ion batteries by adding a social perspec-

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tive. Second, we illustrate the application of the SHDB to a specific case study. Third, we support battery manufacturers and other stakeholders in designing socially beneficial supply chains.

The remainder of this paper is organized as follows: The supply chain of lithium ion batteries is described in Section 2, and the S-LCA methodology using the SHDB is discussed in Section 3. The assessment setup and the implementation in openLCA are presented in Section 4, the results are discussed in Section 5, and conclusions are drawn in Section 6.

2. The supply chain of lithium-ion batteries

The main components of a lithium-ion battery pack in electric vehicles are the battery cells in which the electric energy is stored, the battery management system (BMS) to monitor and control the state of the cells, and the pack container with a cooling system to protect the cells from external influences. The battery cells consist of two electrodes, a separator, electrolyte, and a cell container with electric connectors. The composition of the electrodes is a major determinant for the performance and the cost of the battery system. For automotive applications, the cathode is typically made of an aluminum current collector and active material containing lithium, nickel, cobalt, and manganese. The anode is made of a copper current collector and graphite as active material. [7]

An overview of the supply chain of lithium-ion batteries with related production activities and material flows is presented in Fig. 1. The raw materials that are used in lithium-ion batteries can be found in different locations. For some of them, geological reserves and production are concentrated in a few countries. The largest producer of lithium is Australia, where it is extracted from the mineral spodumene. Other significant producers are Chile and Argentina, where the lithium is extracted from concentrated brines. The production of nickel is diversified geographically, with Indonesia, the Philippines, and Canada being the top three producers. Cobalt production is highly concentrated in DR Congo with a share of more than 60%. Minor producers of Cobalt include Russia and Australia. Manganese production mainly takes place in South Africa, China, and Australia. Production of aluminium and graphite is concentrated to more than 50% in China, with minor shares in Russia and Canada for aluminum, and India and Brazil for graphite. The largest producers of copper are Chile and Peru, followed by China. [8]

The raw materials are used as inputs for the production of intermediates such as lithium-cobalt-nickel-manganese oxide for the cathode active material, or lithium-hexafluorophosphate for the electrolyte. The production of these intermediates is usually done by specialty chemicals companies located in China. [9]

The next stage of the supply chain is cell production. It involves electrode production, cell assembly, formation, and aging [10]. Until 2015, Japan and South Korea were the leading countries with regard to production capacities for battery cells, but now China is the biggest producer and its capacity is growing rapidly [11]. With the operation of Tesla's Gigafactory, production has also started in the United States. Projects for European cell production in Sweden and Poland are also underway [1].

The assembly of battery packs is usually done by the car manufacturers in facilities that are located at or close to where the electric cars are built. The largest battery producer of electric vehicles in 2017 was China, with an output of ca. 600,000 cars, followed by the Unites States with

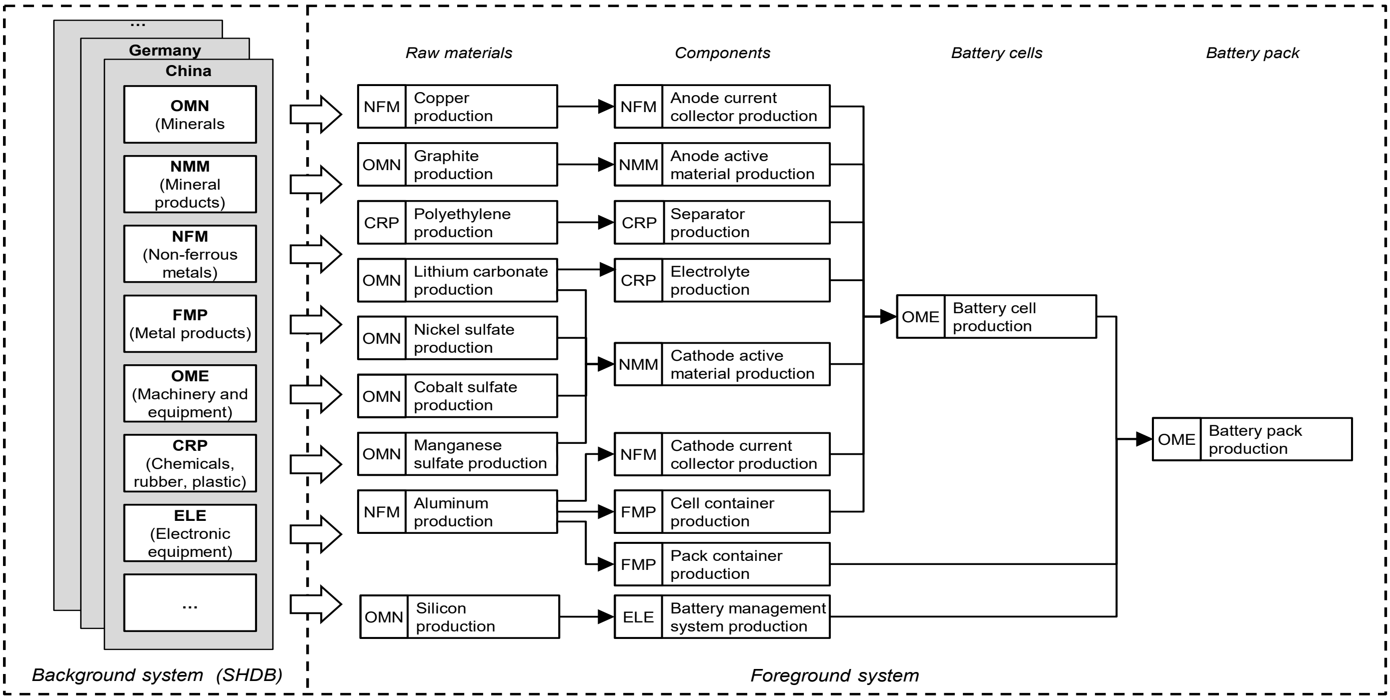

Fig. 1 Supply chain model of the lithium-ion battery pack with system boundaries of the foreground system and background system as well as assignment of activities to (country-specific) industry sectors from SHDB

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200,000 cars and Germany with 145,000 cars [12]. Major car manufacturers like BMW, Daimler, or Volkswagen have recently announced that they will increase the transparency of their supply chains for electric car batteries and improve the social situations of the stakeholders that are involved. To this end, they need to assess the social risks that are related to each of processes in the supply chain.

3. The social hotspots database in the context of social life cycle assessment

S-LCA is a methodology to analyze the potential positive and negative social impacts of products along their life cycle, comprising all activities that are related to the extraction and processing of raw materials, manufacturing, distribution, use, maintenance, recycling, and final disposal. Social impacts are considered as the consequences on the stakeholders in the context of these activities. S-LCA seeks to foster improvements in the product's supply chain by providing information on socio-economic aspects for decision-makers and by stimulating a dialogue on the social impacts. [13]

The general methodology of S-LCA is similar to the methodology of environmental life cycle assessment (LCA) as both methods are based on the ISO 14040 framework. While the procedure of goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation is common, S-LCA differs in the data that is collected. In contrast to LCA's focus on physical quantities of natural resources and emissions, S-LCA emphasizes the socio-economic interactions of the activities and analyzes their organizational and societal context in the supply chain. In this regard, S-LCA provides complementary information to LCA and thus enables a more comprehensive picture of product sustainability. [13]

Since social impacts depend on the specific context of the product's supply chain, S-LCA requires the collection of site-specific data. Depending on the objective of the study, it may also be possible to use data at a less granular spatial level to analyze the social hotspots in the supply chain. Social hotspots are defined as activities that are located in a region where a situation occurs that may be considered a problem, a risk or an opportunity, in relation to a social theme of interest. [13,14]

A comprehensive data source to analyze social hotspots is the social hotspots database (SHDB). The SHDB seeks to provide access to best available social risk and opportunity information at the most granular level possible as well as to provide methods and tools to calculate and summarize this information into a quantitative assessment of the social performance across a product supply chain and life cycle. It uses a multi-regional input-output model that is based on the Global Trade Analysis Project (GTAP) and contains 6,441 unit processes comprising 113 regions with 67 industry sectors. [14]

The SHDB methodology is related to life cycle attribute assessment (LCAA) [15]. It is assumed that each unit process has a number of different attributes, or characteristics, relative to a large set of social issues. The activity variable used in the SHDB is labor intensity expressed in work hours. The work hours are estimated from GTAP data on wage payments within each region and industry sector. Thus, the SHDB can be used to identify how many work hours are involved for each unit process in the supply chain for a given final demand. Furthermore, the sociosphere flows are expressed as work hours at a specific risk level for each risk indicator, per USD of process output. [14]

The SHDB covers 146 risk indicators, which can be aggregated into 24 impact categories. The risk indicators represent a qualitative assessment of risks, but the combination with labor intensities introduces quantitative data that allow for aggregation across processes. In inventory analysis, the work hours within each risk category are compiled, and in the characterization phase of impact assessment, the different risk categories are expressed relative to the medium risk level by multiplying them with respective characterization factors, representing the relative probability of an adverse situation to occur. The characterization factors used in the current version of SHDB impact are presented in Table 1. [14]

Table 1 Characterization factors for social risk categories

Risk category	Characterization factor
no risk	0.0
low risk	0.1
medium risk	1.0
high risk	5.0
very high risk	10.0

4. Assessment setup and implementation

The goal of this study is to identify the social hotspots in the supply chain of lithium-ion batteries used in electric vehicles. For that purpose, a representative state-of-the art battery pack with a capacity of 52.9 kWh and a mass of 314.3 kg is considered. The cell chemistry is specified to be NMC-G, i.e., the cathode active material is lithium-nickel-manganese-cobalt oxide and the anode active material is graphite. The material composition and the cost structure of the battery pack are based on the Lithium-Ion Battery Performance and Cost Model for Electric-Drive Vehicles (BatPaC) by Argonne National Laboratory [16].

The scope of the study comprises the extraction and processing of raw materials, the production of intermediates, the production of battery cells, and the assembly of the battery pack as the final product (Fig. 1). The unit processes in the foreground system represent the physical flows of materials and products. They are connected to the processes in the background system by socio-economic flows representing the value of the services from country-specific industry sectors. Data for processes in the foreground system are extracted from different sources related to the production of lithium-ion batteries. Data for the background processes are drawn from the SHDB.

To connect the activities to the country-specific industry sectors of SHDB, assumptions about the production locations have to be made. Even if the number of possible locations for each activity is limited, the combinatorics of activities leads to a large number of possible configurations for

Table 2 Production activities in the supply chain of a lithium-ion battery pack with corresponding SHDB sectors and production shares of countries for three alternative configurations

Stage	Process	SHDB sector	Value added [USD]	Supply chain configuration		
				1. CN-focused production	2. DE-focused production	3. Responsible raw materials
Battery pack	Battery pack production	OME	147.72	CN 100%	DE 100%	CN 100%
	Pack container production	FMP	1371.92	CN 100%	DE 100%	CN 100%
	BMS production	ELE	592.46	CN 100%	DE 100%	CN 100%
Battery cells	Cell production	OME	1719.15	CN 100%	DE 100%	CN 100%
Components	Anode current collector production	NFM	221.54	CN 100%	CN 100%	CN 100%
	Anode active material production	NMM	228.78	CN 100%	CN 100%	CN 100%
	Separator production	CRP	681.59	CN 100%	CN 100%	CN 100%
	Electrolyte production	CRP	432.53	CN 100%	CN 100%	CN 100%
	Cathode active material production	NMM	1010.35	CN 100%	CN 100%	CN 100%
	Cathode current collector production	NFM	68.76	CN 100%	CN 100%	CN 100%
	Cell container production	FMP	15.11	CN 100%	CN 100%	CN 100%
Raw materials	Copper production	NFM	178.42	CL 56%, PE 25%, CN 19%		CL 100%
	Graphite production	OMN	406.72	CN 76%, IN 15%, BR 9%		BR 100%
	Polyethylene production	CRP	6.47	CN 100%		CN 100%
	Lithium carbonate production	OMN	262.67	AU 49%, CL 37% , AR 14%		AU 100%
	Nickel sulfate production	OMN	193.81	ID 48%, PH 27%, CA 25%		CA 100%
	Cobalt sulfate production	OMN	485.32	ZM 86%, RU 8%, AU 7%		AU 100%
	Manganese sulfate production	OMN	28.41	ZA 53%, CN 25%, AU 22%		AU 100%
	Aluminium production	NFM	197.07	CN 83%, RU 9%, CA 8%		CA 100%
	Silicon production	OMN	143.01	US 83%, RU 9%, CA 8%		US 100%

Countries: AR-Argentina, AU-Australia, BR-Brazil, CA-Canada, CL-Chile, CN-China, DE-Germany, ID-Indonesia, IN-India, PE-Peru, PH-Philippines, RU-Russia, US-United States, ZA-South Africa, ZM-Zambia. For SHDB sector abbreviations, see Fig. 1.

the supply chain. We limit our analysis to three illustrative supply chain configurations (Table 2). The first configuration describes a China-centered production, where the battery packs, battery cells, and components are manufactured in China. The production of raw materials is allocated to the top three producing countries from 2017. The share of the top three countries is scaled to 100% while the ratio between the countries is kept constant. Since data for DR Congo is not available in SHDB, we use its neighboring country Zambia to approximate the social context of cobalt production. The second configuration describes a Germany-centered production, i.e., the downstream activities of pack assembly and cell production are shifted from China to Germany. The third configuration focuses on a more responsible sourcing of raw materials by replacing the actual production mix with single sourcing from one of the top three countries that presumably exposes the lowest risks.

Fig. 2 shows the breakdown of the added value for the 52.9 kWh battery pack with a total value of 8,392 USD. The added value at each of the stages corresponds to the input from country-specific industry sectors. It is estimated based on the prices of intermediate products, assuming that there are no regional price differences.

The model was implemented in openLCA version 1.7 on a standard Windows 64 bit notebook. Calculation of the product system takes about 20 seconds.

5. Results and discussion

The results obtained from the S-LCA can be analyzed in several ways. Each of the risk indicators and categories can be compared for different supply chain configurations and can be disaggregated to analyze the contribution of individual processes, industry sectors, or countries. We discuss four selected risk categories that are frequently associated with the supply chain of lithium-ion batteries, namely the risk of child labor (CL), the risk of corruption (C), the risk of occupational toxics and hazards (OTH), and the risk of poverty (P). For each risk category, we compare the three supply chain configurations described above and analyze the contribution of the production processes, which have been grouped according to the four supply chain stages raw materials, components, cell production, and pack assembly (Fig. 3).

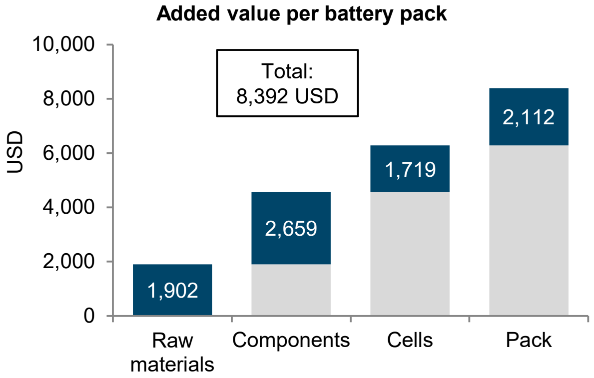

Fig. 2 Breakdown of added value for the battery pack along the supply chain

When comparing the total risk hours related to the different supply chain configurations, it can be observed that the China-focused production exposes the highest risk in all categories. Both other supply chain configurations, i.e., the shift of cell and pack production from China to Germany as well as the more responsible sourcing of raw materials lead to significant reductions in risk hours. Thereby, the rank order of supply chain configurations is not the same for all risk categories. With regard to child labor, occupational toxics and hazards, and poverty, the Germany-focused production shows the lowest number of risk hours, whereas

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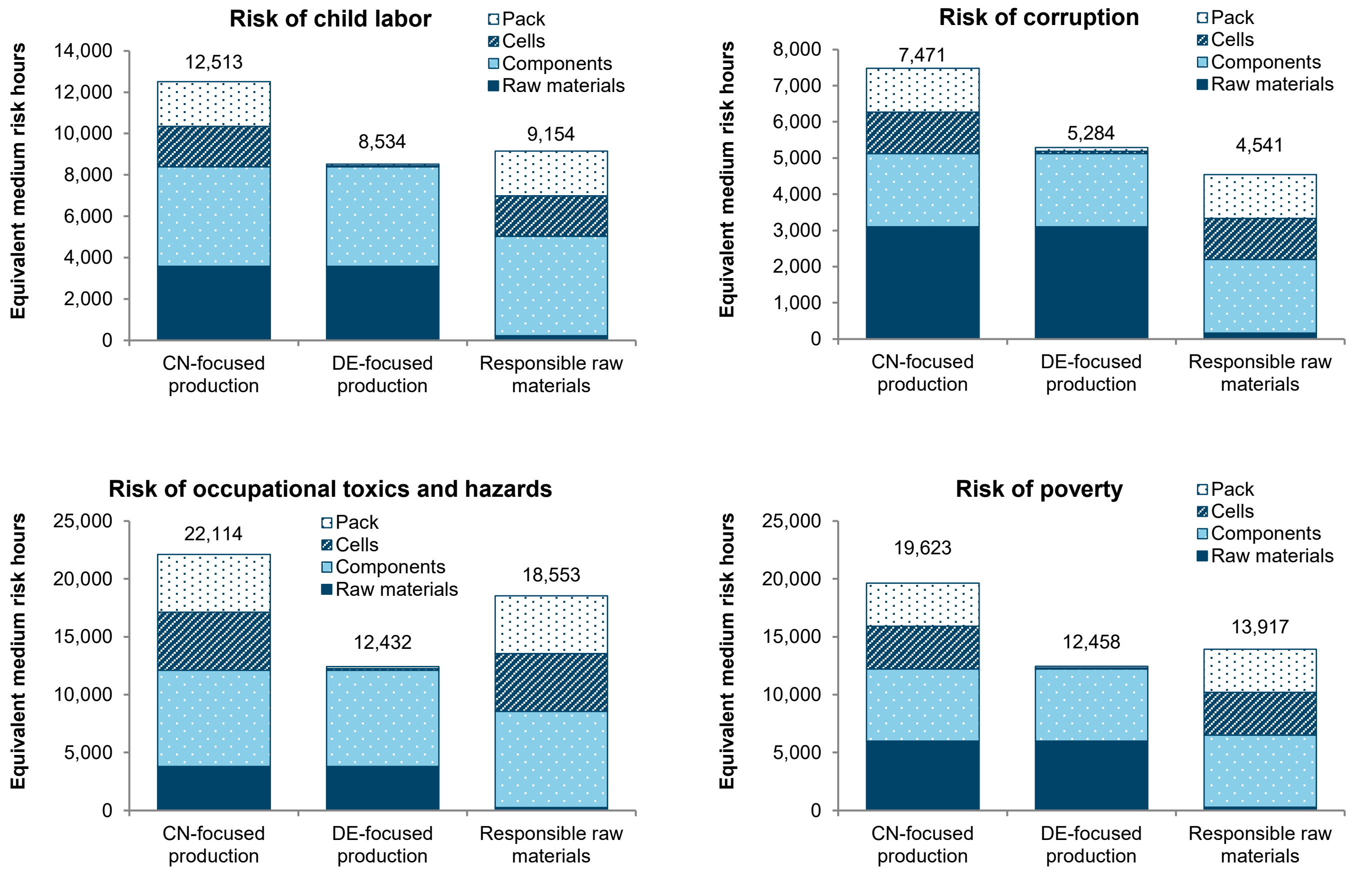

Fig. 3 Assessment results for selected social risks of different supply chain configurations

in terms of corruption, the responsible sourcing of raw materials exposes the lowest risk. This can be explained by the high impact of the raw materials stage on the risk of corruption in the China- and Germany-focused supply chain configurations. The substantial differences in total risk hours across the investigated supply chain configurations underline the importance of a spatially explicit modeling of the production processes as variations in the locations can have major influence on the results.

Analyzing the contribution of the different supply chain stages to the total risk hours, it can be observed that the relative shares are quite different depending on the risk category and the supply chain configuration although the value added is quite evenly distributed (Fig. 2). The Germany-focused production exposes much lower risks in the cell production and pack assembly stage compared to the China-focused production. In fact, each of these stages contributes to about 1% of the total risk hours only because the respective industry sector *machinery and equipment* in Germany is associated with no risk to low risk regarding the analyzed risk categories. The responsible sourcing of raw materials also leads to a considerable reduction of risk hours compared to the China-focused production. By sourcing the raw materials from countries with low risk levels, only a small number of risk hours related to that stage remains.

The results confirm that significant risks originate from the production of raw materials, with graphite production, cobalt sulfate production, and nickel sulfate production being the main contributors based on actual production shares. However, the analysis also shows that the risk associated with other stages in the supply chain should not be neglected.

To further reduce the risk hours, a Germany-focused production could be combined with the responsible sourcing of raw materials. Yet, such a strategy must be formulated with caution. First, production capacities cannot simply be allocated to countries with low social risk levels. There are many more factors that need to be considered in location decisions. Secondly, a company might not wish to avoid the high risk countries, but to purposefully settle there with the attempt to manage the risks and to leave a positive impact.

Moreover, the responsible raw materials configuration may be restricted by the supply capacities of the respective countries. If demand for lithium-ion batteries in electric vehicles reaches up to 1,300 GWh per year in 2030 as projected the by Bloomberg New Energy Finance [1], the raw materials required would be 1.2 million tons of cobalt sulfate, nickel sulfate and manganese sulfate each as well as 0.8 million tons of lithium carbonate. Compared to the production volumes from 2017 in the selected countries [8], this amounts to an increase by a factor 44 for lithium, 239 for cobalt, 6 for nickel, and 529 for manganese for the mobility sector alone. Considering that the raw materials are also required for other applications, such large increases in production capacities are very unlikely and material must be sourced from other countries as well.

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From a sustainability perspective, not only are the social aspects relevant but there are several tradeoffs with other indicators and dimensions. For example, sourcing lithium in Australia seems to have social benefits as it leads to lower risk compared to Chile. However, the technologies are different (spodumene vs. brines) and the technology in Chile has advantages with regard to many environmental indicators.

6. Conclusions and outlook

Focusing on lithium-ion electric vehicle batteries, this contribution illustrates how the S-LCA methodology can be used to identify social hotspots in the supply chain. From this, recommendations on the supply chain design, i.e., the locations where individual production processes are carried out, can be derived in order to lower the social risks associated with the sourcing of raw materials and intermediates as well as the production of cells and battery packs. As we have shown in the case study, these decisions are an important lever to mitigate child labor, corruption, occupational and toxic hazards, or poverty. Depending on the risk category and the measures considered, equivalent risk hours can be reduced by 16–44%.

For manufacturers of electric cars and batteries, the results imply that they should carefully consider where to locate their production facilities and where to source the necessary materials and components. To arrive at a more comprehensive perspective of supply chain sustainability, the analysis of social risk should be complemented by economic and environmental considerations. This, however, would lead to a multi-criteria design problem which requires related optimization techniques to solve, given the large number of feasible supply chain configurations a decision maker might face in industrial practice. A first framework to guide such decisions, which opens up promising avenues for future research, is presented by Thies et al. [17].

Moreover, several limitations to the proposed methodology on S-LCA can be identified, which should be subject of future work. First, only average values for country-specific industry sectors are used to estimate the social risks associated with each of the production processes, which is due to the use of the SHDB. Second, the estimation of risk hours based on approximated work hours via the added value of the processes might be influenced by fluctuations in the price levels between countries although no modifications in the production process itself or in its social context have been made. Third, transport processes have been neglected in our analysis, which may not only affect the feasibility of particular supply chain configurations, but may also incur additional social risks. Fourth, the SHDB is most meaningful for relative assessments, i.e., for the comparison of alternative supply chain configurations or comparisons of the different indicators. The results of a single risk category for a single supply chain configuration would be difficult to interpret from an absolute perspective.

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