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A Practical Approach for Social Life Cycle Assessment in the Automotive Industry

Hannah Karlewski [1,*], Annekatrin Lehmann [1], Klaus Ruhland [2] and Matthias Finkbeiner [1]

1 Chair of Sustainable Engineering, Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany
2 Group Environmental Protection, Daimler AG, 70546 Stuttgart, Germany
* Correspondence: slca@karlewski.de

Received: 31 March 2019; Accepted: 13 June 2019; Published: 16 August 2019

Abstract: Identifying social impacts along the life cycle of their products is becoming increasingly important for companies. Social Life Cycle Assessment (SLCA) as a possible tool has not been conducted so far within industries with complex international supply chains using mainly company-specific data. As a novelty, this work presents a practical SLCA approach along with the first case studies for the automotive industry, based on a previously developed indicator set and an extensive data collection. Social data was collected from companies along the life cycle of two specific car components, while analyzing data availability, validity and comparability. To obtain product references, both a top-down and a bottom-up approach for quantitative indicators based on time effort and data availability on the process level were devised. Also, two options were developed for how qualitative indicators (e.g., *written principles* for *Corruption*) can be applied together with quantitative performance indicators (e.g., *number of accidents*). The general practical applicability of the approach could be demonstrated by four quantitative and seven qualitative indicators. It is a first step towards analyzing the social performance of products with complex supply chains on a company level. Remaining challenges include social data availability and quality and obtaining data at the process level (allocation). These should be addressed in future studies.

Keywords: social life cycle assessment; automotive industry; case study; social data collection

1. Introduction

The analysis of social topics during the production, use and disposal of products is becoming increasingly important for companies in terms of their social responsibility towards a sustainable development. End consumers are also paying more and more attention to these social topics (e.g., [1–4]), also sensitized by numerous news in media. There have been reports in the last years mainly in the textile and IT industries about social abuses like child labor, forced labor, poor wages and harassment by supervisors (e.g., [5–10]). Also, the disposal of European electronic waste in Africa and its social impacts is mentioned regularly (e.g., [11–13]). The automotive industry has been in focus as well [14,15]. One way to assess social aspects of a product along its entire life cycle, from resource depletion to disposal, is offered by the Social Life Cycle Assessment (SLCA) method (e.g., [16]).

1.1. The Status in Research

The publication of the Guidelines for Social Life Cycle Assessment (SLCA) of Products (hereinafter: Guidelines) [16] and their corresponding Methodological Sheets for Subcategories in Social Life Cycle Assessment (hereinafter: Methodological Sheets) [17] marked a significant milestone. Therefore, it has been a major basis for this work. However, the huge amount and the diverse topics of the publications in this field indicate that there are still a variety of challenges in SLCA. Before the Guidelines were published, there were already studies on SLCA, but the focus was more on developing methods and approaches. One example is the Product Sustainability Assessment-Methodology (PROSA) [18], which also contains an approach for SLCA. The extensive set of social aspects and indicators from PROSA has also been considered in this work. The results of a case study about notebooks are however more qualitative due to the deficiency of quantitative product-based data [19]. Further studies exist, for example for the salmon and milk industry [20,21], for waste management [22] or for comparisons between detergents [23]. In the latter study a method for social aspects not relating to a product but describing an attribute of a process (like a fair-trade certification) was developed. In this method called the Life Cycle Attribute Assessment (LCAA) the indicators are related to a share of a product life cycle (e.g., percent or working hours) (see also reference [24]). It has been applied in a case study with greenhouse tomatoes [25] and is used in this work for qualitative and semi-quantitative indicators.

After 2009, the focus of case studies turned more towards the application of the Guidelines. There are examples in the electronic industry [26–28], the textile industry [29], the energy sector [30–33], the building industry [34–36], agriculture [37–43], manufacturing [44], mining [45], mobility [46], water resources management [47], the tourism industry [48] and the waste management industry [49–51].

Because the Guidelines do not describe a binding way of proceeding, the case studies differ often mainly in the method or the scope of SLCA (see also reference [52]). In addition, there are still studies that do not follow the Guidelines (e.g., [53–58]).

While some authors calculate the social impacts as being analogous to those of a Life Cycle Assessment (LCA, thus being compatible with Life Cycle Sustainability Assessment (LCSA)) based on the functional unit of a product system (e.g., [43,59]), others describe these impacts more qualitatively (e.g., [28]). Some of the studies use only generic data (e.g., [26,29]), while others collect company-specific data for key processes (e.g., [37]). Noticeably more and more studies use the term SLCA, although no product system is considered, but company assessments are carried out with the social aspects of the Guidelines (e.g., [48,50,52]).

In summary, the case studies in many publications focus primarily on products which either have a less complex life cycle within one country or only a reduced number of stakeholders, life cycle phases, mass and energy flows or social aspects compared to the suggestions of the Guidelines. Slowly more and more parameters have been included in the case studies and more complex products are being considered. One extensive study for example has been published by Martinéz-Blanco et al. [43].

Regarding impact assessment, color or point scales are frequently used which indicate different risks or performance in relation to reference values (e.g., [27,36,38,51]). Based on the Guidelines Parent, Cucuzzella and Revéret [60] described this approach as a task force approach (type 1 of impact assessment) in contrast to impact assessment using impact paths (type 2) [61,62].

In the beginning, theoretical studies on SLCA focused more on the development of methods, the fundamental considerations on possible challenges and the differences to LCA. Since then, studies have increasingly focused on the further development of SLCA such as in the field of impact assessment (e.g., [63,64]). In general, however, the status and further procedure of the SLCA method itself are also discussed (e.g., [65–68]).

While the goal in many studies on SLCA has been to establish a process reference (micro level), an evaluation at the company level (meso level) would also be conceivable [69]. Because many social aspects of companies are addressed at the organizational level, the Organizational LCA (OLCA; the abbreviation is used analogously to SLCA as in reference [70]) could be a promising approach for which a Guidance on Organizational Life Cycle Assessment [71] and the ISO/TS standard 14072 [70] were published some years ago [72]. Like the LCA, it analyzes various environmental impacts, but extends the life cycle approach to organizations. In reference [73] the authors propose a framework for Social Organizational LCA (SOLCA).

1.2. The Status in Industry

As a result of the developments described at the beginning of this chapter, companies are increasingly also taking social aspects into account with their suppliers. However, these actions have so far been addressed primarily within Sustainable Supply Chain Management and have not been related to the life cycle of a product (e.g., [74]). But there are more and more approaches in the industry as well.

One example is BASF. Its eco-efficiency method was supplemented by social aspects in 2005 and has since been called SEE (Socio-Eco-Efficiency) Balance (see references [75,76]). Based on experiences with the SEEBalance method, BASF developed a method for measuring and evaluating sustainability in agriculture in 2012—AgBalance [77]. BASF was also part of a Working Group on Life Cycle Metrics in the chemical industry, which developed a first attempt of a guideline to measure and report social impacts of chemical products during their life cycles [78].

Several companies that have joined forces to form the Roundtable for Product Social Metrics published a Handbook for Product Social Impact Assessment at the end of 2014. The Handbook proposes a practical method for companies to analyze social aspects of products during their life cycles [79]. The latest Handbook is from September 2018 [80,81].

In the automotive industry there were two PhD theses which addressed social aspects. At Daimler, Karlewski developed a practical SLCA approach [82] (this article is based on parts of this thesis), while at BMW Tarne assessed SLCA as part of LCSA [83–86]. Another company that deals with social aspects of products in the automotive industry is Ford. In this approach called the Product Sustainability Index (PSI), the social aspects are—together with the other dimensions of sustainability—considered in the development of a car. As in LCSA, the ecological aspects are covered by LCA, while the economic aspects are represented by Life Cycle Costing (LCC). However, in the PSI, the social aspects are only considered in the use phase. This includes vehicle safety for occupants and pedestrians as well as mobility capacity. Vehicle noise and substance management (interior air quality) can also be taken into account [87]. However, there is no scientific derivation of the social aspects.

1.3. Research Needs

The publication of the Guidelines was an important step towards the standardization of SLCA. It further progressed SLCA activities in research and industry. While in the beginning the focus had been mainly on theoretical work and rather basic case studies, researchers started to include more complex products, more stakeholders and life cycle phases and more detailed mass and energy flows in the last years. In general, when comparing SLCA to LCA, there is still a great need for more standardized methods and indicators and for further case studies [62,88–91].

In particular, analyses in business environments that assess the relevance and feasibility of SLCA are still rare (see reference [92]). This also affects the questions for which social data are available from several, possibly internationally operating, companies, and which data can be compared between different companies. SLCA studies with mainly company-specific data have not been conducted so far in industries with complex international manufacturing and supplier structures. Previous studies have mainly used generic data, such as data from the Social Hotspot Database (SHDB) [93]. Using company-specific instead of generic data is advantageous because it makes the results more meaningful and accurate. Also, social impacts in the use phase of a product and their consideration in SLCA have been hardly investigated. Besides, there is still a need for research in the field of impact assessment of SLCA, such as for the standardization of reference points or impact pathways. Further challenges exist when integrating SLCA into LCSA.

SLCA should be adapted to the respective industry, for example by including stakeholders or analyzing the specific impact of the product [89,94,95]. This has not yet been done systematically in the automotive industry. Similarly, there is neither a theoretical derivation of the social properties of cars, nor any consideration of these properties within the framework of SLCA.

In summary, SLCA studies are needed, which consider as many of the following points as possible:

- consideration of the entire life cycle of a product,
- priority use of company-specific data in industries with complex, international manufacturing and supplier structures,
- inclusion not only of material but also of energy flows, and
- compatibility of SLCA with LCA and LCC in the context of an LCSA.

In addition, the following topics give rise to more detailed investigations:

- availability and comparability of social data in the context of different, internationally operating companies,
- consideration of social impacts in the use phase of a product, and
- further development of impact assessment.

For the application of SLCA in the automotive industry, research is also needed regarding:

- analysis and development of social aspects and indicators considering the characteristics of the automotive industry,
- involving stakeholders from the automotive industry in prioritizing and evaluating social aspects, and
- theoretical derivation of social car properties.

1.4. Objectives of This Paper

Based on the research needs, the central question addressed in this paper was how (and indeed if) SLCA in the automotive industry—as an example of an industry with complex, international manufacturing and supplier structures—based on company data can be conceptualized and conducted in case studies. Therefore, the main goal was the development of a practical SLCA approach including its application with case studies of two car components (inner part of the rear door, made of steel in the case of one component and aluminum in the other). Furthermore, a short overview about the results of the social data collection being the basis for the developed method is given. The focus was on company-specific data for gaining insight into which data is available at company/organizational level and which can be used for SLCA.

2. Materials and Methods

The method that was used to develop a practical SLCA approach is described in Section 2.1. The social data collection (Section 2.1.1) was the basis for calculating the reference values (Section 2.1.2) and the social data (Section 2.1.3). The way the applicability of the SLCA approach was tested in case studies is explained in Section 2.2. The SLCA approach itself although including some methodological parts is presented as a result in Section 3, because its development was one of the main objectives of this work.

2.1. Practical Approach for SLCA in the Automotive Industry

To develop an SLCA approach for the automotive industry, social aspects and indicators were devised considering the characteristics of this industry. The procedure was described comprehensively in a previous publication [82] and is shown in Figure 1 (the individual steps of the figure are shown bold hereafter). As there was no automotive-specific social aspect set, which could be used for an SLCA approach in the automotive industry, **social aspects** were derived from the Guidelines and their Methodological Sheets. Additional sources included the Global Reporting Initiative guidelines (GRI guidelines) [96], PROSA, SEEBalance and internal discussions at Daimler. This set of social aspects was analyzed in order to determine how the aspects could be specifically adjusted and fitted to the structure of suppliers and the international nature of the automotive industry, including the present and future material composition of an automobile. They were classified into life cycle-oriented and end consumer-oriented social aspects. The former concerns the behavior of companies involved in the life cycle of the vehicle towards their stakeholders (society, business partners and competitors, employees, local community), while the latter refers to the behavior of an automotive company towards the end consumers and to social car properties, i.e., the use phase of a car. In this paper, only the life cycle-oriented social aspects are addressed. For the prioritization and evaluation of the social aspects, a survey of more than 400 stakeholders of Daimler was conducted. The development of **indicators** used to characterize the social aspects included consultation with experts of Daimler, along with extensive research into the literature. To categorize the indicators, a new systematic approach was deduced from the PLAN, DO, CHECK, ACT (PDCA) management cycle. The PDCA indicators describe management processes and are used to analyze whether a company has defined (written) principles for the respective social aspect (PLAN), has developed measures/systems to implement the principles (DO), has introduced control measures to monitor the implementation (CHECK) and has established processes to react to violations (ACT). The performance indicators represent measurable parameters of the social aspects. On the basis of these social aspects and indicators, a **data collection** form was designed (see Appendix A, Table A1). To analyze the data availability, validity and comparability between companies, social data along the entire life cycle of five different automobile parts, as well as for a whole car during the use phase at Daimler, were collected. Additionally, the challenges involved in such primary data collection were investigated. The results of the data collection were the basis for the development of the **calculations for an approach using SLCA** in the automotive industry. Subsequently, the applicability of the approach was analyzed by conducting **case studies**.

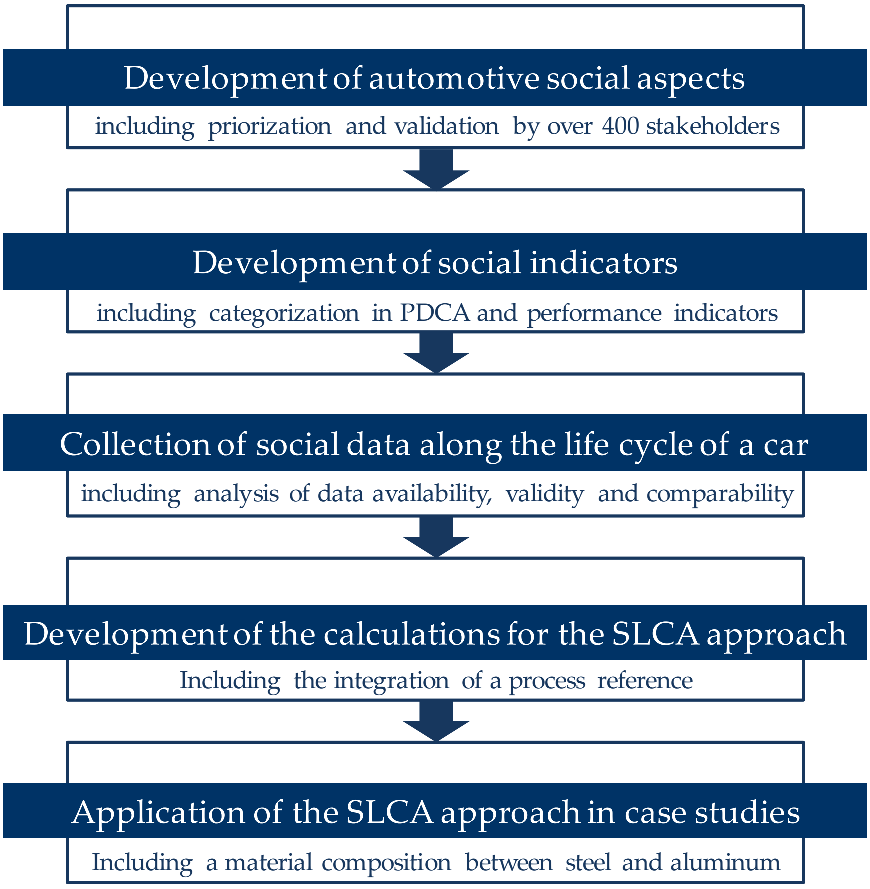

Figure 1. Overview of the procedure for developing an SLCA approach in the automotive industry. The development of automotive social aspects and indicators is comprehensively explained in reference [82]. This paper addresses the data collection and the final calculations of the SLCA approach, including case studies.

This paper focuses on the presentation of the data collection and the final calculations of the SLCA approach including case studies.

2.1.1. Collection of Social Data along the Life Cycle of a Car

In order to gain experience regarding the data availability of the social aspects and indicators on organizational/company level as well as the methodological approach and to get social data as a basis for the calculations of the SLCA approach, exemplary social data along the life cycle of a car were collected. The Guidelines and others (e.g., [73,97]) also see the necessity for company-specific data, but at the same time advise to use generic data because of time and cost efficiency. In this work, we used intentionally only company-specific data. The results are presented in Section 3.1.1.

The focus of the social data collection was on the following questions:

- Which of the social aspects and indicators are available in the different companies or communicated?
- What are the challenges in data collection?

Three criteria were decisive in the selection of companies for data collection:

1. considering the entire life cycle of a car,
2. covering a large proportion of the materials contained in a car; and
3. including materials that have already been the focus of attention in other sectors regarding their social impacts (such as textiles or platinum metals).

As shown in Table 1 the data collection was divided in four phases:

In the supply chain **(phase 1),** the respective manufacturers and suppliers of various materials were examined. Due to the large number of individual parts of an automobile, the components considered were selected on the basis of the material composition of a Mercedes-Benz vehicle [98]. A total of five direct material or component suppliers (and their upstream chains) were surveyed: steel, textile, biopolymer, platinum metals and aluminum. The aim was to map the main flows of materials and energy. Individual processes were neglected for reasons of confidentiality and simplification.

For the car production **(phase 2)** in two of the five data surveys (biopolymer and platinum metals), the direct supplier delivers the finished component to Daimler, where it is installed in the car. For the other three (steel, aluminum, textiles) the component is produced at Daimler. Daimler was therefore surveyed, independent of the material.

The social data collection in **phase 3** was carried out at one dismantling and one shredder company in Germany. In addition, an officially registered recycling company in Ghana was surveyed. Since many smaller and unregistered companies are common in this sector in Ghana, the company represents only a small formal part of this sector.

The term energy **(phase 4)** refers to electricity, process energy and fuel. Social data were collected from an electricity producer and a mineral oil company (including—if available—the companies in the upstream chain) as an example. This means that the specific energy suppliers of the individual companies are not represented.

In addition to the gathering of social data, company data like the number of employees (i.e., working hours) and mass and energy flows were also collected.

In total, 22 companies were analyzed regarding social aspects. A large portion of these companies (14) are globally active, with 7 in one country in Europe and 1 in Africa. Based on the number of employees, most of these companies are large companies (with more than 500 employees), while 5 are medium-sized companies. No small companies were surveyed (company size structure was judged according to reference [99]). The companies were contacted by telephone or e-mail. If possible, the company was visited on site to present the topic and aim of the data collection through a presentation and discussion. Web conferences were organized with most of the remaining companies. In additional telephone calls, the data collection form and the procedure were discussed. For 6 companies, only sustainability reports and/or homepages could be analyzed, while for the others direct contact was possible.

Table 1. Overview of the materials (or energy) and life cycle stages considered in the data collection process. The life cycle stages considered are marked with x. The color fields illustrate the four phases according to which the various processes are presented in this chapter (middle blue = phase 1, dark blue = phase 2, light blue = phase 3, grey = phase 4).

Materials/Energy	Resource Depletion	Tier 1–Tier n	Car Production	Car Use	Dismantling	Shredder
Steel	x	x	x		x	x
Textile	x	x	x		x	x
Biopolymer	x	x	x		x	x
Platinum metals	x	x	x		x	x
Aluminum	x	x	x		x	x
Energy	x	x	x	x	x	x

2.1.2. Calculation of the Reference Values

Social data require a process reference for use in SLCA that is analogous to LCA. Ideally, they can be collected directly from the company, including the process reference (referred to as the bottom-up approach in this work). However, this is not always possible for various reasons (see Section 3.1.1), often the social data are only available at the company level [16,97]. Therefore, this paper describes also an alternative procedure for calculating the process reference (referred to as the top-down approach in this work). After defining and quantifying the functional unit, it is important to specify the reference flows [16]. In Environmental LCA databases, precise process references exist which can be used for determining the material and energy flows of the considered components (see step 1 in Figure 2). Because the databases use mass and energy units, it is necessary to link them to the social data by using an activity variable. The activity variable working hours was chosen in this work as the reference variable, since many social aspects are associated with it. Alternatively, other reference values, such as turnover, number of units or mass, can also be selected [16]. For some processes, the activity variable working hours can be taken from the LCA database GaBi within the framework of the Life Cycle Working Environment (LCWE) approach [100]. For example, Martinéz-Blanco et al. [43] use this data source. However, the information relates mainly to the US economy and cannot be used for any other country. Also, for some processes the individual process steps are not listed in detail. In this work the working hours of the companies (step 2 in Figure 2) were related to the mass and energy data of the company (step 3, Figure 2) and offset with the mass and energy flows of the components' life cycles in order to be able to indicate the contribution of a company to a process step or component (steps 4a and 4b, Figure 2). With the help of the calculated reference values, the social data collected at company level for use in SLCA could be converted at the product level. A similar approach was used by e.g., [101]. These calculations are shown in the context of the presentation of the approach in Section 3.1.2 and with application examples in Section 3.2.1. The transfer from the component level to the car level is discussed in Section 3.3.5.

2.1.3. Calculations with the Social Data

The following steps in Figure 2 show how the social data can be prepared for SLCA. Step 5 identifies the social aspects and indicators to be included in SLCA. In the steps 6a and 6b, the performance and PDCA indicators are calculated, for which the use in SLCA is then presented in step 7. Step 6a differs between the bottom-up and the top-down approach (see Section 2.1.2). The underlying calculations are described in Section 3.1.3, the application with case studies is shown in Section 3.2.2.

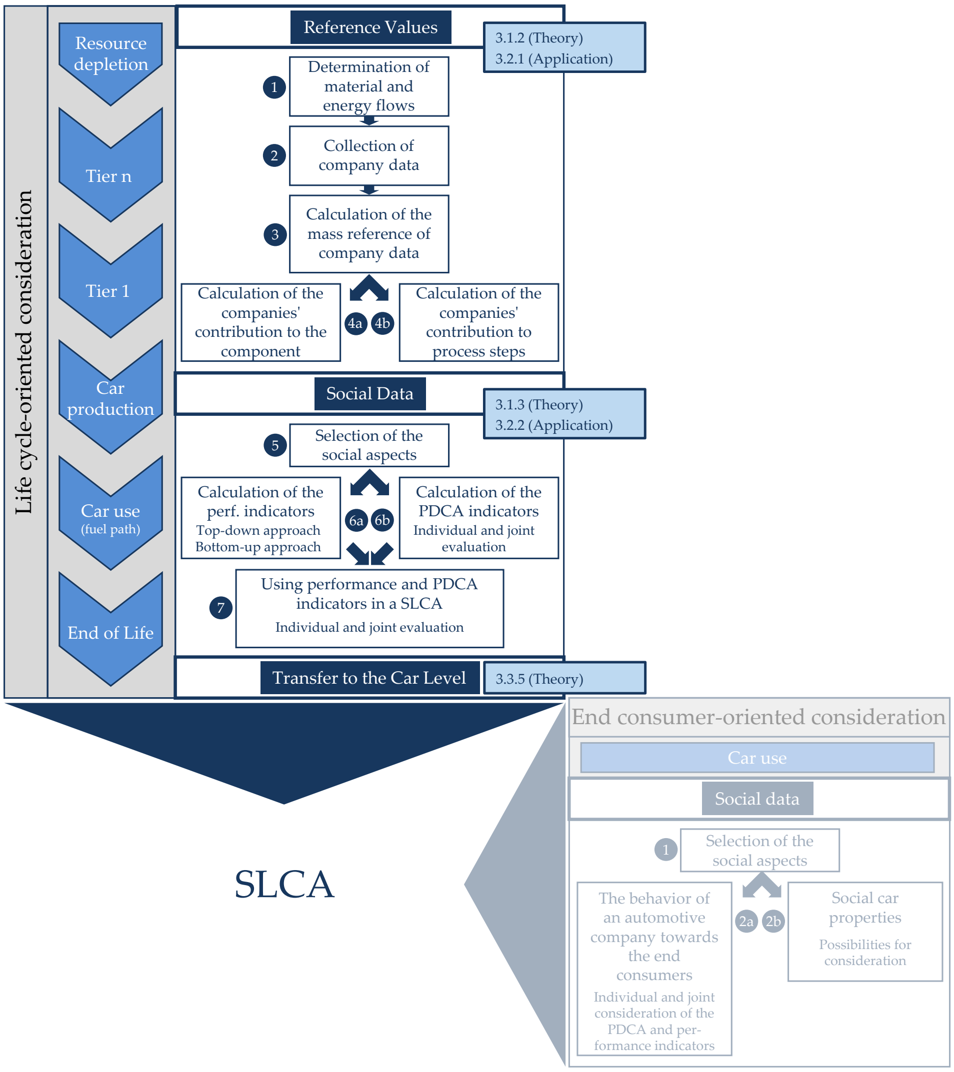

Figure 2. Overview of the approach for SLCA in the automotive industry. The life cycle-oriented approach is shown on the left side and is explained in Sections 2.1.2 and 2.1.3. The end consumer-oriented approach is shown on the right and is addressed in reference [82].

2.2. *Application of the SLCA Approach in Case Studies*

The company responses to the data collection form were applied to the developed calculations of the SLCA approach to test the general practical applicability of the method (Section 3.2). In order to show the possibility to support decisions in the product development, a material comparison between steel and aluminum was carried out.

The mass and energy flows of the components' life cycles were taken from GaBi [102] (22nd service pack) and ecoinvent data sets [103] (Version 2.2). Additional sources were references [104,105]. Detailed information and assumptions are given in Appendix B.1.

3. Results

Based on the results of the social data collection, an approach of a practical SLCA method for the automotive industry was developed and is presented in Section 3.1 (see reference [82] for more details about the end consumer-related social aspects). The applicability of the SLCA approach was examined in case studies and is shown in Section 3.2. The results are used to analyze and discuss the central question about the feasibility of a practical SLCA method in an industry with complex international supply chains and company-specific data in Section 3.3. Since the data used are related to individual components, the transfer to the car level is also discussed in Section 3.3.5.

3.1. Practical Approach for SLCA in the Automotive Industry

3.1.1. Collection of Social Data along the Life Cycle of a Car

It was possible to gain life cycle-oriented, company-specific social data from resource depletion to disposal for two specific components (inner part of the rear door, made of steel in the case of one component and aluminum in the other). This data was used to further develop an approach for a practical SLCA method in the automotive industry (see Sections 3.1.2 and 3.1.3). When considering PDCA and performance indicators together, the data availability was high for almost half of the life cycle-oriented social aspects (see Figure 3). The highest response rates were recorded for the social aspects *Public Commitment to (Social) Sustainability* (1), *Corruption* (3), *Behavior in Competition* (6), *Social Responsibility* (9), *Freedom of Association* (10), *Hours of Work* (13), *Forced Labor* (14), *Health and Safety* (16), *Social Benefits/Social Security* (17), *Dialogue with the Local Community* (23), *Indigenous Rights* (25) and *Access to Immaterial and Material Resources* (27, 28) (red mark in Figure 3). For these, the data availability within the framework of this work is described as good. On the social aspect of *Technological Development* (4), there were also many answers regarding the performance indicators; PDCA indicators were not asked here. The latter also applies to the social aspect of *Economic Development* (2). There was no feedback on the PDCA indicators for *Armed Conflicts*. In principle, more social data could be obtained on PDCA indicators than on performance indicators. For the PDCA indicators, feedback on control mechanisms (CHECK) or processes to respond to non-compliance (ACT) was lower than on the written principles (PLAN) and implementation measures (DO) of the social aspects.

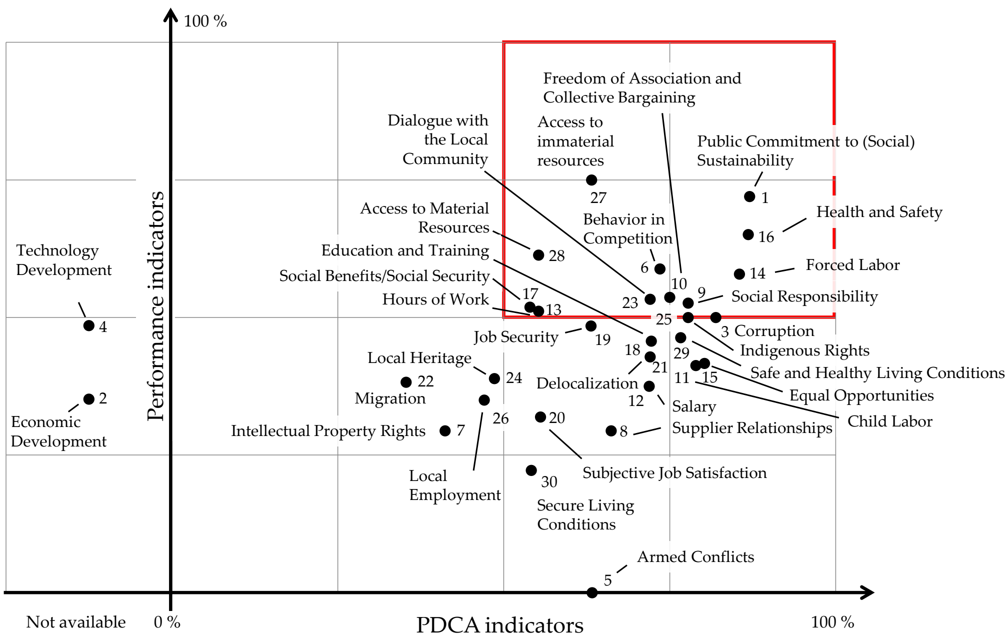

Figure 3. Evaluation of the PDCA and performance indicators regarding data availability in the surveyed companies. The answers to the social PDCA and performance indicators were set in relation to the maximum possible answers. The values in this figure are given as percentages. The social aspects within the square marked in red had good data availability in the primary data collection (response rate over 50%). No PDCA indicators were asked for the social aspects 2 and 4.

Table 2 summarizes the companies' assessments of the comparability of different companies regarding the PDCA and the performance indicators, as well as their meaningfulness in general.

Table 2. Overview of the social aspects with their corresponding numbers and an assessment of the social indicators in terms of their comparability between different companies and their meaningfulness. For the PDCA indicators, + means that the companies considered an assessment and comparison to be possible, − means that the feedback was negative or critical in this respect and 0 was given if the feedback was very different. For the performance indicators, + means that the companies considered an assessment and comparison of at least one performance indicator to be possible, − means that the feedback was more negative or critical for all performance indicators and 0 means that the feedback was ambiguous. No PDCA indicators were asked for the social aspects 2 and 4.

No.	Social Aspect	PDCA	Perf	No.	Social Aspect	PDCA	Perf
1	Public Commitment to (Social) Sustainability	+	−	16	Health and Safety	+	0
2	Economic Development		−	17	Social Benefits/Social Security	+	0
3	Corruption	+	−	18	Education and Training	+	+
4	Technology Development		−	19	Job Security	0	+
5	Armed Conflicts	−	−	20	Subjective Job Satisfaction	0	0
6	Behavior in Competition	+	+	21	Delocalization	0	+
7	Intellectual Property Rights	−	0	22	Migration	0	0
8	Supplier Relationships	−	−	23	Dialogue with the Local Community	−	−
9	Social Responsibility	+	0	24	Local Heritage	−	−
10	Freedom of Association and Collective Bargaining	0	0	25	Indigenous Rights	0	+
11	Child Labor	+	0	26	Local Employment	−	−
12	Salary	+	0	27	Access to Immaterial Resources	−	−
13	Hours of Work	+	+	28	Access to Material Resources	−	+
14	Forced Labor	+	−	29	Safe and Healthy Living Conditions	−	−
15	Equal Opportunities	+	+	30	Secure Living Conditions	−	0

Accordingly, the PDCA indicators and the performance indicators of the social aspects *Economic Development* (2), *Technological Development* (4), *Behavior towards Suppliers* (8), *Dialogue with the Local Community* (23), *Local Heritage* (24) and *Safe and Healthy Living Conditions* (29) were assessed by the companies as unsuitable (−, −) in terms of comparability and meaningfulness. The social aspects of *Behavior in Competition* (6), *Hours of Work* (13), *Equal Opportunities* (15) and *Education and Training* (18) were considered positively by the companies, as were the PDCA and performance indicators (+, +).

There are various reasons for the different evaluations that occurred in the other social aspects. For example, companies rated some social aspects in general and the corresponding PDCA indicators as being basically positive but evaluated the performance indicators as difficult to measure or not (yet) meaningful (+, −). Additionally, one social aspect in general and the corresponding PDCA indicators were regarded as being difficult to compare between companies, but the performance indicators were considered to represent a sub-area of the social aspect well (−, +). Neutral evaluations (0) indicate that the feedback did not allow for a clear trend.

In addition to the evaluation of the social indicators, all challenges that arose during the company-specific data collection process are described in the following section. These are taken up again in Section 3.3.

Challenges in the primary data collection

- Obtaining data at the process level

The goal of an SLCA is to collect social data for the individual processes along the life cycle of a product. Information on mass and energy flows is important for this, but companies often do not publish it for reasons of confidentiality. The data are usually only available at the organizational level, which is why an allocation must be carried out. At this point, the question arises regarding what proportion of the data must be allocated to administration and what proportion of administration must be allocated to the product under consideration. The allocation is getting even more complex if several products are developed or produced at one location or if the development or production extends over several locations (see Figure 4). The LCA still faces challenges with regard to allocation as well [106].

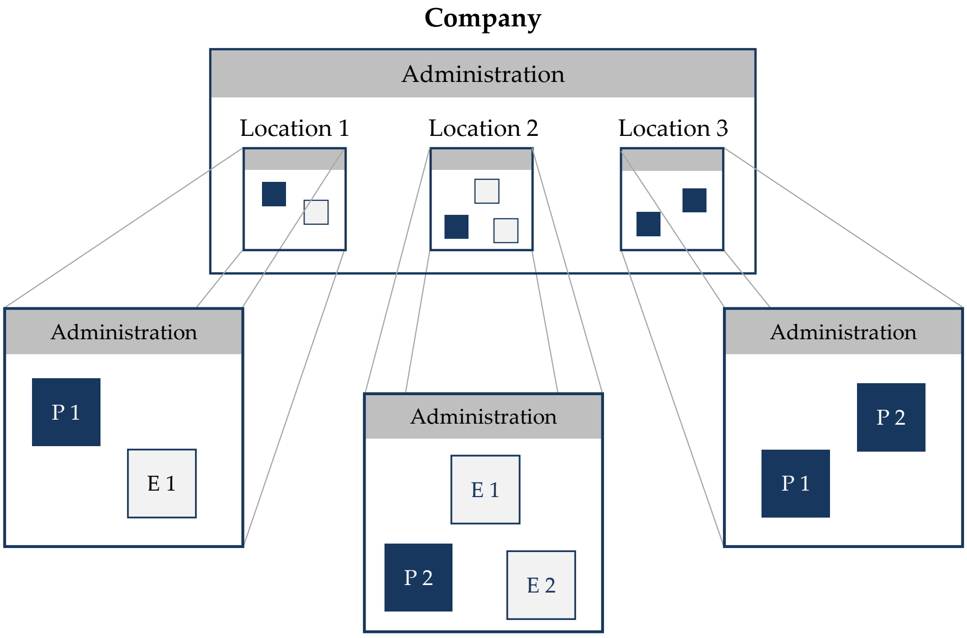

Figure 4. Exemplary representation of a company with three locations, two products and production and development areas. The company is expected to have three locations. The production (P) of product 1 (P1) and/or 2 (P2) and/or the development (E) of product 1 (E1) or 2 (E2) takes place at the respective locations.

Furthermore, most of the social aspects of companies are mainly surveyed at the organizational level and can only be related to processes with difficulty. After discussions with several companies regarding the feasibility of the social aspects developed in reference [82], it is theoretically possible to collect data at the process level on the following social aspects: *Economic Development*, *Social Benefits/Social Security*, *Salary*, *Hours of Work*, *Health and Safety*, *Equal Opportunities*, *Freedom of Association and Collective Bargaining*, *Education and Training*, *Job Security*, *Child Labor* and *Forced Labor*. However, even with these social aspects, in practice they may either not be considered at the process level or the information at the process level may be subject to confidentiality.

If social data have not been specifically recorded for a process in a company, they could be related to the process with a suitable activity variable, such as working hours. However, these are also often confidential.

- Obtaining location information with company data

Many of the indicators, such as the social aspects *Salary* or *Hours of Work*, can only be evaluated if the local situation or the cultural background of the social data is known. In the published data, there is usually no reference to the place of production, or the companies only provide social data as an average at organizational level—although they often operate at several locations in different countries (see Figure 4). Even if the company allows the publication of social data of individual sites in principle, there is often no central office, especially in large companies, to coordinate the data of the different sites. For example, each location must be requested individually, which involves a great deal of effort. Thus, an evaluation of indicators with a local reference is very difficult or even impossible in these cases.

- Definition of cut-off-criteria

In the upstream chain, only components consisting of one material each were examined in this primary data collection. Nevertheless, many of them turned out to be very complex during the data collection due to the diverse material flows. An analysis of all specific energy flows in the upstream chain would have greatly increased the complexity of this process. Therefore, cut-off criteria had to be defined. Some of these were defined a priori (for example, in the biopolymer example, only direct suppliers whose materials account for more than 5 percent by weight of the component were considered). In other cases, the cut-off criteria had to be selected during the process if, for example, the materials contained (as in the case of the textile fabric finisher) were confidential. For the energy flows, one mineral oil producer and one electricity producer (including—if available—the companies in the upstream chain) were analyzed as examples.

In future studies, especially for products with complex material and energy flows, criteria must also be defined in order to be able to implement the data collection in a foreseeable timeframe. These should be harmonized and standardized so that the results are transparent and comparable. Confidentiality of processes can be a major obstacle.

- Comparability of social data between different companies

Apart from cultural differences in the evaluation of social indicators, there are also significant differences between companies in the definition and reporting of social indicators. For example, the indicator *number of accidents per year* appears at first glance to be clearly defined. However, companies report very different accident data (e.g., number of accidents compared to number of accidents with one day lost). This challenge can also be observed in the comparison of different sustainability reports for other indicators.

In guidelines for sustainability reporting, such as the GRI guidelines, many indicators are not sufficiently precise to guarantee comparability between companies. A stronger focus should be placed in future on the concretization and standardization of indicators. However, this is also a major challenge, as many companies have already well established, often significantly different, data collection systems.

- Collection of company-specific social data in the supply chain

In some cases, the social data collection was not possible down to resource depletion, as some companies only knew their direct suppliers or bought raw materials on stock exchanges. For this reason, the social risks in the upstream chains of the biopolymer material were examined using the SHDB as an example. The results were not integrated into the discussion of the indicators as they refer to risks for social aspects in specific countries or industries and cannot be applied directly to suppliers. The different types of data collection and evaluation prevent the comparability of the results.

In addition, many companies are very reluctant to publish social data. Due to the lack of influence of the OEM over the entire life cycle, an obligation of these companies is not feasible in all cases and it is also questionable whether such an obligation would lead to reliable results. Collecting social data in ways other than direct contact or use of published documents is not possible in the context of corporate relationships. In addition, many companies do not consider data from the media or from NGO investigations to be independent.

- Collection of deviations from legal regulations

When a company is asked about for example the minimum wage or the maximum weekly working time, it will only answer something different from the legally required regulations if it can give more positive values. This means that no negative deviations can be identified. In addition, it is often not possible to answer questions on country-specific laws, as most companies provide only information at the organizational level.

- Concerns of companies about the collection of social data

The companies contacted were often skeptical about social data collection at the beginning, as many social data are confidential. However, in this work, the reluctance of companies usually subsided after reference was made to the research character of the work. In addition, companies were assured that their data would be treated accordingly and that the responses would have no impact on business relations. In principle, however, the success of a data collection depends strongly on the reasons and the argumentation.

- Effort of companies in completing the data collection form

The data collection form was very detailed in this work, as it was intended to be used to analyze the social aspects and indicators on which companies provide feedback. However, this fact led to the disadvantage that some companies did not complete the questionnaire at all or only did so partially due to a lack of capacity. Above all, the time required for collection and preparation of the data represented a high expenditure for the companies.

- Translation of the data collection form

When collecting data from companies from different countries and cultures, it is very important to adapt the different translations accordingly, maybe even working with native speakers.

3.1.2. Calculation of the Reference Values

Social data need a process reference for use in SLCA. If this requirement cannot be fulfilled during data collection (top-down approach), the mass and energy flows of the components' life cycle and the company data have to be offset against each other in order to be able to indicate the contribution of a company to a process step or component (see steps 1–4b, Figure 2).

Step 1: Determination of the material and energy flows of the component

After defining the functional unit, the material and energy flows are, for example, taken from LCA databases or directly collected at companies from the life cycle of the component under consideration. This results in the relevant material composition and energy consumption for each life cycle phase. In addition, further (actual or generic) companies relevant for the primary data collection can be determined.

If a company carries out several process steps and the social data are only available at the company level, the process steps must be combined into one at this point. In this case, the social effects of the process steps cannot be calculated individually.

Step 2: Collection of company data

The following data of the participating companies are collected in addition to the social data:

- mass of their products per year and
- number of employees.

The total number of working hours of the companies per year can be calculated from the number of employees (for example based on reference [107]).

Step 3: Calculation of the mass reference of company data

From the previous calculations, the hours worked per company for each kilogram produced can be calculated using the following formula:

$$e_{\mathrm{x}} = \frac{H_{\mathrm{x}}}{M_{\mathrm{x}}} \tag{1}$$

x: Company A, B, C, ...
e_{x}: Hours worked per kilogram by company x.
M_{x}: Total mass of production of x per fiscal year.
H_{x}: Total working hours of x per fiscal year.

The working hours per company per kilogram can be used to calculate the working hours per company per component or also broken down by process steps (steps 4a and 4b), depending on the issue at hand.

Step 4a: Calculation of the companies' contribution to the component

Using the factor $\frac{H_{\mathrm{x}}}{M_{\mathrm{x}}}$ and the material and energy flows from step 1, the working hours per company for the component (see Figure 5) can now be calculated using the following formula:

$$h_{\mathrm{x}} = e_{\mathrm{x}} \times m_{\mathrm{x}} \tag{2}$$

x: Company A, B, C, ...
h_{x}: Working hours for the component per company x.
m_{x}: Mass of the component relevant to the company x.
e_{x}: Working hours per kilogram of the company.

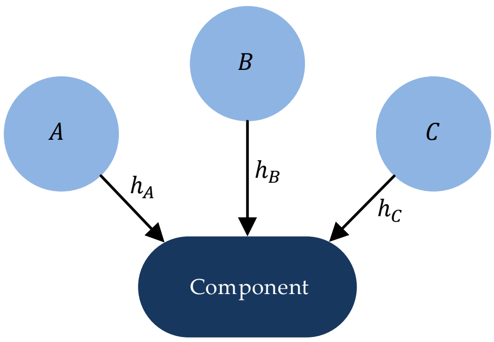

Figure 5. Representation of the hours worked per component by companies A, B, C (h_A, h_B, h_C).

Step 4b: Calculation of the companies' contributions to individual process steps

The working hours of the companies per component cannot only be given over the entire life cycle of the component under consideration, but also per process step of the component:

$$h_{\mathrm{x,n}} = \frac{H_{\mathrm{x}}}{M_{\mathrm{x}}} \times m_{\mathrm{x,n}} \tag{3}$$

x: Company A, B, C, ...
n: Process step n.
$h_{\mathrm{x,n}}$: Working hours for the company component x in process step n.
$m_{\mathrm{x,n}}$: Mass of the component relevant to the company x in process step n.
H_{x}: Total working hours of x per fiscal year.
M_{x}: Total mass of production of x per fiscal year.

Social indicators can now be related to the calculated working hours per company. In most cases, the company carrying out the respective step as well as at least one energy company contribute to a process step.

3.1.3. Calculations with the Social Data

The collected social data can be related to a component or the individual process steps with the aid of the reference values according to the following approach (see steps 5–7, Figure 2):

Step 5: Selection of the social aspects

Ideally, in an SLCA, a company should consider at least those social aspects as being very important to the company's stakeholders. However, only social aspects can be analyzed for which data is available from companies along the life cycle. The comparability between companies and the meaningfulness of the social aspects are other important points. In addition, the process reference of the indicators should also be considered in an SLCA, analogous to the LCA (see Section 3.1.2).

In order to consider all the importance classifications of the social aspects, these could be included in the framework of the impact assessment as measures of weighting (in contrast, in reference [108], the weighting component is considered more as part of the evaluation). For this purpose, the LCA contains the optional component weighting, which should not be applied, however, due to the evaluations carried out in a publication aiming at comparative statements. If this is nevertheless desired, it is recommended to add statements on uncertainty and sensitivity [109]. However, a company can also include the prioritization of social aspects in its interpretation of the results of an SLCA.

Step 6a: Calculation of the performance indicators

The performance indicators can be represented by two different approaches. The top-down approach is discussed below, followed by the bottom-up approach.

Top-down approach

With the top-down approach, the respective social indicators and the total working hours per company are recorded and related to the working hours per process step:

$$I_{x,n} = \frac{I_x}{H_x} \times h_{x,n} \tag{4}$$

x: Company A, B, C, . . .
n: Process step n.
$I_{x,n}$: Social indicator of the company x in process step n.
I_x: Social Indicator of the company x.
H_x: Total working hours of x per fiscal year.
$h_{x,n}$: Working hours for the company component x in process step n.

For calculating the respective social indicator per component, the individual process steps must be summed up. Since the social indicators in this approach are averaged across all processes of a company, it is possible that single processes are misrepresented. In addition, Equation (1) shows that the top-down approach can only be used to depict mass-dependent processes. If the functional unit in an SLCA or social indicators are independent of mass, i.e., depend on other factors, such as the number of units, this can lead to incorrect results of the top-down approach. Thus, in some cases, the bottom-up approach may offer advantages.

Bottom-up approach

For the bottom-up approach, the social data are recorded specifically for each process step of the component, i.e., indicator per functional unit. This allows a mass-independent calculation of the indicator. Since the calculation must be carried out specifically for each process step, no general formulas can be specified here. However, in Section 3.2.2, some examples are shown for component manufacturing and dismantling.

In order to be able to compare the result of an indicator of the bottom-up approach with the result of the same indicator of the top-down approach, an estimate for the administrative part can be added. The company is divided into three areas: production, development and administration. It is assumed that the hours worked in administration are equally divided between the hours worked in production and the hours worked in development.

The calculation of the working time required for a production hour in administration can be calculated using the following formula:

$$T_{\mathrm{V}} = h_{\mathrm{V}} \times \frac{\frac{h_{\mathrm{P}}}{h_{\mathrm{P}}+h_{\mathrm{E}}}}{h_{\mathrm{P}}} = \frac{h_{\mathrm{V}}}{h_{\mathrm{P}}+h_{\mathrm{E}}} \quad (5)$$

T_{V}: Administration working time in hours per production hour.
h_{V}: Working hours administration.
h_{P}: Working hours production.
h_{E}: Working hours development.

Step 6b: Calculation of the PDCA indicators

The PDCA indicators can be evaluated individually or collectively. These two options are discussed below. In addition, different reference values are addressed.

Individual evaluation of the PDCA indicators

The answers *Yes*, *No* and *not relevant* or no answer to the individual PDCA indicators from the primary data collection can be assigned to the working hours of the respective company and aggregated over the entire life cycle. This procedure was developed based on the LCAA [23,24]. The answers of the companies that do not provide any information in the primary data collection or that evaluate the social aspect as not relevant for them should be specifically examined. On the one hand, it is possible that this indicator is not communicated in public reports. On the other hand, the company can deliberately not respond. In the latter case, it can be assumed that the company does not address the indicator. If a company indicates that a social aspect is not relevant to it, it should be checked whether this answer is realistic. Social risk databases such as the SHDB can be used for this purpose. If the risk in the country in which the company operates is high for the social aspect, then the company should be analyzed in more detail during the evaluation. The evaluation and comparison with a social risk database can also be carried out for the other answers.

This approach offers the possibility of integrating social aspects that can only be measured to a limited extent by performance indicators, such as *Forced Labor*, into an SLCA. These social aspects would then only be included in the evaluation through PDCA indicators. In principle, a similar procedure would be suitable for qualitative performance indicators.

Joint evaluation of the PDCA indicators

In addition to the evaluation of individual indicators, all PDCA indicators can also be calculated together. For this purpose, the results of the percentage evaluation of the individual PDCA indicators can be averaged. With this procedure, however, the distribution between the individual indicators and the participating companies cannot be read off from the result (exception: 0 and 100%). For example, it is not possible to distinguish whether a few companies in the product's life cycle have not implemented any PDCA indicators or whether many companies do not address individual indicators. To avoid this, the respective process steps and indicators would have to be specifically analyzed. Alternatively, individual PDCA indicators can also be defined as being mandatory. In order to give a *Yes* rating to working hours, a company would have to meet the defined indicators.

For both the individual and the joint evaluation of the PDCA indicators, the calculations can be performed not only per company, but also per process step. The working hours calculated from Equation (3) can be used. In addition, as an alternative to working hours, the indicators can also be related to other parameters, such as turnover. This depends on the parameter with which the indicator is related. For the *written principles* of the social aspect *Corruption*, for example, it is possible to relate these to both working hours and turnover.

Step 7: Using performance and PDCA indicators in an SLCA

Below are several ways to apply the performance and PDCA indicators in an SLCA. They can be used in conjunction with each other or individually.

Individual use of the indicator types

If the indicator types are not to be offset against each other, they can be included directly and individually in the SLCA (results in step 6).

Joint use of the indicator types

The following two options for the joint use of performance and PDCA indicators are outlined below.

<u>Definition of scores for the indicators</u>

The performance indicators can be scored for the allocation of performance and PDCA indicators. For example, the desired value of a performance indicator is 100% and the undesired value is 0%. A score of 50% could be defined by the industry average. For the PDCA indicators, either the percentage coverage of hours worked can be used directly as a score, or the same score as for the performance indicators can be used. For an overall result of the various indicators of a social aspect, the scores can be averaged. This is of course also possible for performance indicators among themselves. The result of the evaluation can be compared with alternative scenarios (e.g., other suppliers, other materials or the predecessor model of a car).

A disadvantage of this procedure is on the one hand that the evaluation can be specified again in each investigation. It must be ensured that comparability between companies is possible. On the other hand, a bad result of a performance indicator could be compensated for by a good result of the PDCA indicators.

<u>Determination of PDCA indicators as a condition for performance indicators</u>

PDCA indicators can be used as a condition for the evaluation of performance indicators. Only the systematic approach of the PDCA indicators can ensure that the performance indicators are measured correctly, and that the results can be interpreted. A possible realization would be the integration of the PDCA indicators into the actual functional unit, such as 160,000 km driven by a car. The integration of additional properties into the functional unit was proposed by Lehmann [47] as part of implementation criteria for technologies. If two cars are now compared, all flows and indicators evaluated for the two cars are related to this functional unit. However, this also means that the comparison can only be carried out if the participating companies comply with all (or previously selected) PDCA indicators of the respective social aspect. The implementation could be established through audits or questionnaires. A disadvantage of this method is that companies that have not implemented a PDCA approach for a social aspect cannot be included in the assessment. Companies could also use this approach to require a systematic procedure for certain social aspects as a condition from their suppliers. This would be independent of the performance indicators.

3.2. Application of the SLCA Approach in Case Studies

In the primary data collection described in Section 3.1.1, it was possible to collect social data for the two materials steel and aluminum along the entire life cycle from resource extraction to shredding (and exemplarily for one mineral oil producer and one electricity producer each, including the companies in the upstream chain). The developed SLCA approach described above is applied to the two materials in the following. For a better comparison, the component inner part of the rear door of a B-Class is considered for both materials (see Figure 6).

Figure 6. 2-D data model of the inner part of the rear door of a B-Class. The figure was taken from the Product Data Management Model of Daimler for the B-Class (W 246).

3.2.1. Calculation of the Reference Values

Step 1: Determination of the material and energy flows of the component

The steel component was assumed to weigh 5.90 kg, the aluminum component 4.13 kg (internal concept comparison). The respective material and energy flows were mapped using life cycle assessment data records, which were taken from GaBi [102] (22nd Servicepack) and ecoinvent data sets [103] (Version 2.2). In the case of aluminum, an EAA study [104] was also used. Further data about recycling were taken from reference [105].

In the use phase, a fuel reduction factor of 0.3 l per 100 kg and 100 km and a service life of 160,000 km was assumed. The functional unit was therefore the *inner part of the rear door of a B-Class made of steel or aluminum, which is installed in a car with 160,000 km of mileage at the given fuel reduction factor*.

From the information described, the relevant material composition and energy consumption were determined for each life cycle phase.

In the further course of the calculations, the process steps were assigned to the various companies, as the social data were recorded at company level. The following process steps resulted for the steel component: mineral oil production (extraction and production of diesel and process energy), electricity production, hard coal mining (for electricity), hard coal mining (for coke), manganese ore mining, iron ore mining, steel coil production (process from production of pig iron, via crude steel and slabs to steel coil, coke production process), component production, dismantling and shredding.

A company carries out several process steps for the aluminum component (bauxite mining to ingot production). These process steps were combined into one (ingot production). This resulted in the following process steps for this component: mineral oil production (extraction and production of diesel and process energy), electricity production, coal mining (for electricity), ingot production, aluminum sheet production, component production, dismantling and shredding.

No company-specific data were available for some individual processes, so only energy flow data were considered for them. The processes are: ferromanganese production (steel), anode production and floating and sinking plant (aluminum). This was also done in the same way for the recycling production waste process for both materials. In order to present the energy companies, one mineral oil producer and one electricity producer were interviewed as examples. Detailed information and assumptions regarding the case studies are given in Appendix B.1.

Step 2: Collection of company data

The following general data were collected from the companies participating in the life cycle: the mass of their products per year, the number of employees and the turnover. From the number of employees, the number of working hours per company and year could be calculated (based on reference [107]); 1450 working hours per year and employee were assumed for German companies and 1765 for the other companies.

Step 3: Calculation of the mass reference of company data

In order to be able to compare the data of all companies on the basis of the same unit, all energy data were also converted to kilograms. Each kWh of electricity was assigned the mass corresponding to the amount of hard coal needed to produce it. For the conversion of mineral oil, the lower calorific value 42.8 MJ/kg was used [110].

The factor $\frac{H_x}{M_x}$ (1) is shown for all companies of the steel component on the left and for all companies of the aluminum component on the right in Figure 7. For both the steel component and the aluminum component, the most hours worked per mass produced are allocated to the company producing the part.

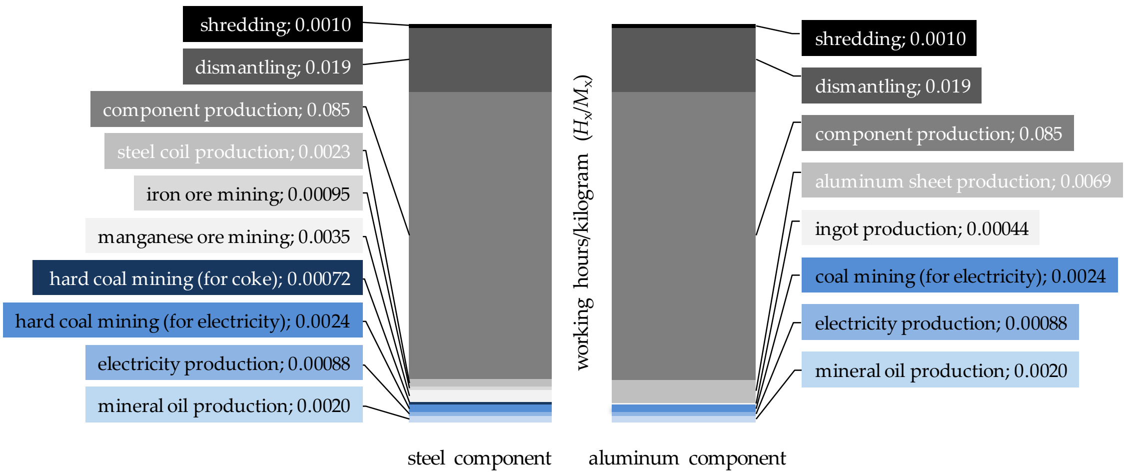

Figure 7. Working hours per kilogram of produced mass of the companies of the steel component (**left**) and the aluminum component (**right**).

Step 4a: Calculation of the companies' contribution to the component

Using the factor $\frac{H_x}{M_x}$ and the material and energy flows, it was possible to calculate the working hours h_x per company for the two components (see Figure 8). The total number of hours worked for the steel component was 0.64 and for the aluminum component 0.61. For both components the most working hours were incurred during component production (steel: 0.50 h, aluminum: 0.35 h). An important factor here is the proportion of manual work compared with automated processes. The difference between aluminum and steel results from the different weight of the two components and is discussed again in Section 3.2.2. For aluminum, more working time was required for dismantling, as the proportion of dismantled components is higher than for steel due to the material value. The working hours required for power generation and supply were less important for the steel component than for the aluminum component, but the mineral oil consumption was higher. The reasons for these differences can be clearly seen in a breakdown by process steps (see step 4b).

Step 4b: Calculation of the companies' contributions to individual process steps

The working hours of the respective companies per process step are shown in Figure 9 for steel and aluminum as Sankey diagrams (for detailed values, see Appendix B.2). The working hours of the energy flows are shown separately from the working hours generated during material processing.

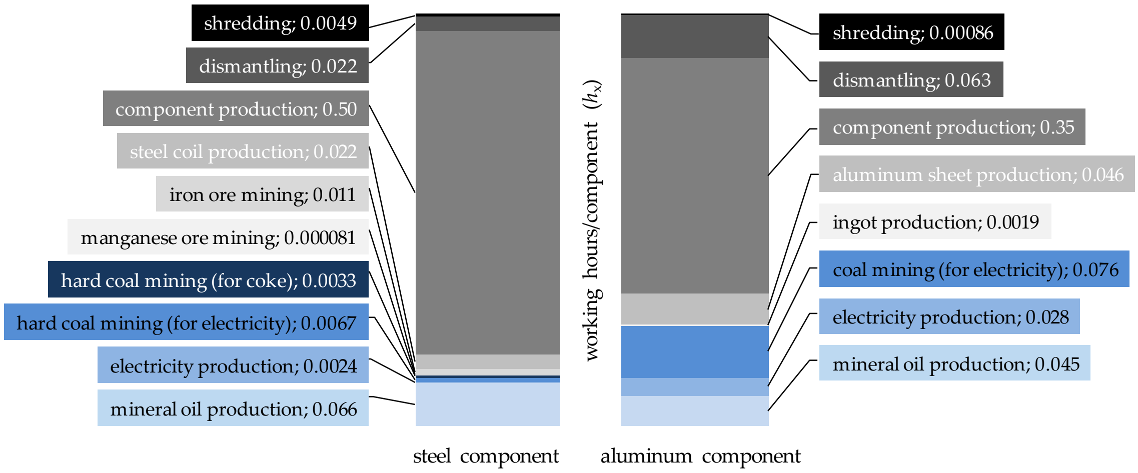

Figure 8. Working hours per company for the steel component (**left**) and for the aluminum component (**right**).

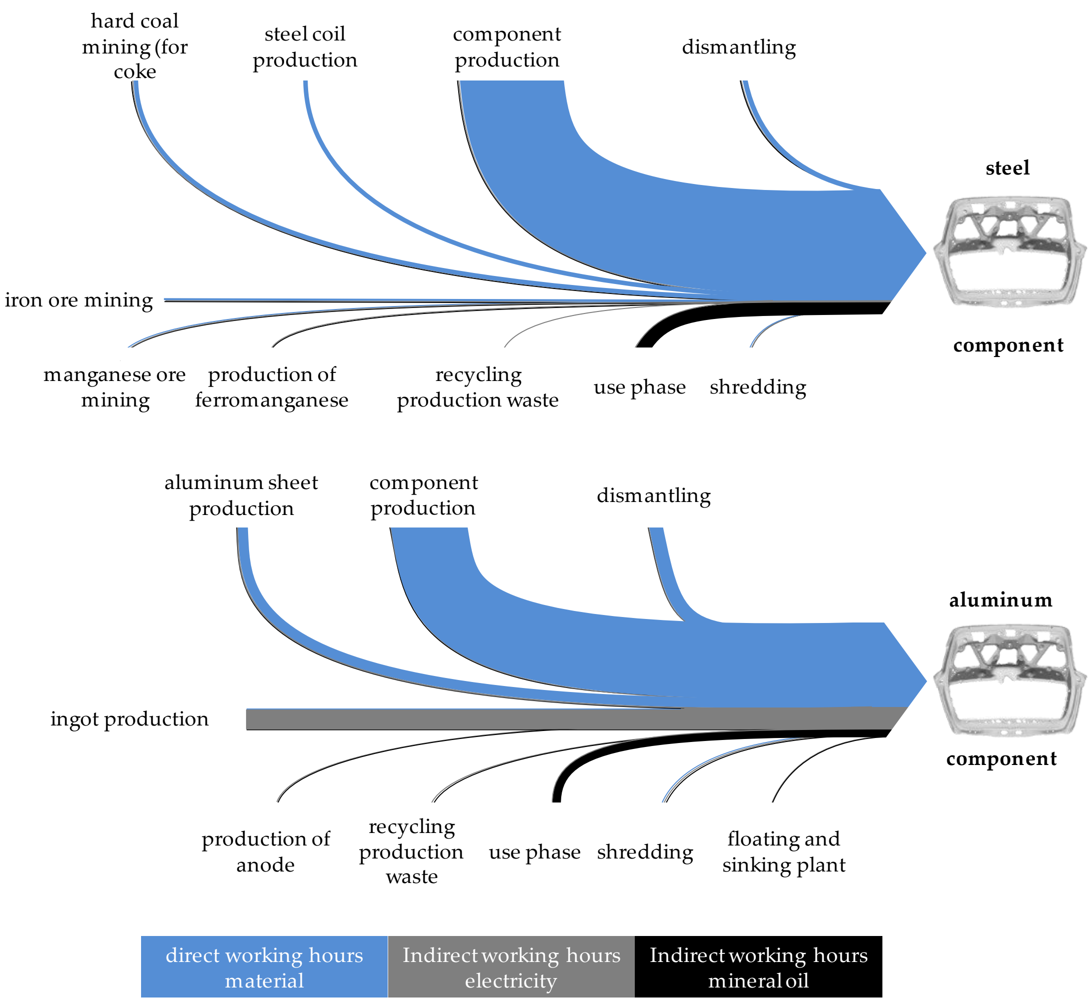

Figure 9. Sankey diagram of working hours for each process step of the steel component (**top**) and the aluminum component (**bottom**). Direct working hours are incurred directly by the company where the process is carried out. Indirect working hours are incurred during energy generation and are assigned to the respective process step. The line thicknesses are proportional to the number of working hours per process step. The working hours of the electricity flow for the steel component are not visible in the figure due to their small quantity.

Figure 8 shows that the working hours caused by electricity consumption are significantly higher for aluminum than for steel. The Sankey diagrams indicate that the reason for this was the large amount of electricity required to producing ingots. The mineral oil consumption for both components was mainly caused during the use phase. The reduced consumption was noticeable here due to the lower weight of the aluminum part.

3.2.2. Calculations with the Social Data

Step 5: Selection of the social aspects

The results of the importance ranking of the social aspects (see reference [82]) and the availability of data (see Section 3.1.1) can be seen in Figure 10. Good data availability was found in the primary data collection for the social aspects within the square marked in red. The very important social aspects were drawn in dark blue. The following social aspects were therefore the most important in this work, both in terms of importance and data availability:

- *Health and Safety* (16),
- *Forced Labor* (14) and
- *Freedom of Association and the Right to Collective Bargaining* (10).

Since the social aspect *Corruption* (3) was on the red mark, it was also included in this list.

In addition, the companies' assessment of the comparability of different companies was analyzed regarding the PDCA and the performance indicators and their meaningfulness in general (see Section 3.1.1). The PDCA indicators for the social aspects of *Forced Labor*, *Health and Safety* and *Corruption* were rated as positive by the companies surveyed in terms of their meaningfulness and comparability. However, this was only the case for some of the performance indicators for the social aspects of *Health and Safety* and *Freedom of Association and the Right to Collective Bargaining*.

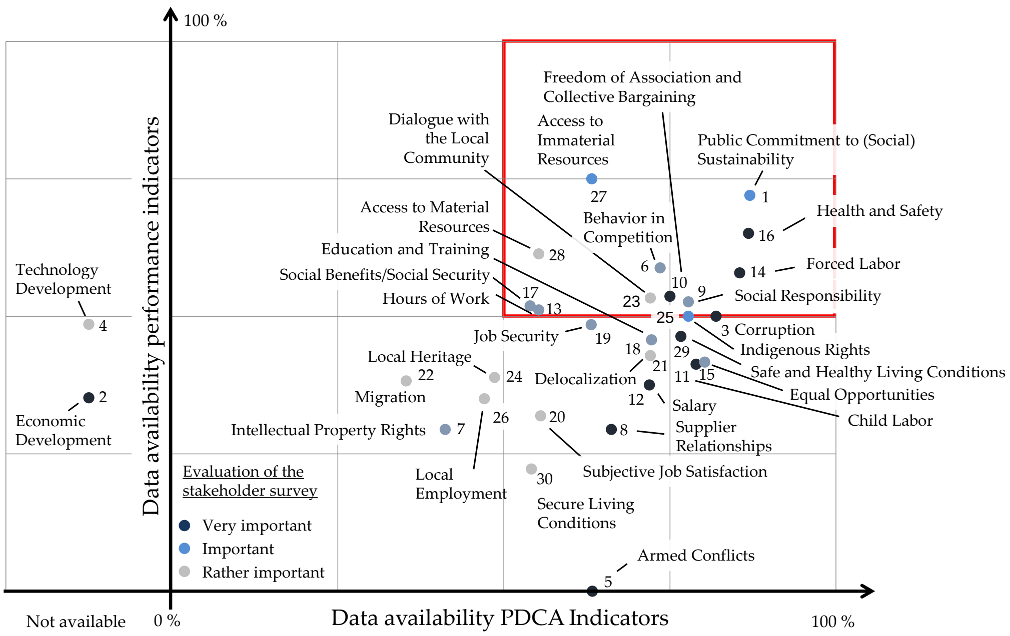

Figure 10. Linking the results of prioritizing the social aspects with the mean values from the survey and the data availability of the PDCA and performance indicators. The answers to the social PDCA and performance indicators were set in relation to the maximum possible answers. The values in this figure are given as percentages. The social aspects within the square marked in red had good data availability in the primary data collection (response rate over 50%). The social aspects prioritized in Section 4 in reference [82] are shown in this figure in dark blue for very important, in light blue for important and in grey for rather important. No PDCA indicators were asked for the social aspects 2 and 4.

A fundamentally good data availability of the performance and PDCA indicators increases the probability that data can also be collected during primary data collection. However, it does not initially say anything about whether this data is also available for all life cycle phases of a product along its entire life cycle or whether it is reported back by the companies when data is collected.

Five performance indicators were continuously reported back by all companies involved in the life cycle of the component:

- *Are you training your employees on your code of conduct or your attitude to social sustainability?* (social aspect 1, *Public Commitment to Social Sustainability*),
- *What is the proportion of employees covered by collective agreements?* (social aspect 10, *Freedom of Association and Collective Bargaining*),
- *How many injuries and non-fatal accidents at work were there in the last year in the company? How many fatal accidents at work were there in the last year in the company?* (social aspect 16, *Health and Safety*) and
- *What is the average number of training days per employee per year* (social aspect 18, *Education and Training*)?

Hereinafter, the indicator *Are you training your employees on your code of conduct or your attitude to social sustainability?* was not considered because the answers were too diverse.

The answers to the PDCA indicators and the qualitative performance indicators were also not consistently available everywhere. In these cases, however, the calculations could still be carried out.

In the context of this work, some examples were selected based on data availability and importance to demonstrate the different possibilities for the calculations in an SLCA. These are

- *Number of (workplace) accidents* (social aspect 16, *Health and Safety*) for the calculation of the performance indicators,
- PLAN indicator of the social aspect *Corruption* (3) and CHECK indicator of the social aspect *Child Labor* (11) for the individual calculation of the PDCA indicators,
- *Are you a member of an initiative for promoting social responsibility along the value chain?* (social aspect 9, *Social Responsibility*) for the integration of qualitative performance indicators,
- PDCA indicators of the social aspect *Health and Safety* (16) for the joint calculation of PDCA indicators, and
- PDCA indicators and one quantitative performance indicator (*number of accidents*) of the social aspect *Health and Safety* (16) for the use of these indicator types in an SLCA.

Step 6a: Calculation of the performance indicators

Top-down approach

The result of the top-down approach from Equation (4) is shown in Figures 11 and 12 as examples of the social indicator *number of (workplace) accidents*, which was defined here as the number of accidents with at least one day lost. The number of accidents reported by companies was converted into this indicator as far as possible. Most accidents occurred both in aluminum and in steel during component production (steel: 3.75×10^{-9}, aluminum: 2.66×10^{-6}), followed by dismantling (steel: 1.19×10^{-6}, aluminum: 3.33×10^{-6}). This was due to the high number of working hours during component production and the relatively high accident rate during dismantling. There was a total of 5.6×10^{-6} accidents per steel component and 6.5×10^{-6} accidents per aluminum component. Further values for the *number of accidents* and the results of the other available social performance indicators *fatal accidents*, *number of training hours* and *working hours with collective agreements* are presented in Appendix B.2.

When comparing the two results in Figures 11 and 12, it can also be seen that more working hours or accidents were attributed to the steel component during component production and dismantling due to the higher mass, although this does not correspond to reality. These two processes are more likely to be assumed to be independent of mass, since the number of accidents depends less on the weight than on the number of units of the component (and possibly other factors). However, the processes available in LCA databases are mostly mass-based, which is why they could not be calculated independently of the mass using the top-down approach. For this reason, the social data used here were analyzed again using a bottom-up approach. The shredding process was also discussed regarding mass (in)dependence. No significant relationship to mass, volume or number of units could be established. Due to the clearer relationship in the processes of component production and dismantling, only these were considered in the bottom-up approach.

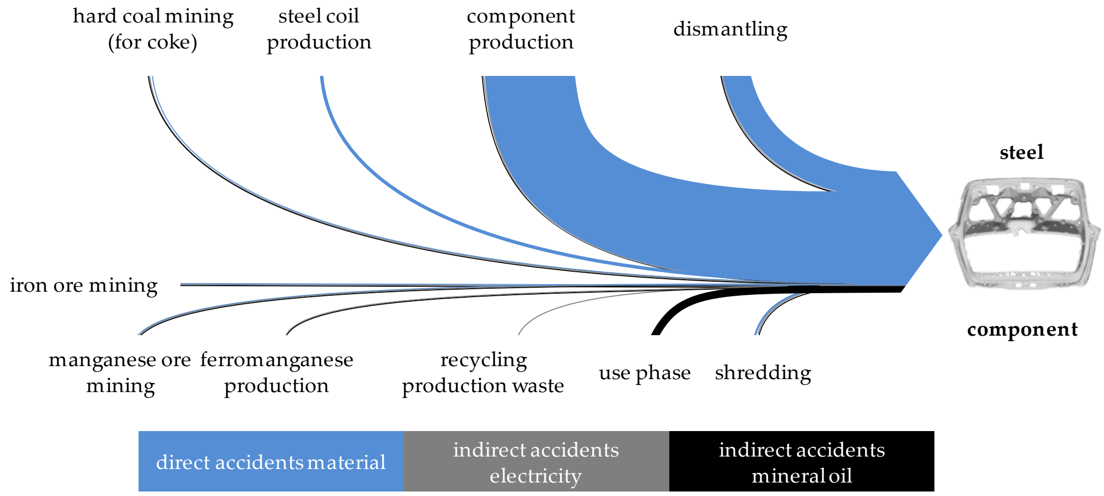

Figure 11. Sankey diagram of accidents for each process step of the steel component. Direct accidents occurred directly at the companies where the process was carried out. Indirect accidents occurred in power generation and were assigned to the respective process step. The line thicknesses are proportional to the number of accidents per process step.

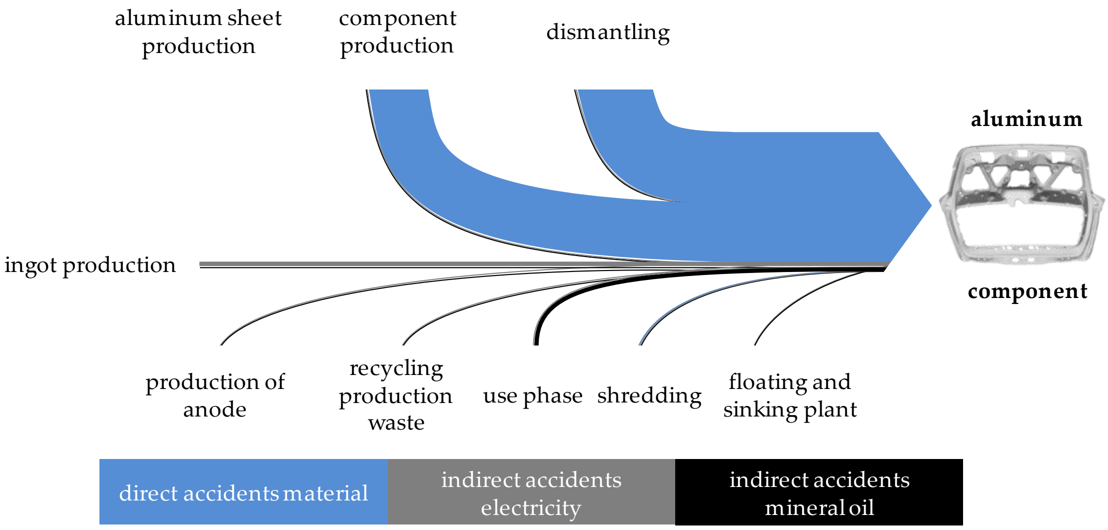

Figure 12. Sankey diagram of accidents for each process step of the aluminum component. Direct accidents occurred directly at the companies where the process was carried out. Indirect accidents occurred in power generation and were assigned to the respective process step. The line thicknesses are proportional to the number of accidents per process step.

It was also analyzed whether the choice of the reference value for the social data, such as turnover or mass instead of working hours, caused a difference in the results. Since the processes in the top-down approach could only be represented using mass and energy flows, it was mandatory to convert using these variables. However, the relationship between working hours, mass and turnover of a company always remained constant in the calculations, so that no differences in the absolute number of indicators per component resulted from the different reference values. The differences could only be calculated relatively (see Figure 13 for the steel component).

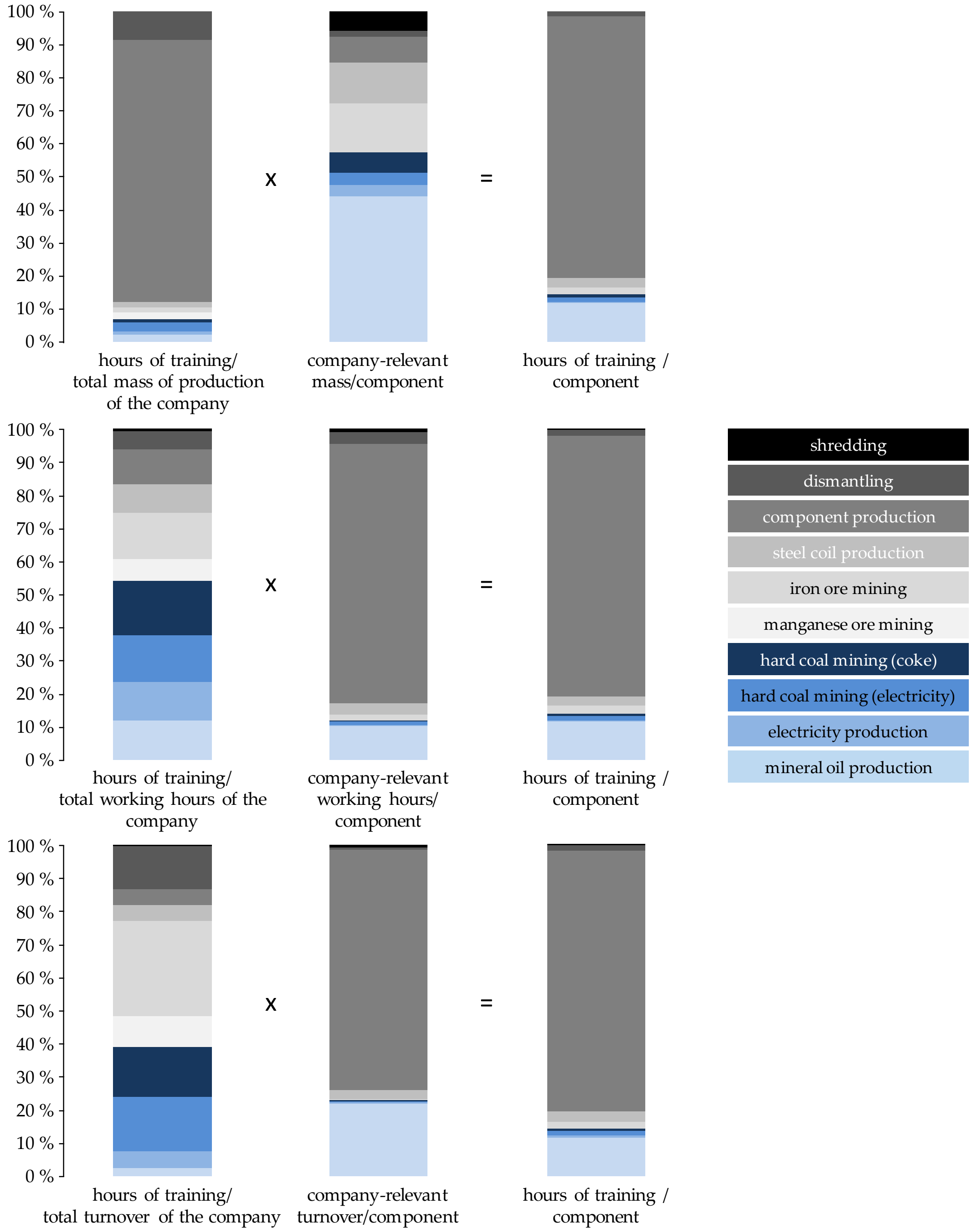

Figure 13. Relative differences in the derivation of the *number of training hours* in relation to the mass (**top**), working hours (**middle**) and turnover (**bottom**) of a company. The differences are shown exemplarily on the component made of steel.

Bottom-up approach

The bottom-up approach was analyzed exemplarily with the indicator *number of accidents* for the two processes component production and dismantling. At each stage of component production (development, press shop, body shop, painting and assembly) and dismantling, the aim was to obtain the indicator number of accidents per component. This was achieved by a specific consideration of different parameters (see Table 3). For example, the accidents in the paintwork were derived from the painted total area on a painted rear wall door. During dismantling, the company's accident data were related to the component with the dismantling time of the component. This made it possible to calculate the number of accidents during component production and dismantling independently of the mass.

Table 3. Bottom-up approach of the indicator number of accidents in component production and dismantling. RW means rear wall.

	Component Production					**Dismantling**
	Development	**Press Shop**	**Body Shop**	**Painting**	**Assembly**	
Considered parameter	Development time/produced RW door	RW door	Number of welding spots of the RW door	Area of the RW door	Assembly time/RW door	Dismantling time/RW door
Reference value	Total working hours of the development department	Number of pressed RW doors	Number of welding spots in the body shop	Painted total area	Total working hours of assembly	Total working hours of dismantling
Aim	Accidents/RW door					
Results	7.67×10^{-8}	9.76×10^{-7}	8.88×10^{-7}	1.35×10^{-7}	8.03×10^{-7}	7.07×10^{-6}

To be able to compare the accident figures of the bottom-up approach with the accident figures of the top-down approach, an estimate for the accident figures of the administration was added. For this work, Equation (5) $T_V = 0.542$ was used. This means that about half an hour of administration was required for one production hour of the component. For the social indicator *number of accidents*, this resulted in 4.20×10^{-6} (without administration it would be 4.09×10^{-6}) accidents per component, regardless of the material used for production.

Figures 14 and 15 compare the results for the number of accidents using the top-down and bottom-up approaches. In total, there were 5.6×0^{-6} accidents per component for steel in the top-down approach and 6.2×10^{-6} accidents per component in the bottom-up approach. For aluminum, it resulted in 6.5×10^{-6} (top-down approach) and 10.4×10^{-6} (bottom-up approach) accidents per component. A comparison of the top-down and bottom-up approaches shows that the top-down approach assigned more accidents to the steel component than to the aluminum component due to the higher mass involved in component production. In the bottom-up approach, the same number of accidents were assigned to the components for this process step, since no difference between the two materials was assumed in the internal concept comparison. The higher proportion of aluminum components dismantled was even more noticeable in the bottom-up approach than in the top-down approach, where fewer accidents were attributed due to the lower weight of the aluminum component.

Although the number of accidents in component production was higher for both components in the bottom-up approach than in the top-down approach, it was of the same order of magnitude. One possible explanation for this is that the component under consideration in this work went through a relatively large number of process steps in the automotive company. As a result, the indicator *number of accidents* was averaged over the various process steps in a manner that was similar to the top-down approach. The reduction in the number of accidents in the top-down approach due to the lower weight of the aluminum component was eliminated in the bottom-up approach. Thus, significantly more accidents were assigned to the component.

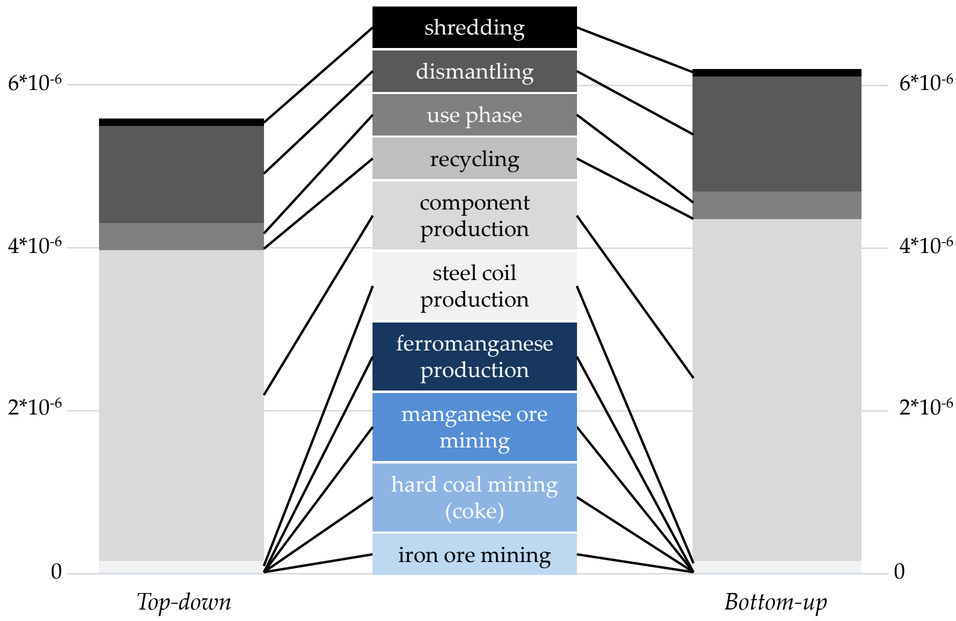

Figure 14. The social indicator *number of accidents* along the life cycle of the steel component in the top-down (**left**) and bottom-up approach (**right**).

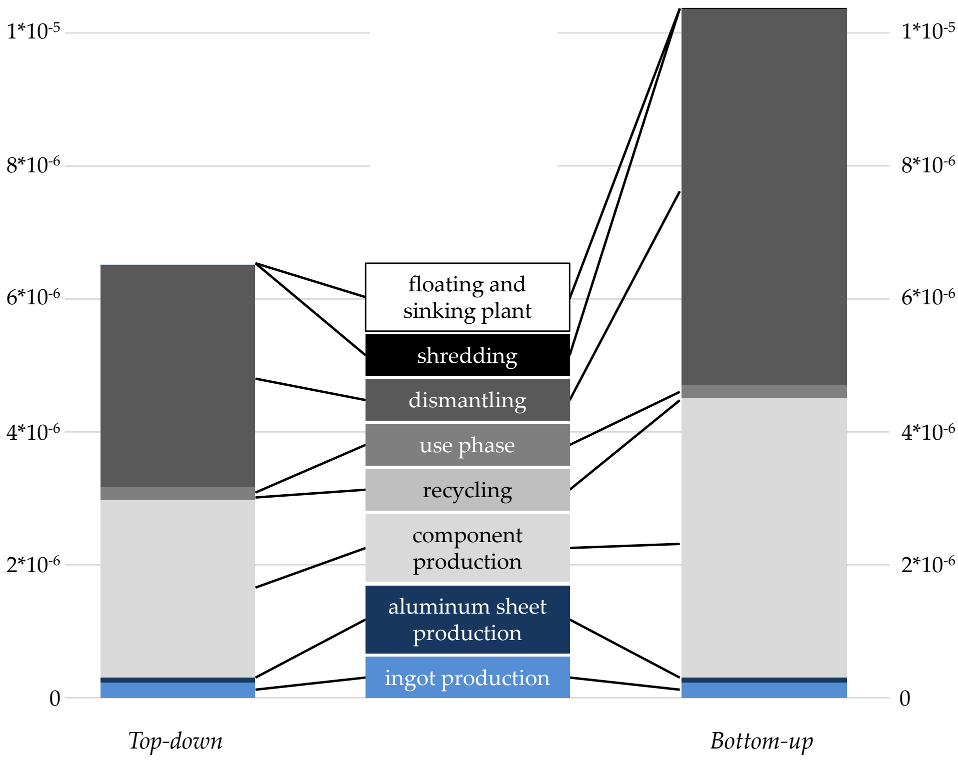

Figure 15. The social indicator *number of accidents* along the life cycle of the aluminum component in the top-down (**left**) and bottom-up approach (**right**).

Step 6b: Calculation of the PDCA indicators

Individual evaluation of the PDCA indicators

The answers to the PDCA indicators from the primary data collection were assigned to the working hours of the respective company and then aggregated over the entire life cycle.

For the indicator *written principles* (PLAN) of the social aspect *Corruption* (see Figure 16), for example, it was found that 96.26% of the working hours for the steel component were covered by written principles, 0.49% were not covered and 3.25% of the working hours were not specified. For the aluminum component, 99.93% and 0.07% of the working hours were covered or not covered, respectively. The companies that had not provided any information for the steel component were those with which a set of indicators other than PDCA indicators (iron ore, manganese ore mining and steel coil manufacturing; see reference [82]) was determined in the primary data collection.

There were also some companies that did not report on the indicator *control mechanisms* (CHECK) of the social aspect *Child Labor* (see Figure 17). In addition to the companies with which a set without PDCA indicators was determined from the beginning, another company was added to this example (see Appendix B.2). As this company operates globally, it should be re-examined for a final evaluation, which was not possible within the scope of this work. Overall, 3.34% of the working hours for the steel component and 3.92% of the working hours for the aluminum component were not reported. In addition to the *Yes* (steel: 95.91%, aluminum: 80.79%) and *No* answers (steel: 0.50%, aluminum: 0.07%), two companies also stated that this social aspect was not relevant to them. For one of the companies, this was considered to be realistic. The company operates in a country in Europe for which the risk of child labor in the SHDB is rated as being very low. However, the other company operates globally. Here it cannot be assumed that the risk of child labor is low in all countries this company operates in. Therefore, this would have to be analyzed in more detail in a final evaluation.

Qualitative performance indicators, such as *Are you a member of an initiative for promoting social responsibility along the value chain?* of the social aspect *Social Responsibility* (9), can also be evaluated in this way. For the steel component, no information was given for 5.10% of the working hours and for 4.27% the answer was *No* (90.63% *Yes*). For the aluminum component, the answer was *Yes* for 89.57% and *No* for 10.43% of the working hours. In this case, too, it would be important to repeat the review of the companies that did not provide any information in order to make a final assessment.

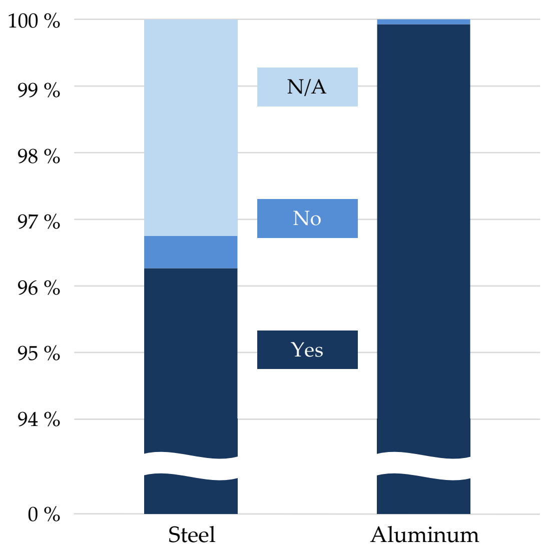

Figure 16. Comparison of responses to the PLAN indicator of the social aspect *Corruption* between the steel component (**left**) and the aluminum component (**right**). The various responses are divided into *Yes*, *No* and *N/A* (no answer) and are expressed as a percentage of working hours.

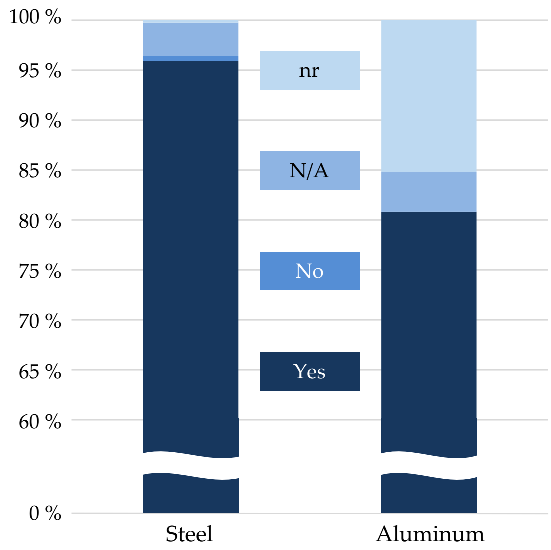

Figure 17. Comparison of responses to the CHECK indicator of the social aspect *Child Labor* between the steel component (**left**) and the aluminum component (**right**). The various responses are divided into *Yes*, *No*, *N/A* (no answer) and *nr* (not relevant) and are expressed as a percentage of working hours.

Joint evaluation of the PDCA indicators

In addition to individual indicators, all PDCA indicators can also be evaluated together. This was done as an example for the PDCA indicators of the social aspect *Health and Safety* and can be seen in Figure 18. For the steel component, 96.51% of the working hours were covered by the PDCA approach, for the aluminum component 99.96%. Not covered made up 0.24% for the steel component and 0.04% for the aluminum component. There were no answers for 3.25% of the working hours of the steel component. However, no answers and the response *No* do not make it clear whether, for example, a company did not provide information on all PDCA indicators or only on one indicator. Here the respective process steps and indicators would have to be specifically analyzed.

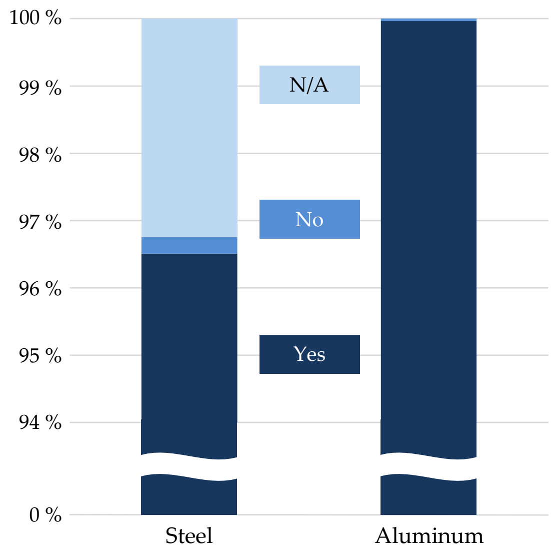

Figure 18. Comparison of responses to the PDCA indicators of the social aspect *Health and Safety* between the steel component (**left**) and the aluminum component (**right**). The different responses are divided into *Yes*, *No* and *N/A* (no answer) and are expressed as a percentage of working hours.

As an alternative to working hours, the indicators can also be related to other variables such as turnover (for detailed values see Appendix B.2). This depends on which variable the indicator is related to. For example, the *written principles* of the social aspect *Corruption* can be expressed both in working hours and in turnover (see Figure 19). For the steel component, 97.54% of turnover were covered by written principles on *Corruption*, for the aluminum component 99.93%. The equivalent not covered percentages were 0.44% for steel and 0.07% for aluminum. For the steel component, 2.03% of turnover was not reported. The indicator related to working hours per process step is shown again on the left in Figure 19 for comparison (see also Figure 16). The differences are because the companies that did not provide any data had proportionately less turnover than working hours per process step (see Figure 20).

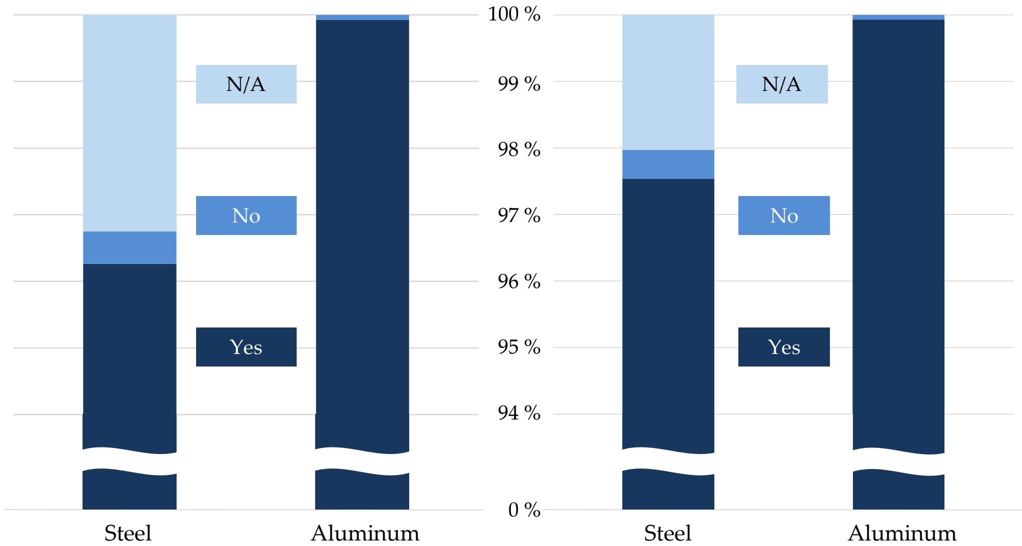

Figure 19. Comparison of responses to the PLAN indicator of the social aspect *Corruption* between the steel component and the aluminum component. The various responses are divided into *Yes*, *No* and *N/A* (no answer) and are expressed as a percentage of working hours (**left**) and percentage of turnover (**right**).

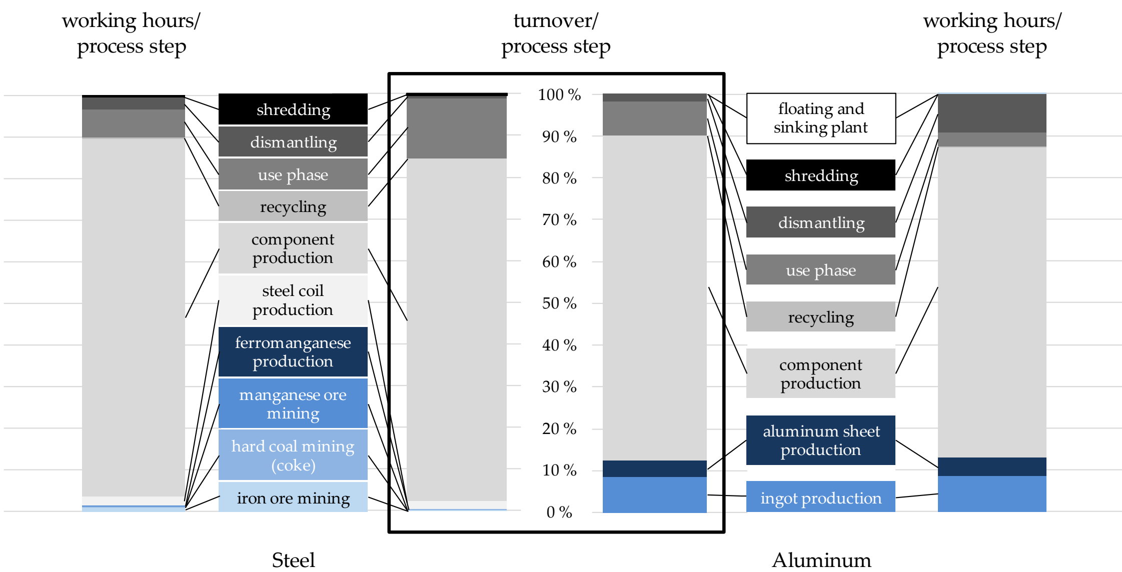

Figure 20. Comparison of turnover and working hours per process step for the steel component (**left**) and the aluminum component (**right**). In the diagrams, the values are given in percent. The value turnover per process step is bordered in black.

Step 7: Using performance and PDCA indicators in an SLCA

Below are several ways to apply the performance and PDCA indicators in an SLCA. The individual use is no longer dealt with explicitly, as it has already been described in steps 6a and 6b with application examples.

Joint use of the indicator types

Definition of scores for the indicators

The procedure is illustrated by the performance indicator *number of accidents* and the PDCA indicators *Health and Safety*. The following rating was set for the performance indicator: 0 accidents per working hour means a rating of 100%, 0.0001 accidents per working hour means a rating of 0% (based on the highest accident rate in primary data collection). For the aluminum component, the rating was therefore 89.32% for accidents throughout the life cycle. In the case of the PDCA indicators, the percentage coverage of working hours was 99.96%, which was used here as a rating. This allowed an average value of 94.64% to be calculated. This can now be compared with alternative scenarios (such as other suppliers, other materials). For example, for the steel component the rating for accidents was 95.01%, and the coverage of PDCA indicators was 96.51%. Thus, the mean value was 95.76%. This means that the steel component would be preferable to the aluminum component.

Determination of PDCA indicators as a condition for performance indicators

Individual or all PDCA indicators can be considered as a condition for the evaluation of performance indicators. A possible realization would be the integration of these indicators into the actual functional unit, such as 160,000 km driven by a car.

In the case of the PDCA indicators for the social aspect *Health and Safety*, for example, one company in the aluminum component stated in the primary data collection that it had not implemented CHECK and ACT indicators. In the case of the steel component, three additional companies did not provide any information. Thus, the PDCA indicators *Health and Safety* could not be integrated into the functional unit if all companies were to be considered. Alternatively, the companies that did not provide any information would have to be specifically addressed again. The company that had not implemented CHECK and ACT indicators could be supported in the corresponding development or a replacement supplier would have to be sought. In addition, it would also be possible to define only one indicator of the PDCA indicators as a condition for the suppliers. If, for example, the PLAN indicator (*written principles*) were selected here, it could be integrated into the functional unit for the aluminum component. For the steel component, the companies that did not provide any information would still have to be contacted.

3.3. Discussion of the Presented SLCA Approach

For the first time in an industry with complex, international production and supplier structures, the practical suitability of life cycle-oriented social aspects and indicators, mostly developed theoretically in the SLCA research community, was comprehensively analyzed.

In the case of the steel and aluminum components, life cycle-oriented company-specific social data from resource extraction to end-of-life vehicle disposal could be collected throughout, which were used for further investigations regarding an approach for a practical SLCA of a car.

In addition, all challenges that arose during the company-specific data collection process were described and analyzed in detail in this work. These are taken up again further on in this section.

In developing the approach and subsequently applying it in case studies, an SLCA study was conducted for the first time with company-specific social data in an industry with complex, international manufacturing and supplier structures at Life Cycle Inventory level. Both mass and energy flows were mapped. Therefore, this work fills the research gaps (Section 1.3) regarding the application of SLCA in industries with complex, international manufacturing and supplier structures like the automotive industry with the priority use of company-specific data. For all energy processes in this work, a mineral oil producer and an electricity producer (including—if available—the companies in the upstream chain) were analyzed as examples.

Two different approaches have been developed for the performance indicators of life cycle-oriented social aspects. In the top-down approach, the social indicators were collected at company level and averaged across all processes of a company. In contrast, in the bottom-up approach the indicators were considered specifically for each process step. In the latter case, unlike the LCA, the administrative and developmental components must be considered accordingly. In both cases, the indicators can then be aggregated along the life cycle. Of the two methods the top-down approach requires less effort, while the bottom-up approach has a higher precision. For the PDCA indicators and the qualitative performance indicators, the LCAA method was integrated into the approach. In addition, this work has shown how these can be used together with the quantitative performance indicators at the Life Cycle Inventory level. On the one hand, this was achieved through scoring, and on the other hand, the PDCA indicators were defined as a condition for the performance indicators.

As a practical application of the approach for an SLCA method in the automotive industry, the first case studies were carried out on the inner part of the rear door, made of steel in the case of one component and aluminum in the other. The case studies showed for individual performance indicators that social data collected from companies can be related to the various processes in the life cycle in a top-down approach. However, the comparison of the top-down approach with the bottom-up approach carried out within this framework revealed that the bottom-up approach for mass-independent life cycle phases (here: component production and dismantling) was more precise than the top-down approach. The feasibility of the LCAA method was demonstrated for a selected set of PDCA indicators. Even if the results of the application of the proposed SLCA approach are not meaningful for the real components due to the assumptions during data collection (see Appendix B.1), the principle of feasibility was nevertheless demonstrated.

The approach would also be practicable for further indicators, but data availability and meaningfulness would have to be considered. Ideally, in an SLCA, at least those social aspects should be considered in a company that are rated as very important by the company's stakeholders.

In summary, the previous chapters showed that an SLCA with company-specific data can basically be carried out in an industry with complex, international manufacturing and supplier structures. However, there are several challenges, and the most important ones are presented below (Sections 3.3.1–3.3.4). Furthermore, in Section 3.3.5, the transfer of the results of individual components to the car level is addressed.

3.3.1. Availability and Quality of Social Data

The data with which the calculations are performed are fundamental to the accuracy and significance of the SLCA. If some of these data are missing or are influenced by other factors, this has a negative effect on the results of an SLCA.

1. Standardization of indicators

During the development and data collection of social performance indicators, it became apparent in this work that clear interpretability is only possible in a few cases. The indicators are often not standardized and therefore cannot be compared between different companies (see also reference [91]). This is also the case for indicators in sustainability reporting guidelines, such as the GRI guidelines. The indicator *number of accidents* used in many case studies is a good example. Some companies only relate this number to their own employees, others also do so to external workers. In some cases, the absolute number of accidents is given, but often only after a certain number of days of absence due to the accident. Some companies also include commuting accidents. The companies have therefore frequently already developed data collection systems that are often different from each other. In addition, many indicators fluctuate from year to year, also depending on the production volume, so averages should be made over several years. In the case of the indicator *complaints*, several companies noted that only justified complaints were meaningful across several social aspects. The interpretation in this respect, however, is specific to each company. The same applies to the indicator *lawsuits*. There were a wide variety of proposals from the companies, such as *justified lawsuits*, *legal disputes* or *lawsuits that were successful in court*, in order to make the aspect objective. At least the last two proposals would be conceivable in constitutional states, provided that the persons or companies concerned have the (financial) opportunity to bring their case before the courts.

For the PDCA indicators, it is equally important to set standards that companies must at least implement in order to obtain a positive assessment.

2. Dealing with the lack of company-specific social data in the life cycle

If, for example, social data collection is not possible for resource extraction because some companies only have an overview of their direct suppliers or buy raw materials on stock exchanges, generic data such as industry data or data from social risk databases could be used. However, it must be considered that different ways of collecting and evaluating data can prevent the comparability of results. A similar situation also exists for the use or the end-of-life phase of a car, since it is beyond the control of the car manufacturer where the end consumer refuels or disposes of his car.

Furthermore, many companies are very cautious about publishing social data. The OEM's influence on the companies of the entire life cycle is not sufficient to oblige everyone to publish. It is also questionable whether the results would be reliable in the event of such an obligation. Within the framework of corporate relations, it is only possible to collect social data through direct contact or the use of published documents. However, many companies do not consider data from the media or from investigations by NGOs to be independent.

3. Positive self-presentation of the companies

It is questionable whether companies will provide answers that would make them appear in a negative light or reveal social grievances. When a company is asked about the minimum wage or the maximum weekly working time, it will only indicate something other than the legally required regulations if it can provide more positive values. Data collection via sustainability reports does not solve the problem either. The reports often have a different depth of information, as the companies themselves determine how extensively they communicate externally [111]. It is usually not clear whether the absence of an indicator or a social aspect means that the company is doing poorly in this respect or whether the issue has not been addressed.

3.3.2. Establishing a Process Reference for the Life Cycle-Oriented Social Aspects

In order to carry out an SLCA analogously to the LCA or to integrate it into a LCSA together with the LCA and LCC, a process reference for the life cycle-oriented social aspects is indispensable. This is often difficult to establish for social data, since many of the social aspects and indicators refer to the behavior and not to the processes of the company. In practice, social data that theoretically relate to processes are usually communicated by companies at the corporate level anyway. For these reasons, a practical SLCA method must offer the possibility of integrating such social data through suitable calculations (such as allocation).

For quantitative indicators, the top-down approach can be used to assign them to processes using an activity variable that has the required process reference (such as working hours). However, these are often confidential. In the present work, the mass and energy flows of the LCA and company-specific data were used to obtain an activity variable with process reference through allocation. However, as with the LCA [106], allocation poses new challenges. Since company data is used to calculate the activity variables for each process step, the variable is automatically averaged over the different countries, activities and products of the company in question. This can lead to imprecise estimates in certain situations:

- In a company, several products are manufactured during whose production large differences occur in the activity variable and in the SLCA only one of these products is considered.
- A company produces the same product in several countries with large differences in the activity variable and in SLCA only one of these countries is analyzed.
- In a company, some parts of a product are manufactured in-house, while others are purchased. Since in this approach the activity variable refers to the mass, too much is allocated to the purchased parts and too little to the self-manufactured parts.
- The total mass output of a company is an important parameter in this approach (see Section 3.1.2). However, in the data provided by different companies, it can refer to different quantities, such as output or sales, and is difficult to compare in such cases.

In certain circumstances, inaccuracies may also occur in the reference of social data to the activity variable:

- The social data are not proportional to the selected activity variable or have no relation at all to an activity variable.
- Although the social data are proportional to the chosen activity variable, they show large deviations in different processes.

With the bottom-up approach, the challenges described for the top-down approach do not arise, since the social data are directly incorporated into the respective process steps and a reference value can be determined specifically. However, this procedure is very time-consuming, since each process step must be considered individually, and a suitable reference value must be determined. In addition, the administrative and development components should be adequately considered. These are already included in the top-down approach.

For qualitative indicators or PDCA indicators, the process reference can be established using the LCAA method. The only limitation here is the inaccuracies for the activity variable mentioned above.

3.3.3. Use of the Calculated Indicators in an SLCA

Several possibilities for the use of the calculated indicators were shown in this work. The challenges are different in each case.

The most direct way is not offsetting indicators. Thus, the major challenge is to analyze a large number of different indicators.

In the calculation of PDCA and performance indicators for a social aspect, evaluations are implemented and then averaged. The following issues must be considered: On the one hand, detailed information is lost with the evaluations and the averaging, on the other hand there is always the risk that the subjectivity of the person carrying out the evaluation can have an effect on the results. In addition, negative results in performance indicators can be offset by positive results in PDCA indicators. However, this should not happen if the PDCA approach is correctly implemented, as the actual goal is to improve performance indicators.

Furthermore, the PDCA indicators can be integrated into the functional unit as a condition for the performance indicators in order to ensure a systematic approach. The difficulty here is that companies or processes which do not implement the PDCA indicators cannot be included in the SLCA. This procedure is only possible in situations in which the PDCA indicators have already been implemented at the participating companies or in which there are corresponding possibilities of influencing them.

The integration of the PDCA indicators into the functional unit would also offer the possibility of integrating social aspects, which relate very strongly to the behavior of a company and can only be analyzed to a limited extent using performance indicators, such as *Forced Labor*, into an SLCA. However, they would not be included in the balance sheet—which is one of the essential functions of SLCA. Whether and how such social aspects can be integrated into an SLCA remains to be seen.

3.3.4. Assessment of the Social Aspects

This work does not include an assessment of the SLCA results but presents an approach for a practical SLCA in the automotive industry at the Life Cycle Inventory level. However, in the development of social aspects and indicators and in primary data collection, issues arose that could create difficulties for the assessment part of an SLCA.

1. Unambiguous interpretation of the social aspects

For many social aspects, an unambiguous interpretation and thus a clear evaluation are (still) difficult. An example of this is *Economic Development*: How can a company be evaluated that has a high turnover and does not attach importance to diversity in comparison to a company with little turnover but a high proportion of disabled persons? The difficult or unclear assessment was also recognized in the research on *Child Labor*, *Hours of Work* and *Intellectual Property* [56,112]. The Guidelines and the other sources do not provide any indications for the assessment either.

2. Additional information for the evaluation of social aspects

Due to the strong link between the social aspects and the companies, some factors, such as the size or sector of the companies, are decisive for an evaluation. For example, *Public Commitment to (Social) Sustainability*, *Corruption*, *Job Security* or *Social Responsibility* had only been addressed by large companies in the primary data collection, but this does not necessarily mean that the smaller companies are poorly rated. In most cases, companies with office activities have a lower social impact than a mining company and should therefore be evaluated differently.

Moreover, social issues are more influenced by cultural and country-specific circumstances than environmental issues (except for a few cases such as water scarcity). In some countries, for example, trade unions are seen more positively (such as in Germany), while in others (such as the US) most workers would reject a union membership. The dependence of assessment on cultural and country-specific circumstances was also noted in reference [43].

Many of the social aspects, such as *Salary*, require information about the local situation for the assessment. In the published data, the reference to the place of production is usually not published or the companies only provide social data as an average at the organizational level, even if they operate in several locations in different countries.

3. Subjectivity of social aspects

Some of the social aspects can only be assessed through qualitative indicators, which often require subjective assessments. In this work, the data on PDCA indicators were easier to obtain, but the responses are often very diverse and more difficult to compare or evaluate between different companies. This makes it difficult to compare SLCA results.

3.3.5. Transfer of the Approach from the Component to the Car Level

Due to the complexity of a car and of the supply chains in the automotive industry, five exemplary materials were selected in the primary data collection based on the material composition of a Mercedes-Benz car (Section 2.1.1). In order to carry out an SLCA of a car, thus to relate the results of the calculations from the component level to a car, different procedures must be selected depending on the life cycle phase (see Table 4). These are described below. It is assumed that the necessary calculations have already been carried out for all components of the car.

Table 4. Transfer of the results from the component level to the car level.

Life Cycle Phase	Reference Value for the Consideration of a Component	Necessary Steps for the Consideration of the Complete Car
Upstream chain	Mass (top-down)	Adding the results of the different components
Manufacturing	Component (bottom-up)	Top-down in relation to the vehicle
Use phase (fuel path)	Mass (top-down), fuel reduction factor	Top-down in relation to the fuel consumption of the vehicle
Dismantling	Component (bottom-up)	Top-down in relation to the vehicle, dismantling rate is to be considered
Shredding	Mass (top-down)	Top-down in relation to the vehicle, shredding rate is to be considered

Upstream chain

For the upstream chain of a car, the social indicators of the upstream chains of the individual components are calculated using the top-down approach and then added together. The top-down approach is suitable for this, as the upstream chains are mainly materials such as steel, which are expressed in mass.

Manufacturing

When looking at manufacturing at component level, it is useful to analyze the social aspects using the bottom-up approach, as these more often depend on the number of pieces than on the weight of the component. This should be checked on a case-by-case basis.

If the entire vehicle is to be considered for the manufacturing phase, it makes sense to apply the top-down approach directly to the entire automotive company and not to examine and add the components individually using the bottom-up approach. Since different models from one manufacturer are more similar than different components within the same vehicle (e.g., rear door and engine), the meaningfulness is comparable, and the effort is significantly lower.

Use phase

In the use phase, the fuel path is considered. This can be mapped both at component and vehicle level together with the expected mileage using a top-down approach. The accuracy is increased at car level, since the calculation of the reduced consumption for individual components is not required.

Dismantling

For dismantling, due to the mass independence of the process (see Section 3.2.2, step 6a), it makes sense to analyze the social impacts with the bottom-up approach for the components. At the vehicle level, however, social indicators can be more efficiently (like the manufacturing phase) represented by a top-down approach in relation to a vehicle. The dismantling rate must be included.

Shredding

In this work, the shredding process is regarded as mass-dependent (see Section 3.2.2, step 6a). Therefore, the social indicators are analyzed using a top-down approach. For the vehicle level, these are converted to the shredding rate of the car.

In summary, at the component level, the bottom-up approach appears to be more precise than the top-down approach for certain life cycle phases. On car level even the less complex top-down approach could be chosen, since the differences between individual components would presumably be averaged. However, in the context of this work, an investigation was carried out only for one component.

4. Conclusions and Outlook

4.1. Applicability of the SLCA Method

The results of this work show that SLCA with company-specific data is also feasible in an industry with complex, international manufacturing and supplier structures such as the automotive industry—at present, however, the method still has some limitations.

An SLCA analogous to an LCA can be realized above all for those life cycle-oriented social aspects that have indicators with process reference or those that can be meaningfully related to processes with an activity variable. These include almost all social aspects that affect the stakeholder employee. When implementing the SLCA, however, issues such as the standardization of indicators, a good knowledge of processes and the area of impact assessment must be considered that have not yet been conclusively established at the current stage of development (see Section 4.3).

Since many social aspects relate to the behavior of companies, these can be mapped well with semi-quantitative or qualitative indicators such as PDCA indicators. Data availability is also significantly higher here than for quantitative indicators, as companies communicate processes rather than performance data. However, the joint use of PDCA and performance indicators in an SLCA remains a challenge for future studies. Both the integration of the PDCA indicators into the functional unit and the joint calculation of the PDCA and performance indicators still have limitations regarding the cases in which they can be applied and the interpretation of the results (see Section 3.3.3). The correct choice depends on the question to be dealt with by SLCA.

For all life cycle-oriented social aspects that have no relation to processes and for which it is not expedient and meaningful to refer these to process level through activity variables, consideration in an SLCA is not foreseeable in the short and medium term. The same applies to social aspects that are not communicated on the process level due to confidentiality reasons. Accordingly, since only data at the organizational level are available for these social aspects, an assessment at this level would be a promising approach that could also facilitate their interpretation. For this challenge (see also Section 3.1.1, *Obtaining data at the process level*), SOLCA provides a solution. It might also offer improvements for the mentioned challenges *Comparability of social data between different companies* (Section 3.1.1) and *Standardization of indicators* (Section 3.3.1), as at least approaches do currently exist for standardizing indicators at the organizational level (e.g., GRI guidelines).

In addition to consideration in SOLCAs, social aspects that are addressed at the organizational level and for which no meaningful reference can be made to processes can also be examined through audits or certifications as part of supplier management. This approach should also be considered for social aspects that are difficult to assess through performance indicators and for which it is questionable whether aggregation along the life cycle makes sense, such as *Child Labor* or *Forced Labor*.

In this work, the social data were collected on a company-specific basis to determine on the one hand whether and how an SLCA based on such data is possible in industries with complex, international manufacturing and supplier structures. On the other hand, generic data never reflect the actual social impact of the companies involved in the life cycle. However, the collection of company-specific data is very time-consuming and poses specific challenges (see Section 3.3.1). Therefore, it may be useful in general to use additional industry or country data when such data is available. One advantage of this is the possibility of carrying out social analyzes of processes for which no company-specific data is available. This can be the case, for example, with raw materials that are purchased on the stock exchange or with processes such as end-of-life vehicle disposal with often unclear global export and trade flows.

It is also possible to use social risk databases such as the SHDB to map risks along the life cycle of a product or along the supply chain. This could be desirable, for example, for companies that primarily wish to avoid damage to their image due to social grievances in the supply chain. Although there are still data gaps in the SHDB for some industries, it already shows how likely a negative social impact is in a country. However, it is not certain whether social grievances will actually occur in a specific company in a high-risk country. Additionally, positive activities of such companies cannot be appreciated.

Ultimately, the question is always what the purpose of an SLCA is and what the company's goals are. Depending on this, social evaluations are already possible today. This also applies to industries with complex, international manufacturing and supplier structures such as the automotive industry.

4.2. Recommendations for the Automotive Industry

Automotive companies should continue to focus on social issues in the life cycle of a car, as the importance for their stakeholders is already high according to the survey in reference [82] and will become even higher. Irrespective of whether the greatest social responsibilities and influence lie with the countries, the companies in the life cycle or the automobile manufacturers, an automobile company can contribute to the improvement of social issues within the scope of its current possibilities.

If an automotive company is interested in identifying and addressing social risks along the life cycle of its products or along its supply chain, it can already draw on existing databases, as mentioned in the previous chapter. This enables it to identify high-risk countries and industries and then analyze the corresponding suppliers in more detail. This possibility can be used within the framework of supplier management but is not sufficient for a holistic product assessment due to the exclusive risk reference. For individual social aspects, this work has shown that it is already possible today to collect company-specific data and use it for an SLCA calculation if the necessary standardizations are considered.

In principle, an automotive company could go one step further and integrate both life cycle and end consumer-oriented social aspects into the development process of its vehicles. Thus, social aspects could be considered when making decisions about materials, concepts and materials as well as for improving the overall vehicle compared with its predecessor. An implementation would already be feasible today for certain social aspects in some areas of development, such as material decisions, using industry data.

However, there is still a long way to go before social issues can be fully considered in the development process, and an SLCA can be devised for a complete vehicle. In the future, a system similar to the International Material Data System (IMDS) [113] could be set up in which suppliers would provide standardized social aspects and indicators. Energy data could be collected on a sector-specific basis. In addition, the prioritization of the social aspects could be carried out across the industry analogous to the survey in reference [82] among the stakeholders of Daimler in order to define a generally accepted set of social aspects. A similar approach was implemented in the aluminum industry by the Aluminium Stewardship Initiative.

4.3. Further Research Needs

The analysis of the present work provides starting points for future investigations.

For those social aspects for which an SLCA is theoretically feasible analogous to an LCA due to its characteristics, the following topics are important for the practical implementation:

- In the future, a strong focus should continue to be placed on the concretization and standardization of the indicators, including the constant reporting of companies. This could be used to set up a database with uniform indicators for different sectors and countries. With the help of such a database, missing company-specific social data could be balanced out and the data received could be evaluated.
- The mining, production and disposal processes and their interrelations with activity variables should be analyzed in more detail and the results of the investigations should be made available. Thus, the detour via the mass output of the companies, which had to be used in this work, would not be necessary and a more exact mapping of the processes would be possible. For example, an SLCA database (analogous to an LCA database) would be desirable in which different

activity variables are listed for each process step. Since companies often treat this information confidentially, they could be listed in such a database on an industry-specific basis and thus maintain confidentiality.

- For the impact assessment in an SLCA within the framework of an LCSA, it is necessary to further analyze the evaluation of the social aspects. The aim of these studies should be to develop a system for evaluating the social aspects that will be included in future versions of the Guidelines or comparable documents.

Since semi-quantitative and qualitative indicators are important components of the description of the social aspects and quantitative indicators are required for an SLCA, further research activities are necessary regarding offsetting. The LCAA approach shows an initial solution here, but additional application examples and further options for integration into an SLCA would be important for future developments.

The SOLCA approach [73] also appears to be a promising method as it addresses the social aspects on the level of their main characteristics. Therefore, social aspects without process reference or data availability at process level can also be considered. Further research on SOLCA—both practical and theoretical—will be crucial in the future.

Author Contributions: H.K. is the first and main author of the article. The research including literature survey, social data collection and development of the SLCA approach including the case studies was carried out by her. H.K., A.L., K.R. and M.F. contributed to the overall research idea, to the research design of the study, to writing, revising, proofreading and approving the final manuscript.

Funding: This paper is based on parts of a PhD thesis which was conducted at Daimler.

Acknowledgments: We thank Walter Klöpffer for his valuable input and the encouraging discussions. Many thanks also go to all companies that participated in the primary data collection.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Detailed Overview of the PDCA and Performance Indicators

Table A1. Detailed overview of the indicators and questions of the social aspects (which are highlighted in grey) used in the data collection form. The PDCA indicators are only listed in detail if they have a slightly different wording than the standard one: The PDCA indicators describe management processes, they are used to analyze whether a company has defined (written) principles for the respective social aspect (PLAN), has developed measures/systems to implement the principles (DO), has introduced control measures to monitor the implementation (CHECK) and has established processes to react to violations (ACT). The performance indicators (Perf) represent measurable parameters of the social aspects. The social aspects of *Economic Development* (2) and *Technological Development* (4) do not include PDCA indicators. Sources from the indicators and more details see reference [82].

Category	Indicators/Questions
1. Public Commitment to (Social) Sustainability	
PLAN	Have you introduced (in writing) and signed social sustainability principles? If yes, which one: Universal Declaration of Human Rights ILO standards UN Global Compact OECD Guidelines for Multinational Enterprises Company’s own code of conduct Other:

Table A1. *Cont.*

Category	Indicators/Questions
DO/CHECK	Have you developed procedures and measures for applying and monitoring these social sustainability principles? If yes, which one: Sustainability management Scorecard Membership in associations/programs for promoting socially sustainable business practices Other:
ACT	Have you established procedures for responding to violations regarding these social sustainability principles respectively regarding complaints? If yes, please specify.
Perf	Do you publish documents containing promises and agreements regarding (social) sustainability? If yes, please specify.
Perf	Have you received awards for your commitment to social sustainability? If yes: How many? Which ones?
Perf	Do you train employees in your code of conduct/position on social sustainability? If yes: How many have you trained last year (in percent)?
Perf	Have you received complaints concerning non-compliance against the principles in the last five years? If yes: How many? What was their nature?
2. Economic Development	
Perf	How much does your product contribute to your country's economic growth? Gross value added (in €) Revenues (in €) Profit (in €) Salaries paid (in €) Contribution to government budget (taxes paid, subsidies received) (in €) Other:
Perf	How much does your product contribute to the economic growth of developing countries (in €)? Imports from developing countries Investment in developing countries
Perf	How many key investment agreements containing human rights provisions or that were vetted under human rights aspects do you have (in number and in percentage of all investment agreements)?
3. Corruption	
PDCA	See table heading
Perf	Are you suffering/have you ever suffered financial losses (in €) from corruption? If yes: What amount? What type?
Perf	Do you train your employees in anti-corruption policy and procedures? If yes: How many have you been trained last year (in percent)?
4. Technology Development	
Perf	Are you involved in external research projects including technology, expertise, know-how or facilities? If yes: in how many? In which ones?
Perf	Do you have research and development partnerships? If yes: How many? Which ones?
Perf	How much (in €) did you invest in technological development last year?
Perf	On average, how many patents do you file per year?
5. Armed Conflicts	
In advance	Do you have business activities in regions with ongoing conflicts? If no, please continue with *Behavior in competition;* if yes please answer the following questions:
PDCA	See table heading
Perf	Have you been involved in conflicts/have there been problems with the local community etc.? If yes: How often? Why?

Table A1. *Cont.*

Category	Indicators/Questions
6. Behavior in Competition	
PDCA	See table heading
Perf	Have lawsuits been filed against you for anti-competitive behavior, forming trusts or establishing a monopoly in the past? If yes: How many? What were the results?
7. Intellectual Property Rights	
PDCA	See table heading
Perf	Have there been claim against you regarding violations of intellectual property rights in the last five years (including court decisions)? If yes: How many? What kinds?
8. Supplier Relationships	
PDCA	See table heading
Perf	How long are the relationships with your suppliers lasting on average in the main components? (new suggestion from one company)
Perf	Have there been complaints from suppliers in the last five years? If yes: How many? What was their nature?
9. Social Responsibility	
PDCA	See table heading
Perf	What percentage of your suppliers did you audit last year?
Perf	Are you a member of an initiative for promoting social responsibility along the value chain? If yes: What initiative?
Perf	Do you have fair trade labels or the like? If yes: How many? Which ones?
10. Freedom of Association and Collective Bargaining	
PLAN	Have you established (in writing) principles concerning freedom of association and the right to collective bargaining? If yes, which ones?
DO	Have you implemented procedures or measures regarding freedom of association and the right to collective bargaining? If yes, which ones? Are unions adequately supported within the company (availability of infrastructure, time, ability to exercise corresponding functions with pay)? Are employee/union representatives invited to participate in planning major changes at the company that will have an effect on working conditions? Are written records and decisions resulting from collective bargaining kept on file? Are minimum periods for giving notice of significant operational changes specified? Do employees have access to a neutral, binding and independent dispute resolution process or an independent counseling office? Other:
CHECK	Have you introduced control mechanisms for verifying whether all employees are ensured freedom of association and the right to collective bargaining? If yes, which ones?
ACT	Have you established procedures for responding to violations of freedom of association and the right to collective bargaining in your company? If yes, which ones?
Perf	What percentage of your employees are covered by collective bargaining agreements?
Perf	Have there been complaints from employees concerning freedom of association or the right to collective bargaining in the last five years? If yes: How many? What kind?
11. Child Labor	
PLAN	Have you established (in writing) principles for preventing child labor? If yes, which ones?
DO	Have you developed procedures or measures to prevent child labor or improve the situation for working children? If yes, which ones? Do you verify the actual age of new employees by means of official documentation? If yes, what percentage? (new suggestion from one company)Are records of employees' name and age or date of birth kept on file? Are working school-age children allowed to attend school (with their parents being compensated for the lost income)? Other:

Table A1. *Cont.*

Category	Indicators/Questions
CHECK	Have you introduced control mechanisms for identifying child labor (including external control offices etc.)? If yes, which ones?
ACT	Have you established procedures for responding to child labor? If yes, which ones?
Perf	How old do employees have to be in order to perform dangerous tasks?
Perf	How old is your youngest employee?
Perf	Have there been complaints concerning child labor in the last five years? If yes: How many? What was their nature?
12. Salary	
PLAN	Have you established (in writing) fair wage principles for your employees? If yes, which ones?
DO	Have you developed procedures or measures for implementing fair wages for your employees? If yes, which ones?
CHECK/ACT	Have you established procedures to regularly review and adjust the fair wages? If yes, which ones?
Perf	How much (in €) does your lowest paid full-time employee earn?
Perf	How much (in €) does an employee with an average wage earn at your company?
Perf	At what intervals are your employees paid?
Perf	How many days of paid vacation do your employees receive per year?
Perf	Is overtime of employees paid? If no, is there another compensation?
Perf	How do you influence the wages of your temporary workers?
Perf	Have there been complaints about wages in the last five years? If yes: How many? What was their nature?
13. Hours of Work	
PDCA	See table heading
Perf	Do your workers have individual flexibility in their hours? If yes, which ones?
Perf	On average, how many hours do employees work each week?
Perf	What is the maximum number of hours employees work per week (full time)?
Perf	After how many consecutive days are employees given at least one day off?
Perf	How many part-time employees work for you (in percent)?
14. Forced Labor	
PLAN	Have you established (in writing) principles for preventing forced labor? If yes, which ones?
DO	Have you developed procedures or measures for preventing forced labor? If yes, which ones? Do your employment contracts establish pay, hours, vacation and conditions for termination? Do you deliver original documents belonging to the employee to the employees again? Employees voluntarily agree to the terms of employment. Other:
CHECK	Have you introduced control mechanisms for identifying forced labor (including external control offices)? If yes, which ones?
ACT	Have you established procedures for responding to forced labor? If yes, which ones?
Perf	Have there been complaints about forced labor in the last five years? If yes: How many? What was their nature?
15. Equal Opportunities	
PDCA	See table heading
Perf	What is the composition of your governing bodies and break-down of your employees (in percent) by gender, age group and minority group membership (elderly, disabled, religion)?
Perf	What is the base pay for women (in €)?
Perf	What is the base pay for men (in €)?

Table A1. *Cont.*

Category	Indicators/Questions
Perf	How many women are in the management level? (new suggestion from one company)
Perf	How many (severely) disabled persons work for you?
Perf	Have there been incidents of discrimination in the last five years? If yes: How many? Which ones?
16. Health and Safety	
PLAN	Have you established (in writing) principles for ensuring and promoting employee health and safety? If yes, which ones?
DO	Have you developed measures or procedures for ensuring/promoting employee health and safety? If yes, which ones? Are you certified according to OHSAS 18001? Are there measures in place (training, protective clothing, etc.) to prevent accidents and illnesses? Are there measures in place for accidents or hazardous situation (e.g., emergency plans)? Do employees have a way to report risks, make suggestions for improvement, etc. to a responsible authority? Do you have an employee counseling program? Do you have programs to combat locally significant health issues? Other:
CHECK	Have you introduced control mechanisms for monitoring compliance? If yes, which ones?
ACT	Have you established procedures for responding to problems with the above-mentioned measures or procedures? If yes, which ones?
Perf	Last year, how many injuries and non-fatal workplace accidents occurred?
Perf	Last year, how many fatal workplace accidents occurred?
Perf	Have there occurred occupational illnesses in the last five years? If yes: How many? What kinds?
17. Social Benefits/Social Security	
PDCA	See table heading
Perf	What social benefits/social security do you offer?
Perf	How much (in €) do you spend on social benefits/social security?
Perf	Are any benefits provided to full-time employees only? If yes, which ones?
Perf	How long (in days) do you continue paying wages in cases of maternity leave?
Perf	How long (in days) do you continue paying wages in cases of employee sickness?
18. Education and Training	
PDCA	See table heading
Perf	How much (in €) do you spend on education and training of your employees?
Perf	What percentages of skilled and unskilled workers do you employ?
Perf	What percentage of trainees/apprentices do you employ?
Perf	What percentage of your employees attend education and training courses?
Perf	What is the average number of days spent on education/training per employee per year?
19. Job Security	
PLAN	See table heading
Perf	What percentages of permanent employees, fixed-term employees, workers from temporary staffing agencies and from contractors do you have?
Perf	How many employees (in percent) are dismissed each year as a share of your total workforce?
Perf	How much has your headcount risen or fallen in the last five years (divided by age, gender and religion)?

Table A1. *Cont.*

Category	Indicators/Questions
20. Subjective Job Satisfaction	
PDCA	See table heading
Perf	What were the results of your last survey meaning for example what percentage of the employees are satisfied?
Perf	Were all the responses confidential?
Perf	Do you communicate your results with your employees?
21. Delocalization	
PDCA	See table heading
Perf	How many people had to be displaced because of the company?
Perf	In recent years, have there been any complaints regarding delocalization? If yes: How many? What kind?
22. Migration	
PDCA	See table heading
Perf	Do you offer annual language and integration courses for foreign/migrant workers?
Perf	In recent years, have there been any complaints regarding this issue? If yes: How many? What kind?
23. Dialogue with the Local Community	
PDCA	See table heading
Perf	Do you meet with stakeholder groups (independent from current events)? If yes: With how many? How often? In what form?
Perf	How do you support community initiatives (through volunteer work or finances)?
Perf	Have you violated any rules of local political or social governing bodies? If yes: In what manner? How often?
24. Local Heritage	
PDCA	See table heading
Perf	Have there been complaints concerning disregard for the local cultural heritage in the past 5 years? If yes: How often? What kind?
25. Indigenous Rights	
In advance	Are you active in a region where there are indigenous populations? If no, please continue with *Access to immaterial resources*; if yes please answer the following questions:
PDCA	See table heading
Perf	Do you meet with indigenous populations? If yes: How often? In what form?
Perf	Have there been complaints concerning disregard for the rights of the Indigenous populations in the past 5 years? If yes: How often? Which ones?
26. Local Employment	
PDCA	See table heading
Perf	What percentage of your employees are hired locally (radius 100 km)?
Perf	What percentage of your suppliers do business locally (radius 100 km)?
27. Access to Immaterial Resources	
PDCA	See table heading
Perf	Do you have education initiatives for the local community? If yes: How many? What kind?
28. Access to Material Resources	
PDCA	See table heading
Perf	Do you provide infrastructure facilities for the community? If yes, which ones?
Perf	Does the company have a certified environmental management system?

Table A1. *Cont.*

Category	Indicators/Questions
29. Safe and Healthy Living Conditions	
In advance	What health risks and opportunities does the population have in the area surrounding the company? Does the company handle radioactive materials and/or promote activities in the field of nuclear weapons/nuclear energy or genetic engineering? Have you established (in writing) principles concerning health issues in the local sur-rounding area? If yes, which ones?
PDCA	See table heading
Perf	How many fatal/non-fatal accidents have there been in the local surrounding area in the last 5 years related to the company's activities?
Perf	Have there been complaints in the last 5 years concerning health issues in the local surrounding area related to the company's activities? If yes: How many? What kind?
30. Secure Living Conditions	
PDCA	See table heading
Perf	Have there been lawsuits/complaints about secure living conditions in the last 5 years? If yes: How often? What kind?

Appendix B Detailed Information on the Case Studies of the Life Cycle Approach

Appendix B.1 Data on the Mass and Energy Flows

Further details, assumptions and the sources of the individual processes of the mass and energy flows of the inner part of the rear door for aluminum and for steel are described below. Figures A1 and A2 show the different processes with numbers, for which numerical values and the literature sources are shown in Tables A2 and A3. The mass and energy flows are based on GaBi [102] (22nd Servicepack) and ecoinvent data sets [103] (Version 2.2). Additional sources were the references [104,105].

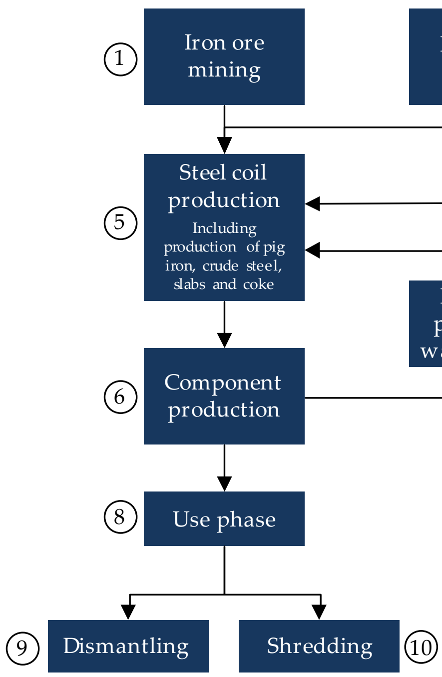

Figure A1. The processes of the steel component considered in the calculations. The asterisk indicates the processes in which only social data of the energy processes could be collected. The numbers are described in Table A2. Detailed explanations of the processes are given in reference [82] (Section 6.1.2). The figure was modified according to the references [114,115].

No social data could be analyzed for some individual processes, therefore only the social data of the energy flows were considered here. These processes were: Ferromanganese production (steel), anode production and the swimming and sinking facility (aluminum). No information on energy and mass flows was available for the other resource extraction processes in aluminum, so these were neglected (see Figure A2). Transport processes and car maintenance were also neglected. The aim was to show the main processes of the steel and aluminum component.

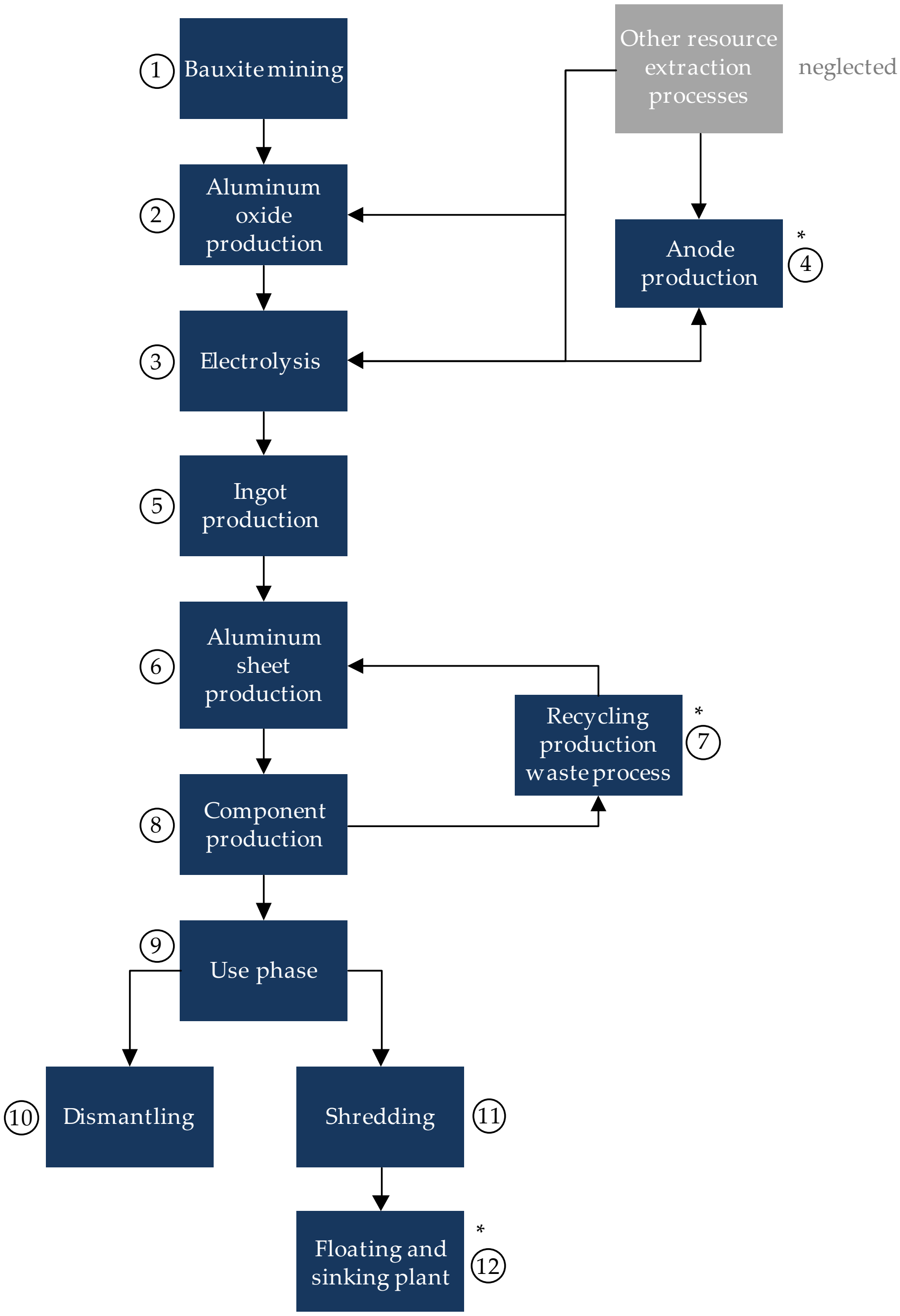

Figure A2. The processes of the aluminum component considered in the calculations. The asterisk indicates the processes in which only social data of the energy processes could be collected. The grey process has been neglected. The numbers are described in Table A3. Detailed explanations of the processes are given in reference [82] (Section 6.1.2). The figure was modified according to reference [104].

There are two main recycling processes in the two processes. On the one hand, scrap is recycled during the production of semi-finished products (steel coil and aluminum sheet). In the case of the steel component, this is already contained in the back-linked data record in GaBi; in the case of the aluminum component, this is integrated in number 6. On the other hand, this is the recycling of the waste during component production. From the latter, only the social data of the energy flows were considered. Overall, however, fewer primary raw materials were used.

Due to the higher material value, a higher dismantling rate was assumed for aluminum. For the energy flows in the individual processes in Tables A2 and A3 one mineral oil producer and one electricity producer were interviewed as examples. The social data of the oil company covered both process energy, such as thermal energy, useful heat or natural gas, and diesel as a fuel. This was possible due to the production spectrum of the oil company. The useful heat, however, was covered by the electricity consumption and the hard coal consumption in the production of useful heat. The data and literature sources for both materials are shown in Table A4. The (lower) calorific values were taken from the technical values in GaBi. These are only listed if assumptions have been made for them (e.g., countries of origin for coal).

Table A2. More detailed information about the processes of the component inner part of the steel rear door. f.: the following page; ff.: the following pages.

Process	Material Input	Material Output	Energy Consumption	Source
1	–	11.3 kg Iron ore	0.0423 MJ Diesel 0.0211 kWh Electricity	[116] (Part II, pp. 10, 13)
2	–	4.63 kg Coal	0.303 MJ Diesel 0.0352 MJ Useful heat 0.0837 kWh Electricity	[117] (p. 54) Country of origin is mainly Australia: Lower calorific value (hard coal): 27.5 MJ/kg (GaBi)
3	–	0.0228 kg Manganese ore	0.00182 MJ Diesel 0.000172 kWh Electricity	[116] (Part VII, pp. 18 f.)
4	0.0228 kg Manganese ore	0.00979 kg Ferromanganese	0.0252 kWh Electricity	[116] (Part VII, pp. 26 f.)
5	11.3 kg Iron ore 3.36 kg Steel from recycling 4.63 kg Coal 0.00979 kg Ferromanganese	9.44 kg Steel coil	The production of steel coils was considered self-sufficient due to coke production.	GaBi, Steel coil, cold-rolled
6	9.44 kg Steel coil	5.90 kg Component	1.65 MJ Useful heat 1.80 kWh Electricity	GaBi, DE steel sheet metal deep drawing (multistage)
7	3.54 kg Offcuts	3.36 kg Steel	1.42 kWh Electricity	[116] (Part II, pp. 57 ff.)
8	5.90 kg Component	5.90 kg Component	1212 MJ Diesel	–
9	1.18 kg Component	1.18 kg Component	0.00488 kWh Electricity	[105] (p. 139)
10	4.72 kg Component	4.72 kg Component	0.478 kWh Electricity	[105] (p. 139)

Table A3. More detailed information about the processes of the component inner part of the aluminum rear door. Thermal energy is generated by burning natural gas and petroleum products [104].

Process	Material Input	Material Output	EnergyConsumption	Source
①	–	18.2 kg Bauxite	0.237 MJ Thermal energy 0.00810 kWh Electricity	[104] (p. 23)
②	18.2 kg Bauxite	8.29 kg Aluminum oxide	78.9 MJ Thermal energy 2.00 kWh Electricity	[104] (p. 24)
③	8.29 kg Aluminum oxide	4.31 kg Liquid aluminum	63.9 kWh Electricity	[104] (p. 27)
④	2.26 kg Anode	0.461 kg Anode residues	6.14 MJ Thermal energy 0.333 kWh Electricity	[104] (p. 25)
⑤	4.31 kg Liquid Aluminum	4.28 kg Ingots	5.49 MJ Thermal energy 0.542 kWh Electricity	[104] (p. 29)
⑥	4.28 kg Ingots 2.35 kg Aluminum from recycling	6.61 kg Aluminum sheets	5.49 MJ Thermal energy 0.542 kWh Strom	[104] (p. 41)
⑦	2.48 kg Offcuts	2.35 kg Aluminum	7.93 MJ Thermal energy 0.313 kWh Electricity	[104] (p. 41)
⑧	6.61 kg Aluminum sheets	4.13 kg Component	13.8 MJ Thermal energy 4.37 kWh Electricity	GaBi, DE Aluminium sheet deep drawing
⑨	4.13 kg Component	4.13 kg Component	708 MJ Diesel	–
⑩	3.30 kg Component	3.30 kg Component	0.0137 kWh Electricity	[105] (p. 139)
⑪	0.826 kg Component	0.826 kg Component	0.0836 kWh Electricity	[105] (p. 139)
⑫	0.826 kg Scrap	0.826 kg Scrap	0.00258 kWh Electricity	[105] (p. 139)

Table A4. More detailed information about the energy processes of the components inner part of the steel and the aluminum rear door. The different energy processes are highlighted in grey.

Process	Material Input	Material Output	Energy Consumption	Source
Electricity				
Hard coal from mine	–	0.417 kg Hard coal	0.03 MJ 0.0147 MJ Useful heat (see below) 0.00746 kWh Electricity	[117] (p. 54) The hard coal of the company surveyed comes mainly from Chile, Colombia, South Africa and Australia. An average lower calorific value of 26.3 MJ/kg was assumed.
Hard coal in the power plant DE	0.417 kg Hard coal	10.0 MJ Hard coal	0.00724 MJ Fuel oil	[117] (p. 91)
Electricity from power plant DE	10.0 MJ Hard coal	1.00 kWh Electricity	–	[117] (p. 186)
Diesel				
Crude oil from onshore production RAF	–	0.970 kg Crude oil	0.343 MJ Diesel 128 MJ Natural gas 1.94 MJ Natural gas/sweet gas 0.175 MJ Sweet gas 0.233 MJ Fuel oil S 0.0179 kWh Electricity	[110] (p. 96)

Table A4. *Cont.*

Process	Material Input	Material Output	Energy Consumption	Source
Diesel, from refinery RER	0.970 kg Crude oil	1.00 kg Diesel	1.69 MJ Naphtha 0.680 MJ Fuel oil S 0.0245 kWh Electricity 2.06 MJ Refinery gas	[110] (p. 165)
Diesel, low in sulfur, from refinery RER	1.00 kg Diesel	1.00 kg Diesel, low in sulfur	0.0427 MJ Fuel oil S0.124 MJ Refinery gas 0.00147 kWh Electricity	[110] (p. 171)
Useful heat				
Hard coal, in industrial furnaces 1–10 MW RER	0.0433 kg Hard coal mix	1.25 MJ Hard coal	0.00521 kWh Electricity	[117] (p. 217)
Useful heat, hard coal, from industrial furnaces 1–10 MW RER	1.25 MJ Hard coal	1 MJ Useful heat	–	[117] (p. 224)

Appendix B.2 Social Data of Companies

Table A5. Presentation of working hours, turnover and available social indicators (highlighted in grey) for each process step of the steel component.

Process Step	Material	Electricity	Mineral Oil	Sum Per Process Step
Working hours (in h)				
Iron ore mining	1.07×10^{-2}	2.92×10^{-5}	2.33×10^{-6}	1.07×10^{-2}
Hard coal mining	3.34×10^{-3}	1.16×10^{-4}	1.66×10^{-5}	3.48×10^{-3}
Manganese ore mining	8.05×10^{-5}	2.43×10^{-7}	9.89×10^{-8}	8.09×10^{-5}
Ferromanganese production	–	3.47×10^{-5}	4.01×10^{-8}	3.47×10^{-5}
Steel coil production	2.18×10^{-2}	–	–	2.18×10^{-2}
Component production	5.01×10^{-1}	2.49×10^{-3}	9.23×10^{-5}	5.04×10^{-1}
Recycling	–	1.97×10^{-3}	–	1.97×10^{-3}
Use phase	–	3.80×10^{-3}	6.56×10^{-2}	6.94×10^{-2}
Dismantling	2.24×10^{-2}	6.73×10^{-6}	7.78×10^{-9}	2.24×10^{-2}
Shredding	4.89×10^{-3}	6.59×10^{-4}	7.62×10^{-7}	5.55×10^{-3}
Turnover (in €)				
Iron ore mining	1.10	1.98×10^{-2}	2.47×10^{-3}	1.13
Hard coal mining	7.98×10^{-1}	7.90×10^{-2}	1.76×10^{-2}	8.94×10^{-1}
Manganese ore mining	1.22×10^{-2}	1.65×10^{-4}	1.05×10^{-4}	1.24×10^{-2}
Ferromanganese production	–	2.36×10^{-2}	4.26×10^{-5}	2.36×10^{-2}
Steel coil production	8.72	–	–	8.72
Component production	$3.98 \times 10^{+2}$	1.69	9.81×10^{-2}	$4.00 \times 10^{+2}$
Recycling	–	1.33	–	1.33
Use phase	–	2.58	$6.98 \times 10^{+1}$	$7.23 \times 10^{+1}$
Dismantling	2.31	4.57×10^{-3}	8.27×10^{-6}	2.32
Shredding	2.11	4.47×10^{-1}	8.10×10^{-4}	2.56

Table A5. *Cont.*

Process Step	Material	Electricity	Mineral Oil	Sum Per Process Step
Number of accidents				
Iron ore mining	7.49×10^{-9}	6.53×10^{-11}	1.16×10^{-11}	7.56×10^{-9}
Hard coal mining	1.92×10^{-9}	2.60×10^{-10}	8.28×10^{-11}	2.27×10^{-9}
Manganese ore mining	1.18×10^{-10}	5.44×10^{-13}	4.95×10^{-13}	1.19×10^{-10}
Ferromanganese production	–	7.76×10^{-11}	2.01×10^{-13}	7.78×10^{-11}
Steel coil production	1.45×10^{-7}	–	–	1.45×10^{-7}
Component production	3.81×10^{-6}	5.57×10^{-9}	4.62×10^{-10}	3.81×10^{-6}
Recycling	–	4.39×10^{-9}	–	1.46×10^{-9}
Use phase	–	8.49×10^{-9}	3.28×10^{-7}	3.37×10^{-7}
Dismantling	1.19×10^{-6}	1.50×10^{-11}	3.89×10^{-14}	1.19×10^{-6}
Shredding	8.99×10^{-8}	1.47×10^{-9}	3.81×10^{-12}	9.14×10^{-8}
Number of fatal accidents				
Iron ore mining	4.65×10^{-10}	2.03×10^{-12}	1.90×10^{-13}	4.67×10^{-10}
Hard coal mining	4.54×10^{-11}	8.09×10^{-12}	1.35×10^{-12}	5.48×10^{-11}
Manganese ore mining	0	1.69×10^{-14}	8.08×10^{-15}	2.50×10^{-14}
Ferromanganese production	–	2.41×10^{-12}	3.28×10^{-15}	2.42×10^{-12}
Steel coil production	0	–	–	0
Component production	3.75×10^{-9}	1.73×10^{-10}	7.54×10^{-12}	3.93×10^{-9}
Recycling	–	1.37×10^{-10}	–	1.37×10^{-10}
Use phase	–	2.64×10^{-10}	5.36×10^{-9}	5.62×10^{-9}
Dismantling	0	4.68×10^{-13}	6.35×10^{-16}	4.68×10^{-13}
Shredding	0	4.58×10^{-11}	6.22×10^{-14}	4.59×10^{-11}
Number of training hours (in h)				
Iron ore mining	3.09×10^{-4}	8.09×10^{-7}	5.80×10^{-8}	3.10×10^{-4}
Hard coal mining	1.16×10^{-4}	3.22×10^{-6}	4.13×10^{-7}	1.19×10^{-4}
Manganese ore mining	1.09×10^{-6}	6.73×10^{-9}	2.47×10^{-9}	1.10×10^{-6}
Ferromanganese production	–	9.61×10^{-7}	1.00×10^{-9}	9.62×10^{-7}
Steel coil production	3.98×10^{-4}	–	–	3.98×10^{-4}
Component production	1.11×10^{-2}	6.90×10^{-5}	2.30×10^{-6}	1.11×10^{-2}
Recycling	–	5.44×10^{-5}	–	5.44×10^{-5}
Use phase	–	1.05×10^{-4}	1.64×10^{-3}	1.74×10^{-3}
Dismantling	2.48×10^{-4}	1.86×10^{-7}	1.94×10^{-10}	2.48×10^{-4}
Shredding	6.74×10^{-6}	1.82×10^{-5}	1.90×10^{-8}	2.50×10^{-5}
Working hours with collective agreements				
Iron ore mining	96%	87%	68%	96%
Hard coal mining	50%	87%	68%	51%
Manganese ore mining	100%	87%	68%	100%
Ferromanganese production	–	87%	68%	87%
Steel coil production	99%	–	–	99%
Component production	95%	87%	68%	95%
Recycling	–	87%	–	87%
Use phase	–	87%	68%	69%
Dismantling	80%	87%	68%	80%
Shredding	90%	87%	68%	90%

Table A6. Presentation of working hours, turnover and available social indicators (highlighted in grey) for each process step of the aluminum component.

Process Step	Material	Electricity	Mineral Oil	Sum Per Process Step
Working hours (in h)				
Ingot production	1.88×10^{-3}	9.24×10^{-2}	5.02×10^{-3}	9.93×10^{-2}
Aluminum sheet production	4.57×10^{-2}	6.69×10^{-3}	1.24×10^{-3}	5.36×10^{-2}
Component production	3.51×10^{-1}	1.77×10^{-3}	2.05×10^{-6}	3.52×10^{-1}
Recycling	–	4.57×10^{-4}	4.30×10^{-4}	8.86×10^{-4}
Use phase	–	2.22×10^{-3}	3.84×10^{-2}	4.06×10^{-2}
Dismantling	6.28×10^{-2}	1.88×10^{-5}	2.18×10^{-8}	6.29×10^{-2}
Shredding	8.56×10^{-4}	1.15×10^{-4}	1.33×10^{-7}	9.71×10^{-4}
Floating and sinking plant	–	3.56×10^{-6}	4.11×10^{-9}	3.56×10^{-6}
Turnover (in €)				
Ingot production	$3.24 \times 10^{+2}$	$6.27 \times 10^{+1}$	5.34	$3.92 \times 10^{+2}$
Aluminum sheet production	$1.69 \times 10^{+1}$	4.54	1.32	$2.28 \times 10^{+1}$
Component production	$3.98 \times 10^{+2}$	1.20	2.18×10^{-3}	$3.99 \times 10^{+2}$
Recycling	–	3.10×10^{-1}	4.57×10^{-1}	7.67×10^{-1}
Use phase	–	1.51	$4.08 \times 10^{+1}$	$4.23 \times 10^{+1}$
Dismantling	9.24	1.28×10^{-2}	2.31×10^{-5}	9.26
Shredding	3.70×10^{-1}	7.83×10^{-2}	1.42×10^{-4}	4.49×10^{-1}
Floating and sinking plant	–	2.42×10^{-3}	4.37×10^{-6}	2.42×10^{-3}
Number of accidents				
Ingot production	3.48×10^{-9}	2.06×10^{-7}	2.51×10^{-8}	2.35×10^{-7}
Aluminum sheet production	4.57×10^{-8}	1.50×10^{-8}	6.20×10^{-9}	6.69×10^{-8}
Component production	2.66×10^{-6}	3.96×10^{-9}	1.02×10^{-11}	2.67×10^{-6}
Recycling	–	1.02×10^{-9}	2.15×10^{-9}	3.17×10^{-9}
Use phase	–	4.96×10^{-9}	1.92×10^{-7}	1.97×10^{-7}
Dismantling	3.33×10^{-6}	4.21×10^{-11}	1.09×10^{-13}	3.33×10^{-6}
Shredding	1.57×10^{-8}	2.58×10^{-10}	6.66×10^{-13}	1.60×10^{-8}
Floating and sinking plant	–	7.96×10^{-12}	2.06×10^{-14}	7.98×10^{-12}
Number of fatal accidents				
Ingot production	3.00×10^{-11}	6.42×10^{-9}	4.10×10^{-10}	6.86×10^{-9}
Aluminum sheet production	2.36×10^{-9}	4.65×10^{-10}	1.01×10^{-10}	2.93×10^{-9}
Component production	2.63×10^{-9}	4.65×10^{-10}	1.67×10^{-13}	3.09×10^{-9}
Recycling	–	3.17×10^{-11}	3.51×10^{-11}	6.68×10^{-11}
Use phase	–	1.54×10^{-10}	3.13×10^{-9}	3.29×10^{-9}
Dismantling	0	1.31×10^{-12}	1.78×10^{-15}	1.31×10^{-12}
Shredding	0	8.02×10^{-12}	1.09×10^{-14}	8.03×10^{-12}
Floating and sinking plant	–	2.47×10^{-13}	3.36×10^{-16}	2.48×10^{-13}
Number of training hours (in h)				
Ingot production	Not published	2.56×10^{-3}	1.25×10^{-4}	2.68×10^{-3}
Aluminum sheet production	5.44×10^{-4}	1.85×10^{-4}	3.09×10^{-5}	7.60×10^{-4}
Component production	7.74×10^{-3}	4.91×10^{-5}	5.11×10^{-8}	7.79×10^{-3}
Recycling	–	1.26×10^{-5}	1.07×10^{-5}	2.34×10^{-5}
Use phase	–	6.14×10^{-5}	9.56×10^{-4}	1.02×10^{-3}
Dismantling	6.93×10^{-4}	5.22×10^{-7}	5.43×10^{-10}	6.94×10^{-4}
Shredding	1.18×10^{-6}	3.19×10^{-6}	3.32×10^{-9}	4.38×10^{-6}
Floating and sinking plant	5.44×10^{-4}	9.85×10^{-8}	1.03×10^{-10}	9.86×10^{-8}

Table A6. *Cont.*

Process Step	Material	Electricity	Mineral Oil	Sum Per Process Step
Working hours with collective agreements				
Ingot production	68%	87%	85%	86%
Aluminum sheet production	68%	87%	69%	71%
Component production	68%	87%	95%	95%
Recycling	68%	87%	–	77%
Use phase	68%	87%	–	69%
Dismantling	68%	87%	80%	80%
Shredding	68%	87%	90%	90%
Floating and sinking plant	68%	87%	85%	87%

Table A7. Presentation of the results of the primary data collection of the PDCA indicators. The social aspects of *Economic Development* (2) and *Technological Development* (4) do not include PDCA indicators. The nine processes/companies considered in the table are hard coal mining (for electricity), hard coal mining (for coke), hard coal-fired power plant (energy company), fuel (oil company), ingot production, aluminum sheet production, component production, dismantling and shredding. For the steel coil, manganese ore and iron ore company, a set of indicators was determined that did not include PDCA indicators. The social aspects are highlighted in grey.

	Yes	No	Not Relevant	No Answer
1. Public Commitment to (Social) Sustainability				
PLAN	9			
DO/CHECK	9			
ACT	8	1		
3. Corruption				
PLAN	8	1		
DO	8	1		
CHECK	8	1		
ACT	8	1		
5. Armed Conflicts				
PLAN	4		4	1
DO	2		4	
CHECK			4	
ACT	1		4	
6. Behavior in Competition				
PLAN	8	1		
DO	7	1		1
CHECK	6	1		2
ACT	8	1		
7. Intellectual Property Rights				
PLAN	4	1		4
DO	3	1		5
CHECK	2	2		5
ACT	3	2		4

Table A7. *Cont.*

	Yes	No	Not Relevant	No Answer
8. Supplier Relationships				
PLAN	8	1		
DO	5	1		3
CHECK	6	1		2
ACT	6	1		2
9. Social Responsibility				
PLAN	7	2		
DO	7	2		
CHECK	5	2		2
ACT	4	2		3
10. Freedom of Association and Collective Bargaining				
PLAN	8	1		
DO	8	1		
CHECK	6	2		1
ACT	7	1		1
11. Child Labor				
PLAN	6	1	2	
DO	6	1	2	
CHECK	5	1	2	1
ACT	6	1	2	
12. Salary				
PLAN	9			
DO	7			2
CHECK/ACT	8			1
13. Hours of Work				
PLAN	6			3
DO	4			5
CHECK	4			5
ACT	4			5
14. Forced Labor				
PLAN	6	1	2	
DO	6		2	1
CHECK	5	1	2	1
ACT	6	1	2	
15. Equal Opportunities				
PLAN	8	1		
DO	7	1		1
CHECK	6	2		1
ACT	7	2		
16. Health and Safety				
PLAN	9			
DO	8	1		
CHECK	8	1		
ACT	8	1		

Table A7. *Cont.*

	Yes	No	Not Relevant	No Answer
17. Social Benefits/Social Security				
PLAN	5	1		3
DO	4	1		4
CHECK	1	2		6
ACT	1	2		6
18. Education and Training				
PLAN	9			
DO	8			1
CHECK	6			3
ACT	5	1		3
19. Job Security				
PLAN	4	2		3
20. Subjective Job Satisfaction				
PLAN	3	2		4
DO	4	2		3
CHECK	6	1		2
ACT	3	1		5
21. Delocalization				
PLAN	7	1	1	
DO	6	1	1	1
CHECK	4	1	1	3
ACT	5	1	1	2
22. Migration				
PLAN	3	1		5
DO	1	1		7
CHECK	1	1		7
ACT	1	1		7
23. Dialogue with the Local Community				
PLAN	8	1		
DO	8	1		
CHECK	7	1		1
ACT	7	1		1
24. Local Heritage				
PLAN	3	2		4
DO	3	2		4
CHECK	2	2		5
ACT	2	2		5
25. Indigenous Rights				
PLAN	4		5	
DO	4		5	
CHECK	2		5	2
ACT	2		5	2

Table A7. *Cont.*

	Yes	No	Not Relevant	No Answer
26. Local Employment				
PLAN	6	3		
DO	3	3		3
CHECK		3		6
ACT	1	2		6
27. Access to Immaterial Resources				
PLAN	8	1		
DO	5	1		3
CHECK	2	1		6
ACT	2	1		6
28. Access to Material Resources				
PLAN	7			2
DO	6			3
CHECK	2	1		6
ACT	4			5
29. Safe and Healthy Living Conditions				
PLAN	9			
DO	9			
CHECK	9			
ACT	8	1		
30. Secure Living Conditions				
PLAN	8		1	
DO	6	1		1
CHECK	3	1	1	4
ACT	3	1	1	4

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