



Harmonizing social life cycle impact assessment and interpretation: a consensus framework for zero-tailpipe emission vehicles

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Abstract

Purpose This study aims to establish a consensus-based framework for Social Life Cycle Impact Assessment (S-LCIA) or Social Life Cycle Performance Assessment (S-LCPA) tailored for Zero-tailpipe Emission Vehicles (ZEVs) by identifying and classifying social impact subcategories and indicators as mandatory and optional along with providing necessary Interpretation parameters. This framework is primarily focused on improving consistency and transparency in S-LCIA or S-LCPA and interpretation application across ZEVs which is also a goal of TranSensus LCA (TSLCA) project.

Methods The categorization of social impact subcategories as mandatory and optional is done through a four-step filtration method, involving: (1) a materiality assessment based on policy relevance and TSLCA stakeholder input, (2) alignment with industry practices such as Drive Sustainability's Sustainability Assessment Questionnaire (SAQ), (3) matching with subcategories from UNEP guidelines, and (4) indicator availability in social databases such as PSILCA and SHDB. Furthermore, Multi-Criteria Decision Analysis (MCDA) is used to select relevant indicators based on feasibility, achievability, interpretability, and relevance. This filtration method is followed by a voting session in which experts from S-LCA and ZEVs participated to select the impact categories and indicators along with interpretation parameters.

Results and discussion The process resulted in identifying a set of 9 mandatory and 14 optional social impact subcategories. The peer voting resulted in the selection of interpretation parameters that is found necessary based on specific factors, including system boundaries, data inputs, and stakeholder perspectives within the TranSensus project.

Conclusions and recommendations The proposed framework ensures harmonization based on a consensus from different stakeholders in the application of impact assessment and interpretation guaranteeing transparency and replicability in S-LCA for ZEVs and is transferable to other sectors. It provides practitioners with a clear foundation for socially responsible impact assessments, particularly in complex product systems like zero-emission vehicles.

Keywords Social life cycle impact assessment · Social life cycle performance assessment · Battery electric vehicle · Zero emission vehicles · Interpretation · Consensus · Harmonisation

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1 Introduction

As the global transition to low-carbon mobility intensifies, zero-tailpipe emission vehicles (ZEVs), particularly electric vehicles (EVs), have emerged as a central solution for sustainable transportation strategies (Rimpas et al. 2025). While these vehicles eliminate direct emissions and contribute to improved urban air quality, the production and supply chain processes raise social and ethical concerns like child labour (Osorio-Tejada et al. 2020), forced labour (Singh and Gupta 2018), discrimination (Dunuwila et al. 2022) etc. during their life cycles, especially within globalized and high-risk supply chains (Anahita et al. 2024; Jose et al. 2025).

Social Life Cycle Assessment (S-LCA) methodology provides a comprehensive framework to assess such impacts across a product's life cycle, including upstream and downstream activities such as raw material extraction, manufacturing, use stage and end of life (UNEP 2020; Pollok et al. 2021). Unlike traditional life cycle assessment (LCA), which primarily evaluates environmental impacts, S-LCA emphasizes human well-being, stakeholder involvement, and social justice (UNEP 2020). It provides a comprehensive perspective on how product systems affect various social dimensions, including labour rights, community well-being, and broader societal outcomes (UNEP 2020).

The social pillar of the life cycle sustainability assessment (LCSA) framework remains underdeveloped relative to its environmental and economic counterparts (Huertas-Valdivia et al. 2020; Pollok et al. 2021). It should be noted that while the methodology is recently standardized through ISO 14075:2024 (Traverso et al. 2025), its application across various sectors such as ZEVs remains limited. Furthermore, it is important to recognize that each S-LCA case study possesses unique characteristics (UNEP 2020), underscoring the necessity of harmonizing studies by sector or area of application (Traverso and Mankaa 2025). As part of the ongoing efforts to harmonize S-LCA for an area of application, the Social Product Declaration-Product Category Rules (SPD-PCR) (Traverso and Bonaffini 2023) and Social Product Declaration (SPD) (Traverso et al. 2023) approaches are gaining increasing momentum. This need for harmonization aligns with the challenges practitioners face in selecting the most appropriate social impact subcategories and indicators for specific sectors (Traverso and Mankaa 2025). In order to address the challenge of harmonizing LCA and S-LCA methods for ZEVs, the TranSensus LCA (TSLCA) (<https://lca4transport.eu/>) project is launched as a European initiative aimed at developing a consistent and sector-specific framework for LCA and S-LCA, ensuring methodological alignment across industry, policy, and research. This initiative involves stakeholders (refer to https://lca4transport.eu/?page_id=623 to see all the stakeholders involved in this

study) from academia, industry and policy, which aims to support the European Commission's climate and mobility strategies with a consensus on life cycle approaches across technologies and regions. This initiative is not only academically significant but also policy-relevant. It offers a replicable model for integrating social dimensions into product sustainability assessments, policy making, manufacturers, and society on how to improve social responsibility within low-carbon mobility transitions (Bouillass et al. 2021). The need for a structured, harmonized consensus based Social Life Cycle Impact Assessment (S-LCIA) or Social Life Cycle Performance Assessment (S-LCPA) (Traverso et al. 2025), framework along with interpretation parameters has intensified for the context of ZEVs.

A core challenge in advancing and harmonising for ZEVs S-LCIA or S-LCPA lies in the selection and prioritization of impact subcategories and indicators together with normalisation and weighting. Existing S-LCA guidelines, such as those by UNEP (2020) provide a broad list of potential stakeholder categories (e.g., workers, local communities, society) and impact subcategories (e.g., child labor, fair salary, cultural heritage). However, these lists are often too generalized for specific sectors (e.g. for ZEVs). As a result, many studies apply different sets of subcategories and indicators, limiting comparability and diminishing methodological coherence (Chabrawi et al. 2025; Joung et al. 2013). To address this inconsistency, recent research advocates for a context-specific yet harmonized consensus-based framework, impact subcategories are clearly distinguished based on their ethical weight, policy relevance, and data availability (Sharma and Manthiram 2020). This fosters comprehensive assessment, identifying hotspots, better transparency and accountability and wider stakeholder engagement. For instance, TSLCA defines a classification between mandatory (i.e. required for compliance with the guideline proposed by TSLCA (Bein and Cerdas Marin 2025)) and optional (i.e. not required for compliance) impact subcategories for S-LCIA or S-LCPA similar to the SPD – PCR (Traverso and Bonaffini 2023) available for Rolling stock. This classification becomes particularly relevant when assessing emerging technologies like ZEVs, where societal expectations around sustainability, human rights, and equitable labour practices are high. Mandatory impact subcategories are typically those that reflect minimum social thresholds, and Optional subcategories, on the other hand, include aspects that provide additional depth for comparative or interpretative purposes. Understanding this distinction helps prioritize risks, interpret trade-offs, and communicate findings in a more decision-oriented manner.

Similarly, the incorporation of S-LCA interpretation parameters is another key component in TSLCA project initiative that provides necessary and relevant context for

analyzing results. Parameters that are used for sensitivity or scenario analysis are the specific aspects or variables that are evaluated during the interpretation phase of S-LCA. During the interpretation phase, these parameters are carefully analyzed to determine their contribution to the overall impacts, check for completeness and consistency of the assessment, and to draw meaningful conclusions and recommendations for improvement. These include for instance regional energy mix during the use phase, the price of materials linked to social hotspots, and assumptions regarding labor hour distributions across geographies and so on. Interpretation parameters help move beyond static social risk ratings and toward dynamic, decision-oriented S-LCA, allowing for deeper stakeholder engagement and more responsible value chain management (Bouillass et al. 2021). Hence, the selection of interpretation parameters is also important to balance social risk and characterize results.

Therefore, the goal of this study is to provide S-LCA practitioners working with ZEVs with a harmonised set of impact subcategories and indicators along with necessary interpretation parameters. The development of a harmonized consensus-based S-LCIA or S-LCPA and Interpretation framework for ZEVs presented in this paper falls within the broader TSLCA project initiative. This common framework enables more consistent and transparent assessment of social impacts, allowing consumers to effectively compare the social risks associated with different ZEVs and make informed choices that favour vehicles with lower social risks. The adoption of a consensus-based selection approach is aligned with the project's Coordination and Support Action (CSA) nature under the Horizon Europe framework, which emphasizes stakeholder engagement and consensus-building, thereby justifying its methodological relevance and application.

1.1 Theoretical background

The lack of consensus-based methodology for ZEV, inconsistent application of stakeholder categories, and improper impact subcategory selection have constrained the widespread adoption of S-LCA. TranSensusD1.1 (2023) (Review of Current Practices on Life Cycle Approaches along the Electromobility Value Chain) reviewed current practices and impact subcategories in S-LCA studies, providing a foundation for identifying which elements among others are still missing (e.g. set of indicators and performance reference points for them) and developing a universal, replicable method. Building on this, TranSensusD1.2 (2024) (Establishing a unified framework for life cycle impact assessment – Integrative review and methodological consensus) analyzed existing methodologies, mapped misalignments, and highlighted gaps that need harmonization, addressing the

evolving needs of practitioners, policymakers, and stakeholders. With these identified gaps, it is evident that a context-specific selection of impact subcategories and proper interpretation of results are not present in the current studies. Also, a lack of consensus at each phase of S-LCA studies is found to be a reason for these inconsistencies, which as mentioned in TSLCA D 1.1 (TranSensus LCA Deliverable 1.1, 2023), that could be solved by engaging stakeholders during the final decision-making process. Taking into account the findings from the deliverables TranSensusD1.1 and TranSensusD1.2, a consensus-based approach is demonstrated through the findings of TSLCA D2.3 (TranSensus LCA Deliverable 2.3, 2025) by categorization of impact subcategories, its corresponding indicators and a detailed use of interpretation parameters for S-LCA.

2 Methods and materials

2.1 Decision making process adopted for proposing a consensus-based framework

The methodology followed to select context-specific social impact subcategories, its indicators and interpretation parameters follows three main steps as explained below and represented in Fig. 1. These three steps mainly include: review of existing S-LCA practices related to automobile sector (TranSensus LCA Deliverable 1.1, 2023, TranSensus LCA Deliverable 1.2, 2024), evaluation of S-LCA aspects as per standards and guideline by 14 S-LCA experts involved in the TSLCA project, and TSLCA stakeholder consultation which includes academia, policy and industries.

Step 1 (Literature Review and Expert Consultation): This step includes the review of current practices of S-LCA of ZEVs detailed in TSLCA D1.1 (TranSensus LCA Deliverable 1.1, 2023). The review questions assessed in this review were based on all the aspects of four phases of S-LCA as mentioned in UNEP (2020) including S-LCIA and Interpretation. It also includes the identification of gaps and needs from current S-LCA studies related to transport sector as mentioned in TSLCA D1.2 (TranSensus LCA Deliverable 1.2, 2024). It seeks for a mutual method that would ensure fair comparisons between products on a social basis based that would be understandable, harmonized, accurate, auditable, accepted, reliable and trustworthy (Bouillass et al. 2021). The consensus-based approach integrates insights from existing literature, policy reports, and relevant documents to account for social hotspots and sensitive social aspects in the identification and prioritization of impact subcategories. The findings are then subjected to discussion among S-LCA experts in the TSLCA consortium, as showed in Fig. 1. Different methods included for these discussions

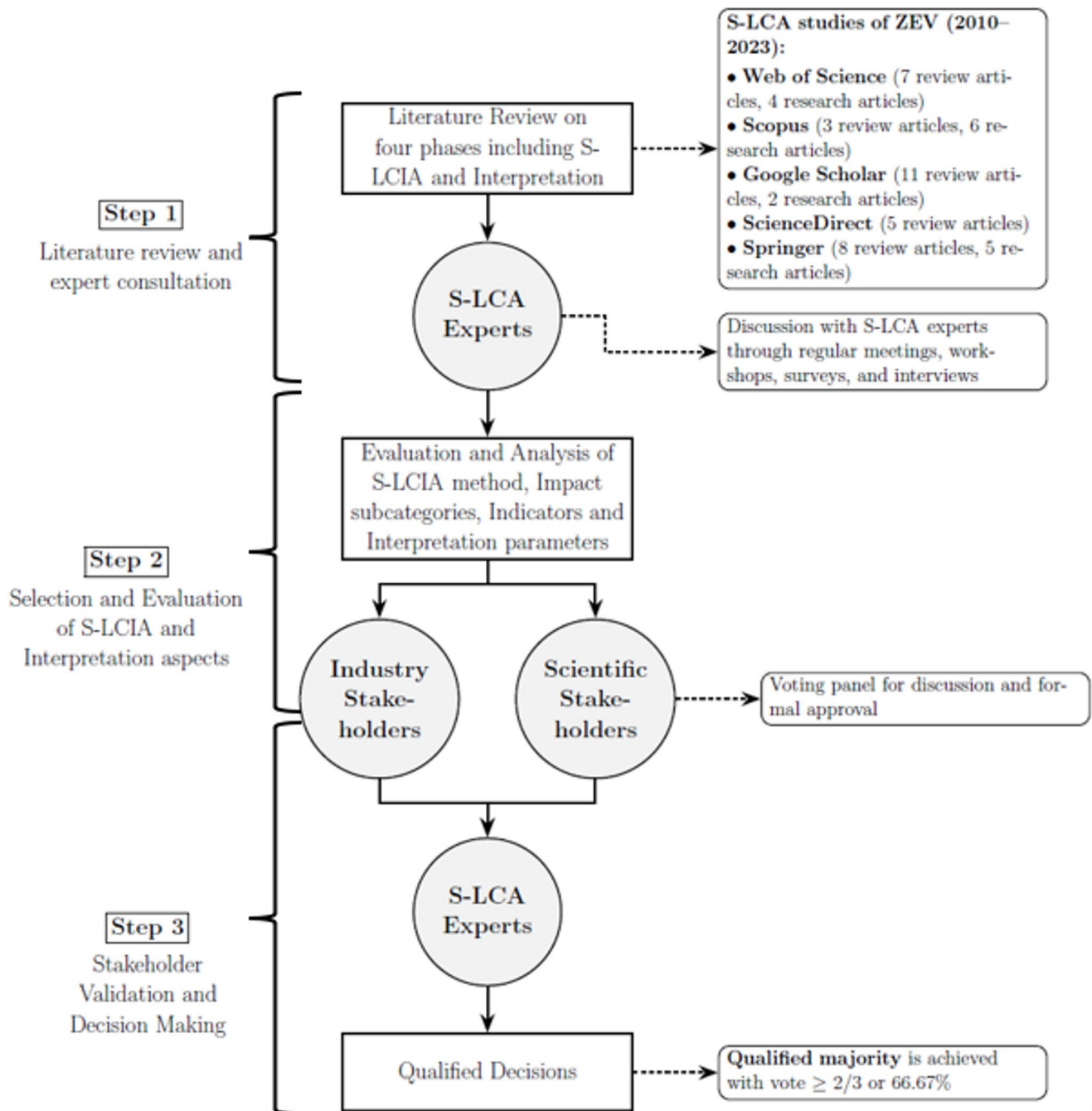


Fig. 1 Methodology adopted for final decision-making of the choice of impact subcategories indicators and interpretation parameters

include regular online meetings, workshops, surveys and interviews as detailed in TSLCA D1.1. S-LCA experts in this discussion involve S-LCA practitioners from academia, industry, research institution and public organization (refer to https://lca4transport.eu/?page_id=623 to see all the stakeholders involved in this study). The most relevant methodological approaches are then selected and analyzed in detail to assess their applicability, strengths, and limitations. This evaluation considers scientific rigor, feasibility, and

alignment with TSLCA project objectives like harmonising S-LCIA or S-LCPA and interpretation phase of S-LCA for ZEVs. The selected methodological approaches are presented in the following sections (Sects. 2.2 & 2.3).

Step 2 (Selection and evaluation of S-LCIA and Interpretation aspects): The reviewed methodological approaches guided the selection of stakeholder categories, impact subcategories, corresponding indicators, and interpretation parameters for ZEVs based on policy documents and

scientific literature spanning the full life cycle and practical considerations, including automotive data collection frameworks and data availability in relevant databases. The S-LCA experts reviewed each aspect for performing a S-LCIA or S-LCPA and its interpretation relying on the selected methodological approaches by a prioritization technique explained in the following sections (Sects. 2.2 & 2.3). This prioritization relies on their classification according to their robustness, reliability and harmonization potential in regard with the area of ZEVs studies. The selected methodological approaches help in the selection of relevant social impact assessment method, the classification of impact subcategories and the interpretation parameters which are considered for final recommendation as a framework after a consensus-based review.

Step 3 (Stakeholder Validation and Decision Making): The recommendations derived in step 2 are shared within a voting panel. This panel consists of 21 stakeholders from the TSLCA project that include S-LCA experts along with other industrial and scientific experts. Each stakeholder is granted with one vote per entity. All recommendations, along with a comprehensive explanatory document, are shared with the TSLCA stakeholders via the EU Survey platform. Some recommendations in step 2 that lacked clarity are identified for further review. These recommendations are subsequently submitted to the voting panel for discussion and formal approval. This voting process ensures that the final recommendation provided is under consensus with all the stakeholders and can be widely accepted for a harmonised recommendation to be proposed under the impact assessment and interpretation framework for ZEVs.

All the recommendations made here are based on the goal and scope definition (proposed reference scale approach) as well as Life Cycle Inventory aspects defined in TSLCA Deliverable 2.3 (TranSensus-LCA final harmonized approach) (TranSensus LCA Deliverable 2.3, 2025). Definition of harmonised framework for Goal and scope and Life Cycle Inventory phase of ZEVs is out of scope of this paper.

2.2 Methodology adopted for a prioritized set of impact subcategories

This section details the methodology of step 1 and 2 of Fig. 1 for social impact subcategory recommendation. Figure 2 shows the process for prioritizing a particular set of impact subcategories with a four-step filtering method during step 2 of Fig. 1.

The 15 impact subcategories (see List 1 in Table 1) after Filtration 1 (more details in Sect. 2.2.1) are determined by a materiality assessment based on the European Financial Reporting Advisory Group (European Financial Reporting Advisory Group EFRAG 2024). This assessment considers

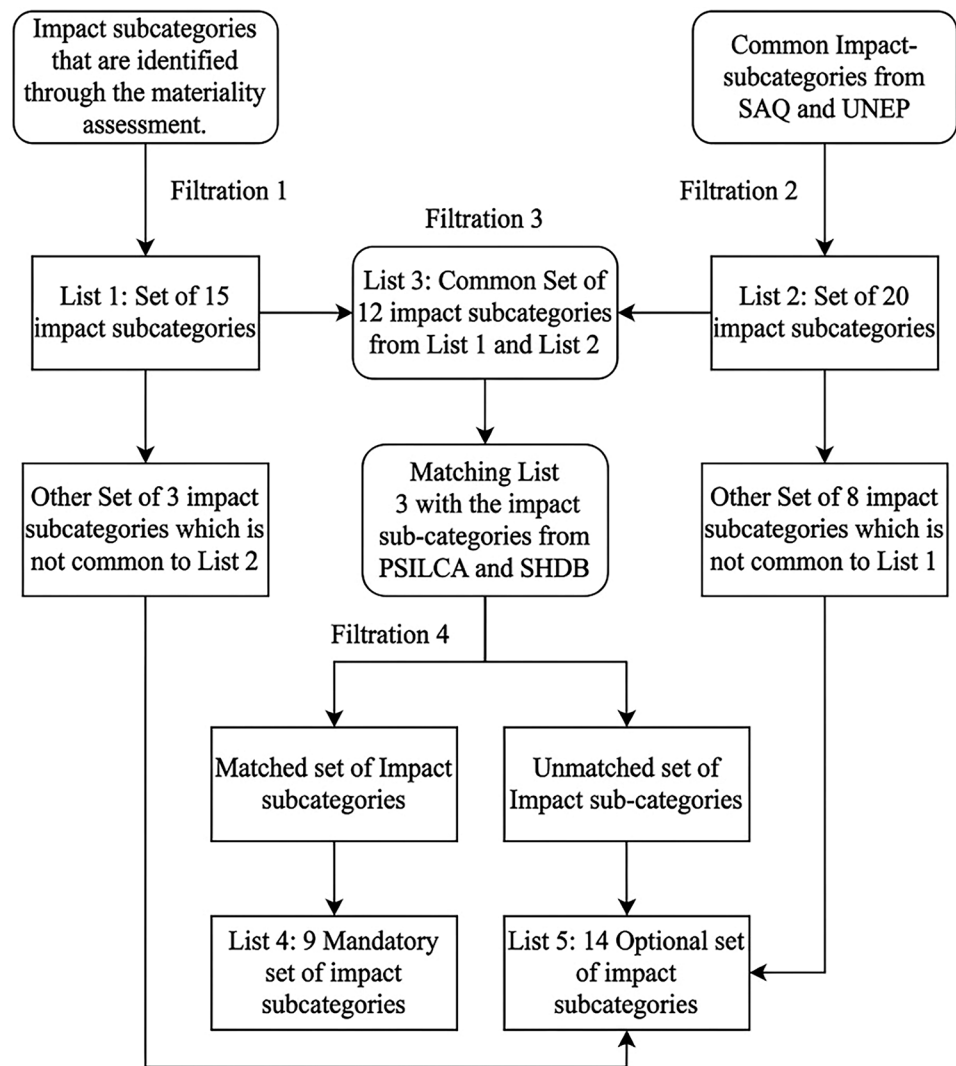
the frequency of their reporting in relevant policies and frameworks related to ZEVs (see Table S1 of the Supplementary Material) and incorporates opinions derived from S-LCA experts in TSLCA. In the second filtering step (more details in Sect. 2.2.2), the impact subcategories outlined in the UNEP Guideline (2020) are matched with the social impact subcategories identified in the Sustainability Assessment Questionnaire (SAQ) from Drive Sustainability (2023), which is used by automotive Original Equipment Manufacturers (OEMs) (see List 2 in Table 1). This step resulted in 20 impact subcategories, which is still a relatively large set. In the third filtration step (more details in Sect. 2.2.3), the impact subcategories from List 1 and List 2 are compared to identifying the common set of impact subcategories (12 in number) (see List 3 in Table 1). Each impact subcategory from List 3 is then matched with impact subcategories from PSILCA (Product Social Impact Life Cycle Assessment) and SHDB (Social Hotspot Database) databases in the fourth filtering step (more details in Sect. 2.2.4). The impact subcategories that are found in these databases are listed as mandatory (see List 4 in Table 1). On the other hand, those impact subcategories, that are not filtered during filtrations 3 and 4 are designated as optional impact subcategories (see List 5 in Table 1). Explore the Lists mentioned in Table 1 to understand the steps followed to find the Mandatory and optional impact subcategories.

2.2.1 Filtration 1: Materiality assessment

In this study, the materiality assessment aimed to identify and prioritize relevant social issues based on their occurrence in policy documents, social frameworks, and prior studies, with the UNEP social impact categories used solely as a framework to classify and structure these issues rather than as predefined ranking criteria. Prior to the materiality assessment, a comprehensive review of scientific and review articles was conducted to identify relevant social impact categories. The subsequent analysis of policy documents and social frameworks confirmed that these categories are consistently represented, ensuring that no social impact categories identified in the literature were excluded. Impact subcategories such as affordability, accessibility, inclusivity, and interoperability were not included in the present assessment due to data limitations and methodological constraints. Their exclusion follows from the lack of standardized quantification methods and reliable data availability in current S-LCA databases.

2.2.1.1 Understanding the context and selecting the S-LCA stakeholders' categories UNEP (2020) have published an updated version of the S-LCA guidelines and defined relevant stakeholder categories along with their impact sub-

Fig. 2 Methodology followed for recommending sets of mandatory and optional impact subcategories for ZEVs S-LCA studies



categories. The stakeholder categories identified by UNEP are Workers, Local Community, Value Chain Actors, Consumer, Society and Children.

2.2.1.2 Identification of potential social impacts The potential impacts on each of UNEP stakeholder categories can be classified into a number of impact subcategories depending on the issues of concern that are potentially affected. The identified impact subcategories from UNEP Guideline (UNEP 2020) cover a wide range of social and socio-economic aspects. These identified list of impact subcategories are then considered for further evaluation.

2.2.1.3 Determination of social material matters based on the materiality of the impacts The list of material social impacts is the result from the materiality assessment process. Taking the system boundary from cradle to grave, the

materiality assessment technique prioritizes the impacts related to ZEVs by considering it as a whole life cycle. As part of this, the study examines how various impact subcategories across different stages of ZEVs including extraction, manufacturing, distribution, use, and end-of-life are considered in relevant policy documents and frameworks (refer to Table S2 in the supplementary material). Additionally, it examines how 14 S-LCA practitioners involved in the TSLCA project address these sub-categories in the context of ZEVs through practitioner consultations (workshops, surveys, and interviews), thereby capturing practical experiences, perceived challenges, and emerging practices in relation to these sub-categories. The total number of reports based on each impact subcategory is taken into consideration while ranking the subcategories. The scoring is done in accordance to the number of policies or frameworks in

Table 1 Multi-stage filtration process for identifying relevant social impact sub-categories

Stakeholder category	Impact Subcategories	Materiality assessment score	Filtration 1: ZEVs policy & frameworks* (List 1)	Filtration 2: automakers** (List 2)	Filtration 3: common to 1 & 2 (List 3)	Filtration 4: S-LCIA or S-LCPA DB*** (List 4)	Classification (Mandatory/Optional) (List 5)
Worker	Health and safety	24	x	x	x	x	Mandatory
	Equal opportunities/discrimination	13	x	x	x	-	Optional
	Child labor	12	x	x	x	x	Mandatory
	Forced labor	11	x	x	x	x	Mandatory
	Freedom of association and collective bargaining	9	x	x	x	x	Mandatory
	Working hours	9	x	x	x	x	Mandatory
	Fair salary	8	x	x	x	x	Mandatory
	Social benefits/social security	6	x	x	x	x	Mandatory
	Sexual harassment	6	x	x	x	-	Optional
Local community	Delocalization and migration	5	x				Optional
	Respect of Indigenous rights	5	x	x	x	x	Mandatory
	Community engagement	5	x				Optional
	Cultural heritage	3		x			Optional
Value chain actors (not including consumer)	Wealth distribution	5	x				Optional
	Fair competition	2		x			Optional
	Respect of intellectual property rights	1		x			Optional
	Supplier relationships	0		x			Optional
Consumer	Health and safety	14	x	x	x	-	Optional
	Consumer privacy	4		x			Optional
	Transparency	1		x			Optional
Society	Corruption	6	x	x	x	x	Mandatory
	Prevention and mitigation of armed conflicts	3		x			Optional
	Ethical treatment of animals	0		x			Optional

*Frequently used by policy and frameworks reports (See Table S2 in Supplementary Material): materiality score ≥ 5

**Source: Sustainability Assessment Questionnaire (SAQ) from Drive Sustainability (2023)

***impact subcategories available in PSILCA or SHDB, only impact subcategories passing filtration 3 are assessed

which the subcategories are mentioned (See Table S1 of supplementary material).

List 1 in Table 1 presents the impact subcategories that are frequently (five or more occurrences) addressed in the considered policy documents and other frameworks across the entire life cycle, as outlined in the UNEP Guideline. The count of 5 is taken through common agreement among the S-LCA experts in TSLCA. On the other hand, several impact subcategories that are not mentioned in List 1 are either rarely (less than 5) or never mentioned in the sources analysed. These impact subcategories that did not reach count 5 are not considered for further evaluation.

2.2.2 Filtration 2: Identifying the relevant impact subcategories from SAQ

Drive Sustainability, 2023 is an alliance of automakers who commit to working together to strengthen the sustainability of the automotive supply chain. Drive Sustainability has

developed a SAQ (Drive Sustainability Progress Report 2023) for the automotive suppliers which aim to introduce key supplier performance indicators on the environmental, social and governance (ESG) topics that are prioritized by the OEM members of the Automotive Partnership (Drive Sustainability Progress Report 2023). In order to map the potential social risks or performance, SAQ has established a collection of social issues that are pertinent to particular domains or stakeholder categories. Several common social issues are identified after carefully comparing the social topics included in SAQ with the impact subcategories mentioned in UNEP guidelines (UNEP 2020). These common issues are presented as List 2 in Table 1, which is organized according to the stakeholder categories from the UNEP guidelines (UNEP 2020).

2.2.3 Filtration 3: Shortlisted impact subcategories

The impact subcategories that is sorted in filtration 1 are then matched to the Drive Sustainability impact subcategories

from List 2. Thus, the impact subcategories that have been shortlisted are given in List 3 of Table 1. Three impact subcategories unique to List 1 and eight unique to List 2 are classified in List 5 as optional impact subcategories. These represent categories not shared between the two lists.

2.2.4 Filtration 4: Identifying and matching the social impact subcategories in PSILCA and SHDB databases with shortlisted impact subcategories

In Filtration 4, the shortlisted impact subcategories from Filtration 3 are compared once again with commonly used S-LCA databases, such as PSILCA and SHDB. This step ensures the feasibility of assessing the proposed mandatory impact categories. If a proposed impact subcategory is marked as mandatory but is not available in these databases, it would be challenging for S-LCA practitioners to practically assess it. More information on PSILCA and SHDB Database can be found on D1.1 (TranSensus LCA Deliverable 1.1 2023).

List 4 in Table 1 shows the final impact subcategories which are classified as mandatory based on the availability of indicators and the corresponding impact subcategories from databases such as PSILCA and SHDB. Other impact subcategories that were shortlisted in filtration 3 but are not found in databases are classified as optional impact subcategory as mentioned in List 5.

This step marks the end of step 2 from Fig. 1 for the selection of context-specific impact subcategory. The recommendations submitted to the voting panel are detailed in Sect. 3, delivering the results of step 3 from Fig. 1.

Although raw social value data related to impact categories such as consumer health and safety can be identified from publicly available sources such as national statistics on road accidents or noise emissions, the feasibility of integrating this impact subcategory as a mandatory category within an S-LCA framework remains limited, despite its relatively high materiality score of 14. While this score reflects the significance of consumer health and safety as identified through the materiality assessment, two methodological constraints justify its classification as optional rather than mandatory. First, S-LCA requires social impact data to be normalized against a common activity variable, typically worker hours, to ensure comparability across life cycle stages and functional units. For consumer-related subcategories, however, no universally accepted reference scale or activity variable is currently established in S-LCA practice, making consistent quantification across studies methodologically problematic. Second, given the life cycle scope of this study, data must be collected consistently across all life cycle stages from raw material extraction through manufacturing, use, and end-of-life. While consumer health

and safety data may be accessible for specific stages or national contexts, obtaining comparable and complete data across the entire supply chain without the support of secondary databases remains a significant practical constraint. It is therefore important to distinguish between materiality which reflects the relevance of an impact subcategory to the system under study and methodological feasibility, which determines whether sufficient and consistent data can be obtained across the full life cycle. Consequently, consumer health and safety is retained as an optional impact subcategory, acknowledging its high materiality while recognizing the current methodological and data limitations inherent to life cycle-based social assessment.

2.3 Methodology adopted for proposing corresponding indicators for mandatory impact subcategories

Building on the impact subcategories identified in Sect. 2.2, this section details the methodology of step 1 and 2 of Fig. 1 for proposing indicators for each selected mandatory impact subcategories. While Sect. 2.2 focused on selecting and prioritising impact subcategories (resulting in a mandatory and optional set), this section takes these subcategories as input and describes the process of identifying and selecting appropriate indicators to measure them.

In order to assess the identified mandatory and optional impact subcategories and to provide valuable information and insights on decision making for the OEMs, impact subcategory indicators can be used as the main metric or tool. Some of the proposed mandatory impact subcategories have multiple indicators. For example, the impact subcategory Health and Safety under the stakeholder category Workers has a total of 20 indicators available across both databases. Therefore, identifying the most relevant indicators for ZEVs is essential to achieve harmonized S-LCA results across different studies.

The idea is the evaluation of an extensive list of social indicators based on specific criteria and propose a shortlist of social indicators that are directly linked to the mandatory list of impact subcategories identified.

The process begins with the identification of social indicators from the most widely used S-LCA databases, PSILCA and SHDB as identified from literature review. Table S3 of Supplementary Material illustrates the number of social indicators identified for each mandatory impact subcategory. An evaluation of each social indicator by S-LCA experts categorizes them as “relevant,” “not relevant,” or “maybe relevant.”

To finalize this selection and propose the social indicators under this study, the methodology proposed by Haslinger et al. (2024) is utilized. This methodology involved a

Multi-Criteria Decision Analysis (MCDA) that evaluated each indicator based on four criteria: i) achievability; ii) feasibility; iii) ease of interpretation, and; iv) relevance as presented in Table 2. Each criterion is scored on a scale from 0 to 3. For instance, in the achievability criterion, an indicator receives the highest score (i.e., 3) when it involves access to specific supplier data obtained by the company, such as those available in Corporate Social Responsibility (CSR) reports or internal health and safety management systems. Conversely, an indicator receives a score of 0 if there is no access to the necessary data or if the data collection phase is too time-consuming.

The relevance of each indicator was evaluated through expert judgement, based on the panel's knowledge of social impacts and their experience in S-LCA practice.

The feasibility criterion evaluates whether the data required to populate an indicator can be realistically collected within the context of the European automobile industry. This criterion ensures that the proposed indicator set is not only scientifically appropriate but also practically implementable, thereby supporting the broader goal of improving the applicability and uptake of S-LCA in industrial practice.

The easiness to interpret criterion evaluates two interconnected dimensions. Clarity refers to the degree to which an indicator yields results that are straightforward to understand and communicate to a range of stakeholders, including industry practitioners, policymakers, and non-specialist audiences. An indicator is considered clear if its unit of measurement, directionality, and relationship to the underlying social impact subcategory are unambiguous and do not require extensive technical interpretation. Awareness refers

to the degree to which an indicator reflects a social issue that is widely recognised and understood within the context of the European automobile industry and its supply chain. An indicator scoring high on awareness captures a social impact dimension that practitioners and stakeholders are already familiar with, thereby facilitating its integration into decision-making processes and stakeholder communication.

While feasibility evaluates whether the data required to measure an indicator can be realistically collected, achievability evaluates whether the social outcome captured by the indicator is actionable within the context of the European automobile supply chain. An indicator may be feasible to measure in terms of data availability yet still reflects a social outcome that is beyond the influence of the actors being assessed, thereby limiting its practical utility for guiding improvement actions and decision-making.

This step marks the end of step 2 from Fig. 1 for the selection of impact subcategory indicator for mandatory impact subcategories identified. The recommendations submitted to the voting panel are detailed in Sect. 3, delivering the results of step 3 from Fig. 1. The expert elicitation process involved 14 S-LCA experts drawn from a diverse range of organisations and backgrounds, including automotive OEMs, academic institutions, research institutions, and governmental research institutions.

While it would be technically feasible to include all indicators for which data is available in PSILCA and SHDB, or to prioritise indicators based on hotspot identification from geographical assessment results, this approach was deliberately avoided for two key reasons. First, the primary objective of the TranSensus project is to achieve harmonisation

Table 2 Criteria considered to evaluate the social indicators (Haslinger et al. 2024)

Criteria	Scale	Reference Point
Relevance	3	High relevance of the assessed impact.
	2	Medium relevance of the assessed impact.
	1	Low relevance of the assessed impact.
	0	No relevance of the assessed impact.
Feasibility	3	Information to be found at company.
	2	Information to be found in database i.e. PSILCA, SHDB, ecovadis, datamaran, RepRisk, Sedex, Supply shift (country level and specific company data) or in relevant open data sources i.e. from NGOs.
	1	Information to be found in reliable online sources (e.g., local and global news).
	0	No information available.
Easiness to interpret	3	High clarity and awareness of the assessed impact.
	2	Medium clarity and awareness of the assessed impact.
	1	Low clarity and awareness of the assessed impact.
	0	No clarity and awareness of the assessed impact.
Achievability	3	Access to supplier specific data from company, already available in CRS reports or via internal reporting (health and safety management systems).
	2	Access to company specific data (e.g., ecovadis, datamaran, RepRisk, Sedex, Supply shift), medium term availability.
	1	Access to regional/country level data from databases (e.g., PSILCA, SHDB, Verisk Maplecroft, NGO sources), long term collection phase.
	0	No access and/or too time extensive collection phase.

across S-LCA studies conducted within the European automobile industry. Allowing practitioners to freely select indicators based on data availability or individual hotspot assessments would result in different studies using different sets of indicators, making cross-study comparisons impossible and undermining the harmonisation goal. Second, consultation with S-LCA practitioners highlighted that limiting the indicator set to the most relevant and impactful indicators is essential to improve the applicability and feasibility of S-LCA in the European automobile industry. An exhaustive indicator set would increase the burden on practitioners and reduce the practical uptake of S-LCA. Therefore, a structured prioritisation approach was adopted to define a focused, harmonised set of indicators that balances scientific rigor with practical applicability.

2.4 Methodology adopted for a consensus-based framework for interpretation

The interpretation, final phase of S-LCA, involves analyzing the results, identifying significant issues, and drawing conclusions. For ZEVs, these results might include comparing the social impacts of different zero-emission technologies, evaluating the social sustainability of the transition to electric mobility, and providing recommendations for improving social performance in the ZEVs life cycle. By integrating these into S-LCA, this study aims to provide a comprehensive assessment tool social aspects of zero-emission vehicles.

This section details the methodology of step 1 and 2 of Fig. 1 for the interpretation parameters recommendation. An initial set of 25 interpretation parameters is identified as observed from current practices and brainstorming among a group of S-LCA experts in the context of ZEVs. This group of experts includes 7 members from academia, industries and research institutes. The selection of parameters is carried out through three consecutive discussions, including a voting session. The first two discussions are conducted by the group of experts mentioned above, and the procedure is explained with the help of Fig. 3.

Interpretation parameters are defined as the contextual variables and methodological choices that govern how S-LCA results are analysed, contextualised, and communicated to stakeholders. They do not alter the underlying measurement of social indicators but determine the frame of reference within which results are interpreted and compared, thereby directly influencing the conclusions drawn from an S-LCA study.

The initial evaluation of 25 interpretation parameters by S-LCA experts categorizes them as “Maybe” relevant; “Yes”, if relevant and “No”, if not. After the initial evaluation by the group of experts as shown in Fig. 3 below, a set of 12 parameters are considered not relevant for recommendation, pointing out the lack of certain factors like negligence of relevance (e.g. vehicle lifetime), privacy concerns (e.g. number of passengers), complicated procedures (e.g. choice of secondary data), lack of harmonization for certain aspects (e.g. reference scale, weighting and aggregation

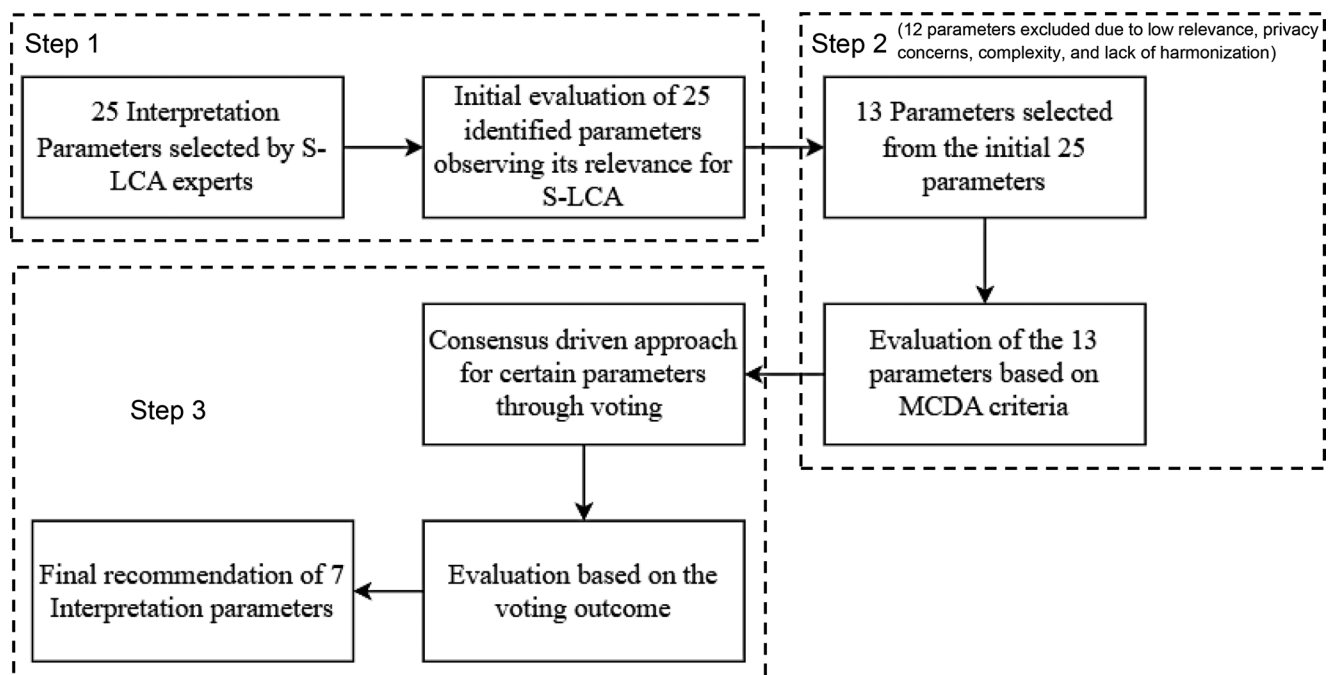


Fig. 3 Methodology adopted for identification of interpretation parameters

criteria) etc. (Refer Table S4 in Sect. 2 of Supplementary Material for more details).

The remaining set of 13 parameters that marked with “Maybe” relevant and “Yes” are considered for further evaluation. The group of experts further evaluated these 13 sets of parameters using a methodology based on MCDA, where each member scored each parameter individually. This approach, similar to the one used for evaluating social indicators, applied three criteria agreed upon by the S-LCA experts: (i) relevance, (ii) data availability, and (iii) ease of interpretation, as presented in Table S5 of the Supplementary Material. Each criterion is scored on a scale from 0 to 3 (0-not relevant, 3-very relevant; 0-not available, 3-available; 0-not easy, 3-very easy). After the scoring procedure, the mean value of the score given for each parameter are calculated across each criterion and finally the total mean of 3 criteria are calculated for all interpretation parameters and are decided whether to be selected or not (See Table S6 in Sect. 2 of supplementary material). Parameters with a final mean score greater than 2, as agreed upon by S-LCA experts, were proposed in three questions for final consensus voting (see Sect. 3.1.2). This step marks the end of step 2 from Fig. 1 for the recommendation of interpretation parameters.

While study-specific interpretation parameters offer greater contextual flexibility, a consensus-based approach was deliberately adopted to ensure comparability of S-LCA results across studies conducted within the European automobile industry. Allowing practitioners to independently define interpretation parameters would introduce variability in how results are contextualised and interpreted, making cross-study comparisons and aggregation of social performance data across the supply chain infeasible. The predefined set of interpretation parameters was developed through a systematic review of current S-LCA practices combined with structured expert elicitation involving 14 S-LCA experts, ensuring that the parameters are both grounded in established practice and validated for the specific industrial and geographical context of the study.

3 Result

The following section presents the finalized set of mandatory (Table 3) and optional (Table 4) impact subcategories, along with their respective indicators (Table 3), as determined through a structured consensus process involving expert voting. In addition, it details the interpretation parameters that were similarly established through consensus. Tables 5, 6 and 7 shows the results of voting related to impact subcategory, indicators and interpretation parameters respectively. These determinations constitute the qualified decisions outlined in Step 3 of Fig. 1 and represent

the outcome of a systematic, participatory decision-making procedure. A qualified decision is achieved when the voting threshold reaches at least two-thirds as qualified majority ($\geq 66.67\%$), as agreed upon by the TSLCA stakeholders in the study. The results reported herein reflect a high degree of agreement among participants, thereby ensuring that the selected subcategories, indicators, and parameters are both methodologically robust and contextually relevant for the intended assessment framework. Columns in Table 1 shows the results at each stage of filtration.

3.1 Voting results

This section presents the outcomes of the voting exercises conducted with stakeholders of the TSLCA project, who participated in their capacity as project beneficiaries as shown in step 3 in Fig. 1. Voting was implemented in three consecutive rounds over the course of the study to progressively refine the decision-making process. Questions pertaining to the impact assessment and the interpretation phase were included in the first and third rounds of voting. The results from each round were systematically analysed by S-LCA experts, who also considered and integrated the qualitative comments provided by participants during the voting process. These analyses informed the subsequent steps of the project and contributed to the consensus-building process.

3.1.1 Voting result for consensus-based framework - stakeholder categories, impact subcategories, and indicators

Table 5 shows that consensus was achieved on the proposal of a set of relevant impact subcategories and stakeholder categories for ZEVs. Table 6 gives the share of cast votes in favor of each of the proposed social impact subcategory indicators with the result submitted to S-LCA experts for final decision. It shows that consensus was reached by a qualified majority ($\geq 2/3$ or 66.67%) on the selection of impact category indicators within the context of ZEVs.

3.1.2 Voting result for consensus-based framework – interpretation parameters

Following the scoring of interpretation parameters using MCDA criteria by S-LCA experts described in Fig. 3, the seven parameters that exceeded the defined threshold were identified. This final list was then submitted to the TSLCA project beneficiaries for voting. The experts agreed not to designate these parameters as mandatory but rather to recommend (which is advisable to implement) them, recognizing that many S-LCA practitioners have limited experience with conducting interpretation and that relevant examples

Table 3 Mandatory social impact subcategory, its indicators with units and database retrieved as outcome of the filtration and voting sessions

Stakeholder Category	Mandatory Impact Subcategory	Impact Subcategory Indicator	Unit	Reference Scale Model	Source/ Data-base
Worker	Freedom of association and collective bargaining	Right of Association, Right of Collective bargaining, right to strike	4-point scale	3 = no risk; 2 = low risk; 1 = high risk; 0 = very high risk; no data	PSILCA
	Child Labour	Children in employment, total	% of all children ages 7–14	0% = no risk; 0% - <2.5% = very low risk; 2.5% - <5% = low risk; 5% - <10% = medium risk; 10% - <20% = high risk; ≥20% = very high risk; n.a. = no data	PSILCA
	Fair salary	Minimum wage, per month and Living wage, per month	USD	Data for LW (Living-Wage) is available; LW-MW (Minimum-Wage) -ratio ≥ 1.2 OR ratio ≥ 1 and MW < 300USD = very high risk; ratio = 1 - <1.2 and MW ≥ 300USD OR ratio = 0.8 - <1 and MW < 300USD = high risk; ratio = 0.8 - <1 = medium risk and MW > 300USD; ratio = 0.5 - <0.8 = low risk; ratio < 0.5 = very low risk	PSILCA
	Social Benefits/Social Security	Social security expenditures	% of GDP	0–2.5 = very high risk; >2.5–7.5 = high risk; >7.5–15% = medium risk; >15–20% = low risk; >20% = very low risk; n.a. = no data	PSILCA
	Forced Labour	Overall country sector risk forced labour and Forced labour risk (Global Slavery Index)	%	1.5 = very low risk; 3.1: 3.3 and 3.4 = medium risk; 4.0 = high risk; 4.2 = very high risk; n.a. = no data	PSILCA
	Working Hours	Weekly hours of work per employee	hr	40 - <48 = low risk; 30 - <40 and 48 - <55 = medium risk; 20 - <30 and 55 - <60 = high risk; <20 and >60 = very high risk; n.a. = no data	PSILCA
Local Community	Health and Safety	Rate of fatal accidents at workplace and Rate of non-fatal accidents at workplace	number/yr and 100 000 employees	0-<7.5 = very low risk; 7.5-<15 = low risk; 15-<25 = medium risk; 25-<40 = high risk; >40 = very high risk; no data	PSILCA
	Respect of Indigenous Rights	Presence of indigenous population	Y/N	0 = no = no risk; 1 = yes = medium risk	PSILCA
Society	Corruption	Corruption Perception Index (CPI)	Semi-quantitative Indicator	80–100 = very low risk (low perceived corruption); 60-<80 = low risk; 40-<60 = medium risk; 20-<40 = high risk; 0-<20 = very high risk (high perceived corruption)	SHDB

Note: If the database listed in the table above is unavailable to the LCA practitioner, it is possible to select equivalent indicators from another database that is available for you

Table 4 Optional social impact subcategory list

Stakeholder category	Optional impact subcategory
Worker	Equal opportunities/discrimination
	Sexual harassment
Local community	Cultural heritage
	Delocalization and migration
	Community engagement
Value chain actors	Fair competition
	Supplier relationships
	Respect of intellectual property rights
Consumer	Wealth distribution
	Health and safety
	Consumer privacy
	Transparency
Society	Prevention and mitigation of armed conflicts
	Ethical treatment of animal

are not consistently available in existing S-LCA studies (Gompf et al. 2020; Karlewski et al. 2019; Aboushaqrah et al. 2020). The voting process strengthened the robustness of decision-making regarding the interpretation parameters in the context of ZEVs. These parameters enabled to contextualize social indicators by engaging to real world variations and uncertainties. See the voting results and the three questions asked in Table 7.

3.2 Result of recommendations on consensus-based framework for impact assessment phase

Those questions that reached a qualified majority from the voting in this study among the voting panel allowed to finalize a harmonized framework for ZEVs. The impact subcategories after the filtrations and voting processes prioritized the set of impact subcategories into mandatory and optional.

Table 5 Voting outcome: relevant social impact subcategories and stakeholder categories

Subject	Questions/Statements	Votes (%)			Result
		Agree	Disagree	No preference	
Proposal of Social Impact Subcategories and Stakeholder Categories	This Study propose the relevant social impact subcategories and stakeholder categories (List 5 of Table 1)	81.82	4.54	13.64	Qualified majority reached

Table 6 Voting outcome: indicators related to qualified social impact subcategories and stakeholder categories

Subject	Questions/Statements	Votes (%)			Result
		Agree	Disagree	No preference	
Impact sub-category Indicators	Should following impact subcategory indicators be included in the proposed list of social indicators?				
	- Rate of fatal accidents & the Rate of non-fatal accidents at work-place (Stakeholder Category: Workers)	100	0	0	Qualified majority reached
	- Right of Association (Stakeholder Category: Workers)	100	0	0	Qualified majority reached
	- Right of Collective bargaining (Stakeholder Category: Workers)	100	0	0	Qualified majority reached
	- Right to strike (Stakeholder Category: Workers)	92	8	0	Qualified majority reached
	- Children in employment, the Minimum wage, per month, the social security expenditures, the Forced labour risk (Global Slavery Index) (Stakeholder Category: Workers)	100	0	0	Qualified majority reached
	- Living wage per month (AV) (Stakeholder Category: Workers)	100	0	0	Qualified majority reached
	- “Weekly hours of work per employee” (Stakeholder category: workers)	93	7	0	Qualified majority reached
	- Overall country sector risk forced labour (Stakeholder Category: Workers)	100	0	0	Qualified majority reached
	- Presence of indigenous population (Stakeholder Category: Local community)	93	7	0	Qualified majority reached
	- Corruption Perception Index (CPI) (Stakeholder Category: Society)	100	0	0	Qualified majority reached

Table 7 Voting outcome: S-LCA interpretation parameters

Subject	Questions/Statements	Votes (%)			Result
		Agree	Disagree	No preference	
S-LCA interpretation parameters	This study recommends including the quantity value for certain components/materials/flows leading to hotspots, the price related to process or materials, quantity of energy consumed during the use phase in the recommended list of social interpretation parameters	100	0	0	Qualified majority reached
	This study recommends including the geographical variation of the value chain, the choice of the activity variable (e.g. working hour vs. value added), the geographical variation of the energy consumed (electricity mix or H2 mix) during usage in the recommended list of social interpretation parameters	100	0	0	Qualified majority reached
	This study recommends including assumptions on data in the recommended list of social interpretation parameters	100	0	0	Qualified majority reached

The following sections provide the final set of social impact subcategories and its indicators of TSLCA harmonized framework.

3.2.1 Mandatory set of social impact subcategories

The mandatory impact subcategories were selected after multiple filtration steps and voting sessions as part of the TSLCA S-LCA framework. These subcategories are presented in Table 3, along with their corresponding indicators,

reference scale models, and units sourced from PSILCA and SHDB. All proposed indicators are at the product level, except for the Corruption Perception Index, which is applied to the impact subcategory Corruption under the stakeholder category Society. For detailed descriptions of the indicators, refer to UNEP (2021), PSILCA documentation (Maister et al. 2020), and SHDB documentation (Norris et al. 2018). The reference scale models provided in Table 3 are sourced from the respective databases listed in the table's final column.

3.2.2 Optional set of impact subcategories

Since S-LCIA or S-LCPA is a relatively new methodology to assess social impacts, the framework also recommends to provide freedom to S-LCA practitioners to choose indicators for optional subcategories depending on individual studies and requirements. The optional impact subcategories that is selected based on the methodology mentioned in Fig. 2 are listed in Table 4.

3.3 Recommended S-LCA interpretation parameters for ZEVs

The review and evaluation process, incorporating the MCDA procedure and subsequent voting, resulted in the recommendation of seven interpretation parameters:

- Quantity value for certain components/materials/flows leading to hotspots
- Geographical variation of the value chain
- Choice of the activity variable (e.g. working hour vs. value added)
- Variation of assumptions on social data
- Price related to process or materials
- Geographical variation of the energy consumed (electricity mix or H₂ mix) during usage
- Quantity of energy consumed during the use phase

The interpretation of S-LCA results for zero-emission vehicles involves several key parameters, as recommended by this study. These parameters facilitate the identification of hotspots and support a comprehensive assessment of social impacts throughout the vehicle's life cycle in different scenarios or sensitive cases.

Quantitative data on specific components, materials, or flows are essential for identifying supply chain hotspots. In the case of Battery Electric Vehicle (BEVs), this may include assessing the social impacts of battery production, particularly those linked to raw material extraction and processing. For example, cobalt mining for battery production is a critical area of concern, with studies indicating that up to 60% of the child labour risks in the product life cycle may be associated with cobalt extraction in the Democratic Republic of Congo.

Geographical variation within the value chain is particularly important, as it reveals how social risks differ across regions involved in vehicle production, from mining sites to manufacturing facilities. For instance, an S-LCA study may find that while the final assembly of a BEV in Germany poses relatively low social risks, lithium mining in Chile for battery production presents significant concerns regarding specific impacts on local communities.

The selection of an activity variable such as working hours or value added can substantially influence assessment outcomes, potentially reshaping the perceived significance

of different life cycle stages. For example, using working hours as the activity variable may draw attention to the social impacts of labour-intensive processes, such as vehicle assembly, whereas using value added may emphasize the importance of high-value components, such as the battery management system.

Variations in assumptions about social data can significantly influence the overall assessment, underscoring the importance of robust and consistent data sources. For instance, revising assumptions about working conditions in rare earth element mining for electric motors from “average” to “poor” could markedly alter the social risk profile of a BEV.

Price-related factors for processes or materials play a role in understanding the economic context of social impacts. As an example, fluctuations in the price of lithium could affect the economic stability of mining communities. A price increase might lead to better wages but could also intensify exploitation of resources.

For most ZEVs, for instance for BEVs, geographical variation in energy consumption during use particularly differences in electricity mix is critical for assessing the social implications of vehicle operation across regions. For instance, a BEV charged in Norway, with its predominantly hydroelectric grid, would present a markedly different social impact profile than one charged in Poland, where a coal-dominated grid may pose greater occupational health risks in energy production. Similarly, for Fuel Cell Electric Vehicle (FCEV) with geographic variation of H₂ production mix.

The amount of energy consumed during the use stage is directly linked to vehicle efficiency and its long-term social impacts. For example, a more efficient BEV that consumes less energy over its lifetime may reduce social impacts associated with electricity generation, such as lowering health risks for power plant workers.

4 Discussion

The novelty of this study is addressing a critical methodological gap in the field of S-LCA, specifically tailored to the context of ZEVs as identified from TSLCA D1.2 (TransSensus LCA Deliverable 1.2, 2024). Unlike general S-LCA guidance documents like UNEP (2020) or ISO 14075:2024, this framework provides a precise approach that provides uniformity in reporting and comparability of results. Several studies have explored social impacts across product life cycles, but very few have attempted to classify and prioritize impact subcategories, indicators and interpretation parameters in a structured manner. Unlike general S-LCA frameworks that is applied to a broad stakeholder categories

and undifferentiated subcategories, this study introduces a standardized structure that prioritizes between mandatory and optional impact subcategories for the ZEVs sector.

Benoît-Norris et al. (2011) introduced the UNEP/SETAC methodological sheets for subcategories of social LCA, providing a foundational reference framework for identifying and structuring social impact subcategories that has been widely adopted in subsequent S-LCA studies. Ekener-Petersen and Finnveden (2013) demonstrated the application of a screening S-LCA approach to identify potential social hotspots across a product life cycle, highlighting the importance of structured indicator selection for meaningful social impact assessment. Karlewski et al. (2019) proposed a practical approach for social life cycle assessment specifically in the automotive industry, addressing the challenges of indicator selection and data availability within the context of automotive supply chains. More recently, Gompf et al. (2021) applied the Analytical Hierarchy Process (AHP) to introduce weights to social life cycle assessment of mobility services, demonstrating the value of structured and transparent prioritisation approaches for selecting and ranking social indicators in the mobility sector.

While these studies have made important contributions to the prioritisation of social impact subcategories, indicators and interpretation parameters, they differ from the present study in several key respects. First, most existing studies have focused on either impact subcategory selection or indicator prioritisation in isolation, whereas the present study simultaneously addresses the prioritisation of impact subcategories, indicators, and interpretation parameters within a single integrated framework. Second, the results of these existing studies were taken into account during the development of the present framework, particularly in the initial identification of candidate impact subcategories and indicators through the systematic literature review. The UNEP/SETAC methodological sheets proposed by Benoît-Norris et al. (2011) served as a key reference for structuring the initial longlist of impact subcategories, while the prioritisation approach proposed by Gompf et al. (2021) informed the design of the expert elicitation and weighting process adopted in this study. However, the present framework deliberately departs from study-specific prioritisation approaches by adopting a consensus-based methodology explicitly designed to achieve harmonisation across S-LCA studies conducted within the European automobile industry. This harmonisation objective, which ensures that S-LCA results are comparable across different studies using the same framework, represents a distinct contribution that goes beyond the scope of existing prioritisation studies reported in the literature. Third, the present framework was specifically developed in the context of zero-emission vehicles, addressing a methodological gap in the existing literature

where structured and harmonised S-LCA frameworks tailored to the social sustainability assessment of ZEVs in the European automobile industry remain scarce.

In comparison to existing literatures, this framework also marks an important evolution in the application of social indicators by utilizing a MCDA to score indicators based on achievability, feasibility, interpretability, and relevance that ensures the practical implementation of the selected indicators. This dual emphasis on academic rigor and real-world usability sets this work apart from many existing S-LCA efforts, which often remain limited to conceptual discussions or overly generic templates.

The framework developed in this study can be currently considered unique as similar frameworks does not exist for any other products. It builds on a methodological progression informed by review of practices in TSLCA D1.1 (TranSensus LCA Deliverable 1.1, 2023), gap analysis in TSLCA D1.2 (TranSensus LCA Deliverable 1.2, 2024), and framework harmonization in TSLCA D2.3 (TranSensus LCA Deliverable 2.3 2025), while also addressing questions raised in literature (e.g., Huertas-Valdivia et al. 2020; Pollok et al. 2021). While studies have explored social impacts in sectors like electronics, textiles, and food, none have offered a harmonized classification of mandatory and optional subcategories validated through both stakeholder input and database verification. This makes the current work a pioneer in the space of sector-specific, structured impact assessment and Interpretation phase framework development. Even though this framework is tailored for ZEVs, the underlying methodology of the four-step filtration and consensus-building process can be adapted for other products and services. By aligning mandatory subcategories with widely recognized frameworks such as the European Regulations (e.g. European Battery Regulation), Social impact guidelines (e.g. Global Slavery Index), Sustainable Development Goals (SDGs), and ISO standards (e.g. ISO 14075) the framework can serve as a valuable tool for regulatory alignment and corporate compliance that helps manufacturers, suppliers, and policy-makers identify social hotspots early in the supply chain and adopt rectification strategies before potential risks.

The S-LCIA and interpretation framework proposed in this study is designed to be applicable across a broad range of S-LCA study objectives within the European automobile industry. Specifically, the framework supports the following intended applications as defined in the TranSensus project: assessing social performance or social risk, decision making, identification of social hotspots, enhancing sustainability reporting, comparing alternatives, supply chain management, and policy development and regulations. The mandatory set of impact subcategories, indicators, and interpretation parameters was developed and validated to ensure

consistent and comparable results across these diverse applications. For example, practitioners seeking to compare different ZEV technologies can apply the same mandatory framework to ensure that results are directly comparable across technology alternatives.

A key limitation of the proposed framework is that the mandatory set of impact subcategories represents a harmonised minimum standard rather than an exhaustive coverage of all potentially relevant social impacts. Certain impact subcategories that may be highly relevant in specific study contexts, geographical settings, or for particular ZEV technologies may not be included in the mandatory set. This reflects the deliberate design choice to balance comprehensiveness with practical feasibility and cross-study comparability. Practitioners are therefore advised to carefully review the optional set of impact subcategories and supplement the mandatory framework with additional subcategories where their specific study objectives, system boundaries, or stakeholder requirements indicate that additional social impacts should be considered. Furthermore, the framework was developed and validated in the specific context of the European automobile industry, and its direct transferability to other industrial sectors or geographical contexts beyond Europe may require additional validation and adaptation.

The added value of the proposed framework relative to existing approaches, including social hotspot analysis aligned with individual study goals and scopes, lies primarily in its explicit harmonisation objective. While social hotspot analysis is a valuable tool for identifying the most significant social impacts within a specific study context, its study-specific nature prevents direct comparison of results across different S-LCA studies. The proposed framework addresses this limitation by providing a consensus-based mandatory set of impact subcategories, indicators, and interpretation parameters that ensures methodological consistency and cross-study comparability across S-LCA studies conducted within the European automobile industry. Importantly, the framework does not replace social hotspot analysis but rather provides a harmonised methodological basis within which social hotspot identification can be conducted consistently. Practitioners can supplement the mandatory framework with optional impact subcategories and study-specific parameters to address the particular social hotspots identified within their individual study context, thereby combining the benefits of harmonisation with the contextual relevance of study-specific approaches.

5 Conclusion

This research addresses a critical gap in S-LCA: the need for a consistent and transparent framework for the selection, classification, and interpretation of social impact subcategories and their corresponding indicators along with interpretation parameters for ZEVs. Through a rigorous literature review and stakeholder-engaged methodology, a harmonized framework that prioritizes social impact subcategories, its indicators and interpretation parameters is proposed. The approach integrates multiple authoritative sources, including UNEP guidelines, policy frameworks related to ZEVs, and the Drive Sustainability initiative, alongside social LCA databases such as PSILCA and SHDB and suggestions from automotive industry.

The multi-phase filtration process, beginning with materiality assessment and culminating in expert voting, enabled a robust consensus on impact areas considered vital for assessing the social sustainability of a technologies which is in transition like ZEVs.

One of the key contributions of this research is the structured prioritization of social impact categories, social indicators and interpretation parameters that are not only policy and scientifically-relevant but also practically relevant and measurable through existing databases. This not only enhances transparency and comparability across S-LCA studies but also improves the practical uptake of S-LCA in both academia and industry. Furthermore, by distinguishing optional subcategories, such as community engagement, consumer privacy, and supplier relationships, this framework respects contextual variability while guiding practitioners toward a more standardized approach. Also, the recommended interpretation parameters that by this study helps to improve social sustainability of automotive life cycle in multi axis.

The implications of this research extend beyond the ZEVs case study. The framework developed herein can be adapted to other industries and technologies, thereby laying the groundwork for broader adoption of consistent impact assessment and interpretation practices. It offers a replicable model for future S-LCA practitioners, policymakers, and sustainability analysts to ensure social dimensions of sustainability are neither overlooked nor inconsistently interpreted.

Several limitations of the present study should be acknowledged. First, the proposed framework was developed and validated specifically within the context of the European automobile industry and the TranSensus project. While the framework is designed to be applicable across a broad range of S-LCA study objectives within this context, its direct transferability to other industrial sectors, supply chain contexts, or geographical regions beyond Europe may

require additional validation and adaptation. Practitioners applying the framework outside the European automobile industry context are therefore advised to critically review the mandatory set of impact subcategories, indicators, and interpretation parameters for their specific context and supplement or adapt them accordingly.

Second, the mandatory set of impact subcategories represents a harmonised minimum standard rather than an exhaustive coverage of all potentially relevant social impacts. Certain impact subcategories that may be highly relevant in specific study contexts, geographical settings, or for particular ZEV technologies may not be included in the mandatory set. Practitioners are therefore advised to carefully review the optional set of impact subcategories and supplement the mandatory framework where their specific study objectives or stakeholder requirements indicate that additional social impacts should be considered.

Third, the framework relies on expert judgement for the prioritisation of impact subcategories, indicators, and interpretation parameters. While the expert panel was carefully composed to ensure diversity of expertise and institutional backgrounds, expert judgement inherently carries a degree of subjectivity. Future research should explore more quantitative approaches to complement and validate the expert judgement process, such as structured sensitivity analysis of selected indicators and impact subcategories once the framework is applied in practice.

Fourth, the framework was developed based on currently available S-LCA databases, specifically PSILCA and SHDB. As these databases continue to evolve and expand their coverage of social indicators and geographical contexts, periodic review and updating of the mandatory and optional sets of indicators will be necessary to ensure that the framework remains aligned with the state of the art in S-LCA data availability.

Looking ahead, several important perspectives for future research can be identified. First, the practical application and validation of the proposed framework across multiple S-LCA case studies within the European automobile industry will be essential to assess its real-world performance, identify areas for refinement, and demonstrate its capacity to deliver comparable and harmonised results across different studies and organisations. Second, future research should explore the extension of the framework to other ZEV technologies beyond passenger cars, including buses, trucks, and two-wheelers, to assess whether the mandatory set of impact subcategories and indicators remains applicable and sufficient across different vehicle categories. Third, the development of recommended but non-prescriptive indicators for the optional impact subcategories represents a valuable direction for future work, providing guidance to practitioners who wish to report on optional subcategories

while retaining the flexibility that characterises the optional component of the framework. Finally, as the European automobile industry continues to transition towards zero-emission mobility, the social impact landscape is likely to evolve significantly, particularly in relation to battery supply chains, critical raw material sourcing, and workforce transitions. Periodic review and updating of the framework will therefore be necessary to ensure its continued relevance and applicability in a rapidly changing industrial and technological context.

Finally, proposed harmonized framework is not merely a methodological advancement but a step toward institutionalizing social justice and ethical responsibility within product sustainability assessments. It empowers stakeholders to make informed, responsible decisions that align with global sustainability goals and social well-being. Future research could involve the systematic implementation of the proposed recommendations and an in-depth examination of how the framework may be adopted and operationalized within prospective impact assessment practices for ZEVs. Future work can explore dynamic updating of impact subcategory and indicator sets as well as interpretation parameters based on evolving societal values, technological changes, and data availability to ensure continued relevance of S-LCA frameworks.

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Declarations

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References

- Aboushaqrah NNM, Onat NC, Kucukvar M, Jabbar R (2020) Life cycle Sustainability assessment of sport utility vehicles: the case for Qatar. In: Sierpiński G (ed) Smart and Green solutions for transport Systems. TSTP 2019. Advances in intelligent Systems and computing, vol 1091. Springer, Cham. https://doi.org/10.1007/978-3-030-35543-2_22
- Anahita JN, Poelzer GA, Zhang SE, Rosenkranz J, Pettersson M, Ghorbani Y (2024) Sustainability challenges throughout the electric vehicle battery value chain, renew. Sustain Energy Rev 191:114176. <https://doi.org/10.1016/j.rser.2023.114176>
- Bein T, Cerdas Marin JP (2025) Consolidated guidelines for a transport specific life cycle assessment (LCA). <https://doi.org/10.24406/publica-4913>
- Benoît-Norris C, Vickery-Niederman G, Valdivia S, Franze J, Traverso M, Ciroth A, Mazijn B (2011) Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. Int J Life Cycle Assess 16(7):682–690. <https://doi.org/10.1007/s11367-011-0301-y>
- Bouillass G, Blanc I, Perez-Lopez P (2021) Step-by-step social life cycle assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios. Int J Life Cycle Assess 26(12):2408–2435. <https://doi.org/10.1007/s11367-021-01988-w>
- Chabrawi AMRO, de Andrade JM, Ugaya CML et al (2025) Towards reliable primary data collection and harmonized set of indicators in S-LCA on the stakeholder worker. Int J Life Cycle Assess 30(6):1036–1054. <https://doi.org/10.1007/s11367-024-02400-z>
- Drive Sustainability Progress Report (2023). Retrieved in 2024. <https://www.drivesustainability.org/ds-progress-report-2023/>
- Dunuwila P, Rodrigo VHL, Daigo I, Goto N (2022) Social impact improving model based on a novel social life cycle assessment for raw rubber production: a case of a Sri Lankan rubber estate. J Clean Prod 338:130555. <https://doi.org/10.1016/j.jclepro.2022.130555>
- Ekener-Petersen E, Finnveden G (2013) Potential hotspots identified by social LCA - part 1: a case study of a laptop computer. Int J Life Cycle Assess 18(1):127–143. <https://doi.org/10.1007/s11367-012-0442-7>
- Eltohamy H, Istrate R, van Oers L, Steubing B, Lokesh K, Raugai M, Hill N, Baars J, Stauß M, Jose D, Hussman J, Lindholm J, Elginoz Kanat N, Tegstedt F, Beylot A, Menegazzi P (2023) TranSensusLCA deliverable D1.1. Review of current practices on life cycle approaches along the electromobility value chain. Retrieved in 2024
- European Financial Reporting Advisory Group (EFRAG) (2024) <https://www.esg-advising.com/insights/european-financial-reporting-advisory-group-efrag>. Retrieved in
- Gompf K, Traverso M, Hetterich J (2021) Using analytical hierarchy process (AHP) to introduce weights to social life cycle assessment of mobility services. Sustainability 13(3):1258. <https://doi.org/10.3390/su13031258>
- Gompf K, Traverso M, Hetterich J (2020) Towards social life cycle assessment of mobility services: systematic literature review and the way forward. Int J Life Cycle Assess 25(10):1883–1909. <https://doi.org/10.1007/s11367-020-01788-8>
- Haslinger AS, Huysveld S, Cadena E, Dewulf J (2024) Guidelines on the selection and inventory of social life cycle assessment indicators: a case study on flexible plastic packaging in the European circular economy. Int J Life Cycle Assess 30(6):1397–1414. <https://doi.org/10.1007/s11367-024-02312-y>
- Hill N, Eltohamy H, Steubing B, van Oers L, Istrate R, Lokesh K, Raugai M, Baars J, Beylot A, Muller SB, Mir D, Jose C, Traverso D, Mankaa Nangah M, Lindholm R, Elginoz J, Lidberg N, Yusufowska M, Wallender S, Tegstedt A, F NM, L S, F P, Sam Pratiwi A, Robertz B, Hussman J, Menegazzi P (2024) TranSensusLCA deliverable D1.2: establishing a unified framework for life cycle impact assessment - integrative review and methodological consensus, TranSensusLCA. Retrieved in 2024
- Huertas-Valdivia I, Ferrari AM, Settembre-Blundo D, García-Muñia FE (2020) Social life-cycle assessment: a review by Bibliometric analysis. Sustainability 12(15):6211. <https://doi.org/10.3390/su12156211>
- Jose D, Mankaa RN, Traverso M (2025) Social risk and performance assessment of battery raw materials: implications for sustainable sourcing and social LCA. Int J Life Cycle Assess 30(10):2280–2299. <https://doi.org/10.1007/s11367-025-02516-w>
- Joung CB, Carrell J, Sarkar P, Feng SC (2013) Categorization of indicators for sustainable manufacturing, ecol. Indic 24:148–157, ISSN 1470-160X, <https://doi.org/10.1016/j.ecolind.2012.05.030>
- Karlewski H, Kaul A, Richter B, Finkbeiner M (2019) A practical approach for social life cycle assessment in the automotive industry. Resources 8(3):146. <https://doi.org/10.3390/resources8030146>
- Life cycle assessment - principles and guidelines for social life cycle assessment of products and organizations (ISO 14075: 2022). Draft. Retrieved in 2024. <https://www.iso.org/standard/81012.html>
- Maister K, Noi CD, Ciroth A, Srocka M (2020 Jun) (All GreenDelta). PSILCA database v.3 documentation. Retrieved in 2024. https://psilca.net/wp-content/uploads/2020/06/PSILCA_documentation_v3.pdf
- Moréac-Njeim G, Monnier É, Bui Van A, Husmann J, Eltohamy H S, Jose B, Kupjetz D et al (2025) TranSensusLCA deliverable D2.3. TranSensus-LCA final harmonized approach. Retrieved in 2024
- Norris CB, Bennema M, Norris G (2018) The social hotspots database, supporting documentation, Update 2019, <https://nexus.openlca.org/ws/files/23286>
- Osorio-Tejada JL, Llera-Sastresa E, Scarpellini S, Hashim AH (2020) An integrated social life cycle assessment of freight transport systems. Int J Life Cycle Assess 25(6):1088–1105. <https://doi.org/10.1007/s11367-019-01692-w>
- Pollok L, Spierling S, Endres H-J, Grote U (2021) Social life cycle assessments: a review on past development, advances and methodological challenges. Sustainability 13(18):10286. <https://doi.org/10.3390/su131810286>
- Rimpas D, Barkas DE, Orfanos VA, Christakis I (2025) Decarbonizing the transportation sector: a review on the role of electric vehicles towards the European Green deal for the new emission standards. Air 3(2):10. <https://doi.org/10.3390/air3020010>
- Sharma SS, Manthiram A (2020) Towards more environmentally and socially responsible batteries. Energy Environ Sci 13(11):4087–4097. <https://doi.org/10.1039/D0EE02511A>
- Singh RK, Gupta U (2018) Social life cycle assessment in Indian steel sector: a case study. Int J Life Cycle Assess 23(4):921–939. <https://doi.org/10.1007/s11367-017-1427-3>
- Traverso M, Bonaffini D (2023) Rolling stock S-PCR. <https://www.environdec.com/spd>. Accessed 12 March 2025

- Traverso M, Bonaffini D, Pedalà MC, Alessi M, Capitano C (2023) SPD-Train HTR 412 blues. <https://www.environdec.com/spd>. Accessed 12 March 2025
- Traverso M, Mankaa RN (2025) The social life cycle assessment of products and organizations-methodological developments and implementations. *Int J Life Cycle Assess* 30(6):1011–1017. <https://doi.org/10.1007/s11367-025-02480-5>
- Traverso M, Petti L, D'Eusanio M et al (2025) Finally, an international standard on social life cycle assessment: ISO 14075. *Int J Life Cycle Assess* 30(12):2559–2564. <https://doi.org/10.1007/s11367-025-02522-y>
- UNEP (2020) Guidelines for social life cycle assessment of products and organizations 2020. In: Benoit Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese, G. (eds). United Nations Environment Programme (UNEP)
- UNEP (2021) Methodological sheets for subcategories in social life cycle assessment (S-LCA) 2021. In: Traverso, M., Valdivia, S., Luthin, A., Roche, L., Arcese, G., Neugebauer, S., Petti, L., D'Eusanio M., Tragnone, B.M., Mankaa, R., Hanafi, J., Benoit Norris, C., Zamagni, A. (eds). 2 United Nations Environment Programme (UNEP)

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