

Social life cycle assessment: a systematic review from the engineering perspective

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ABSTRACT

Social Life Cycle Assessment (SLCA) has emerged as a crucial element in sustainability discussions, gaining traction in academic research and industry practices. In response to increasing consumer awareness, governmental regulations, and corporate responsibility, sustainable production models have been widely adopted, influencing engineering projects to address not only environmental but also social impacts. This systematic review aims to explore the application of SLCA within the engineering field, focusing on key trends, methodologies, and challenges engineers face when implementing SLCA. To achieve this purpose, 196 peer-reviewed studies published between 2010 and 2024 were analysed through bibliometric and content analysis. The results reveal an increasing trend in SLCA research, with key contributions from energy, mechanical engineering, and chemical engineering fields. Despite its growing relevance, several methodological challenges persist, including a lack of standardisation, data availability issues, and difficulties in integrating SLCA with environmental and economic assessments. The findings of this research can facilitate academic researchers, industrial managers, and policymakers in implementing SLCA practices in engineering applications for a comprehensive sustainability assessment.

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1. Introduction

Pursuing technological innovation, cost-efficiency, and process optimisation has traditionally driven engineering. Engineers have played a pivotal role in societal advancement by developing new technologies, infrastructure, and systems that improve the quality of life. However, the engineering profession has experienced a significant shift in recent decades, moving from a primary focus on technical and economic objectives to a broader consideration of sustainability. This shift is driven by the growing recognition that engineering projects must also address their environmental and social impacts. As global challenges such as climate change, resource depletion, and social inequalities become more acute, engineers are increasingly expected to integrate sustainability into the core of their practices (García-Muiña et al. 2021).

Sustainability has thus become a cornerstone of modern engineering ethics and professional standards. The concept of sustainable development, which gained prominence through the Brundtland Commission's 1987 report, defines sustainable development as that which meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development 1987). This principle has been widely adopted in engineering codes of conduct worldwide. For example, the American Society of Mechanical Engineers (ASME) mandates that engineers consider environmental impact and sustainable development in their professional duties. Similarly, the UK Standard for Professional Engineering Competence (UK-SPEC) requires engineers to conduct their work in a manner that contributes to sustainable development (Ashby 2023). These guidelines highlight the evolving role of engineers, who are now tasked with balancing technical excellence with environmental stewardship and social responsibility (Olakitan Atanda 2019).

This expanded focus on sustainability is also reflected in the development and adoption of the Social Life Cycle Assessment (SLCA). SLCA is a methodology developed by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) to evaluate

the social and socio-economic impacts of products and processes across their entire life cycle (UNEP Setac Life Cycle Initiative 2022). By addressing both positive and negative social impacts, SLCA facilitates informed decision-making and enhances the comprehensiveness of sustainability assessments across sectors and activities (Cadena et al. 2019). Unlike traditional Life Cycle Assessment (LCA), which primarily addresses environmental impacts, SLCA emphasises the social dimensions of sustainability, such as human rights, working conditions, health and safety, cultural heritage, governance and socio-economic impacts, making it a crucial tool for engineers who seek to ensure that their projects positively contribute to society (Ekener, Hansson, and Gustavsson 2018).

The importance of integrating social considerations into sustainability assessments is increasingly recognised by global initiatives and frameworks that emphasise social responsibility. Initiatives such as the United Nations Global Compact and sustainability reporting schemes like the Global Reporting Initiative (GRI) underscore the necessity for organisations to address social performance, including impacts on value chain actors, workers, consumers, and local communities (Martínez-Blanco et al. 2015). This global shift towards recognising and addressing social impacts has led to the growing adoption of SLCA, particularly in engineering fields where projects often have significant social implications (Guarino, Cellura, and Traverso 2020).

The relevance of SLCA is particularly evident in the manufacturing and industrial sectors, where the social impacts of engineering activities are profound. Manufacturing not only produces goods that meet societal needs but also has substantial implications for labour practices, community well-being, and socio-economic development (Sutherland et al. 2016). SLCA provides a framework for understanding these impacts, enabling engineers and decision-makers to ensure that manufacturing activities are socially responsible and aligned with broader sustainability goals (Pack et al. 2020).

The concept of sustainable development has evolved over the years, with various interpretations and applications across different contexts. The Brundtland Report's definition has been widely accepted, but the complexity of sustainability, encompassing environmental, economic, and social dimensions, has led to the development of numerous frameworks and methodologies aimed at operationalising this concept. With this purpose, the United Nations' 2030 Agenda for Sustainable Development, which outlines 17 Sustainable Development Goals (SDGs), represents a comprehensive effort to address global challenges (Guarino, Cellura, and Traverso 2020). Key SDGs that focus on social sustainability include No Poverty, Good Health and Well-being, Quality Education, Gender Equality, Decent Work and Economic Growth, Reduced Inequalities, and Peace, Justice, and Strong Institutions. These goals emphasise the importance of equity, human well-being, and inclusive growth in achieving a sustainable future.

Given the growing importance of social sustainability, this paper explores the current methodologies and frameworks employed in SLCA, particularly within engineering applications. The review is structured around three key research questions:

- (1) What are the current methodologies and frameworks employed in SLCA of engineering applications, and how do they address social impacts in the life cycle of engineering projects or products?
- (2) What are the key social indicators used in SLCA studies of engineering applications, and how are they used to define the social aspects of engineering projects or products throughout their life cycle?
- (3) What are the main challenges and limitations associated with conducting SLCA studies on engineering applications, and how can these challenges be addressed to enhance the integration of social considerations in engineering decision-making processes?

This review addresses these questions to provide a comprehensive understanding of SLCA in the context of engineering, highlighting the progress made and the challenges that remain. The goal is to contribute to the advancement of SLCA methodologies, thereby enhancing the ability of engineers and decision-makers to create more socially sustainable projects and products.

1.1. Methodology

The systematic literature review (SLR) approach selected for this study is a reliable method that ensures a comprehensive and unbiased synthesis of existing literature (Jamwal et al. 2021). A systematic review

thoroughly examines published articles to address a specific research question, utilising a structured methodology to identify relevant studies and minimize distortions and errors (Petti, Serreli, and Di Cesare 2018). This study adheres to the step-by-step review protocol established by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), which guides the selection of relevant articles for constructing a literature portfolio (Ramos Huarachi et al. 2020). The PRISMA method begins with identifying articles from various databases, followed by screening these articles based on predefined inclusion and exclusion criteria, assessing eligibility, and finally, compiling a literature portfolio with the included studies (Moher et al. 2009).

1.2. Identification of articles

The selection of relevant articles for this study began with defining a set of keywords commonly associated with SLCA, as outlined in Table 1. Seven keywords were identified as referring to SLCA. “Social organisational life cycle assessment” was also included, as several engineering organisations use this method to conduct SLCA. These keywords were combined using the Boolean Operator “OR” to form the search query employed in the search engines. These terms were cross-referenced with the subject filter “ENGI” to focus specifically on engineering applications.

The literature search was conducted using two comprehensive databases, Scopus and Web of Science, selected for their extensive coverage of peer-reviewed journals and their relevance to engineering and life cycle assessment. The search strategy targeted titles, abstracts, and keywords (TITLE-ABS-KEY), ensuring a focused and thorough exploration of relevant literature. To capture recent developments in the field, the search covered the period from 2010, following the publication of the Guidelines for SLCA of Products (UNEP SETAC 2009), to 2024. This process initially identified 274 research documents in Scopus and 310 in Web of Science.

1.3. Screening of articles

After the initial search stage, a rigorous set of inclusion and exclusion criteria was employed to select relevant articles. Firstly, a set of inclusion criteria were applied as follows:

- Articles published in the English language,
- Articles from peer-reviewed journals and conference proceedings,
- Articles in full length.

The articles listed from the databases were combined, and duplicates indexed in both databases were excluded. Following this step, 397 articles were retained for the following screening process. A step-based screening process was implemented to refine the selection further. In the first step, the keywords and abstracts of the research articles were screened for relevance using a set of exclusion criteria:

- Review articles were excluded to avoid redundancy and focus on original research contributions.
- Studies related to agriculture, food, textile production, water, and waste treatment were excluded unless they involved technological applications pertinent to engineering. However, studies within these sectors were included when they demonstrated engineering-relevant technological applications. For

Table 1. Database search query.

Context [TITLE-ABS-KEY]	“Social life cycle assessment” OR “Social life cycle analysis” OR “Social life cycle approach” OR “Social sustainability assessment” OR “Social sustainability analysis” OR “Social organisational life cycle assessment” OR “Societal life cycle assessment”
Subject [TITLE-ABS-KEY]	“ENGI”
Year	2010 – 2024

example, SLCA studies on textile supply chains were reviewed under the “Supply Chain”. Similarly, papers on wastewater and solid waste treatment involving chemical, energy, or environmental engineering innovations were included and categorised under relevant engineering domains.

- Articles that focused solely on defining baseline SLCA guidelines or validating impact pathways without practical application in engineering were excluded.

After applying these exclusion criteria, 203 articles were taken to the second screening step, which included a full-text review. During this step, seven articles were excluded as they were irrelevant to the engineering field. Following these screening processes, 196 articles were identified for inclusion in the review. All article titles and abstracts retrieved in the data set were inspected and the full articles skimmed to eliminate potential bias in the results. The literature review search and selection process workflow, including the number of articles found, included, excluded, and retained, is summarised in [Figure 1](#).

1.4. Analysing of articles

A standardised data extraction form was designed to capture essential information from each article systematically. This form included fields for bibliographic details, study objectives, SLCA methodologies and frameworks employed, engineering applications, social impact categories and indicators assessed, and the primary findings and conclusions. To facilitate the analysis, Microsoft Excel, Mendeley, NVIVO software, and VOSviewer software were utilised. All identified articles were imported into Mendeley to prevent duplication and ensure comprehensive coverage. At the same time, key details such as title, author, year, journal or conference, and database were recorded in Excel spreadsheet. The article folder was then exported from Mendeley as a RIS file and imported into VOSviewer for visual mapping and NVIVO for content analysis.

The extracted data were analysed using both descriptive statistics and thematic analysis. Descriptive statistics quantified aspects such as publication trends, sources, and the distribution of research across various engineering sectors. Thematic analysis was employed to identify and interpret key themes related to SLCA methodologies, indicators, and challenges within the engineering context. NVIVO’s capabilities for systematic data management facilitate the thematic analysis, allowing for the identification of recurring themes and the synthesis of review results (Caldera, Desha, and Dawes 2017). This dual approach provided both a quantitative overview and a qualitative understanding of the field’s evolution.

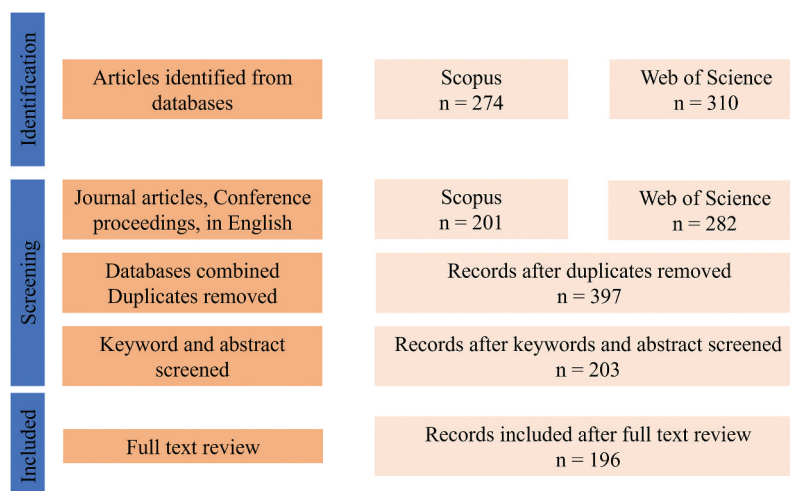


Figure 1. Literature review search and selection process.

2. Descriptive analysis

2.1. Publication year and source

SLCA has experienced significant growth as a research area in engineering, as illustrated in Figure 2. Over the past decade, there has been a continuous increase in SLCA-related publications, reflecting the growing recognition of its importance in sustainability research and practice. This upward trend highlights the increasing interest and commitment from both academia and industry to integrate social dimensions into life cycle assessments, particularly in engineering contexts.

The identified research articles for this study were published across 55 different journals and conference proceedings. Notably, about 62% of these articles were published by five key journals. The International Journal of Life Cycle Assessment has produced the maximum number of studies (58), followed by Journal of Cleaner Production (32), Sustainable Production and Consumption (15), Journal of Industrial Ecology (9), and Sustainability (Switzerland) (6). The remaining sources each published a maximum of three studies, with 44 journals contributing only one article on SLCA in engineering. Further analysis of annual publications reveals that the International Journal of Life Cycle Assessment has consistently published studies yearly since 2013 (Figure 2).

2.2. Engineering area

The identified research articles were classified according to their specific engineering focus areas, highlighting where SLCA is gaining significant traction. As illustrated in Figure 3, the primary engineering fields where SLCA is increasingly important include Energy (30%), Mechanical Engineering (19%), Civil Engineering (13%), and Chemical Engineering (11%). Each of the remaining engineering areas accounts for less than 5% of the studies, while articles not specific to any engineering area accounting 4%.

The Energy sector encompasses studies on electricity generation, fuel production, batteries, hydrogen production, bioenergy, biorefineries, and waste treatment for energy production. Mechanical Engineering includes manufacturing activities, particularly within the automotive and aerospace industries. Civil Engineering studies examine the social impacts of buildings and pavements, while Chemical Engineering studies focus on the SLCA of chemical product production. A comprehensive list of reviewed articles, categorised by their engineering focus area, is provided in Table 2.

2.3. Bibliographic analysis

A bibliographic analysis of the articles was performed using VOSviewer software, which generates visual maps based on bibliographic data from reference manager files, utilising the VOS (visualization of similarities) method (Ramos Huarachi et al. 2020). Co-authorship and keyword co-occurrence were the chosen types of analysis for this study. In these visual maps, the size of each circle or frame represents the

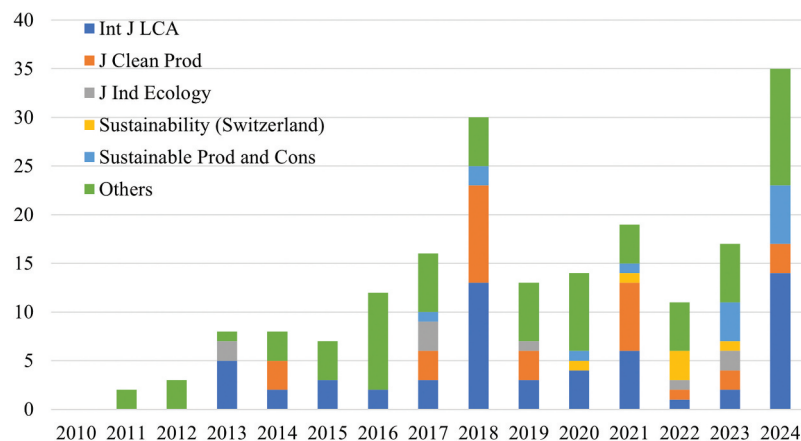


Figure 2. Publications by year and journal.

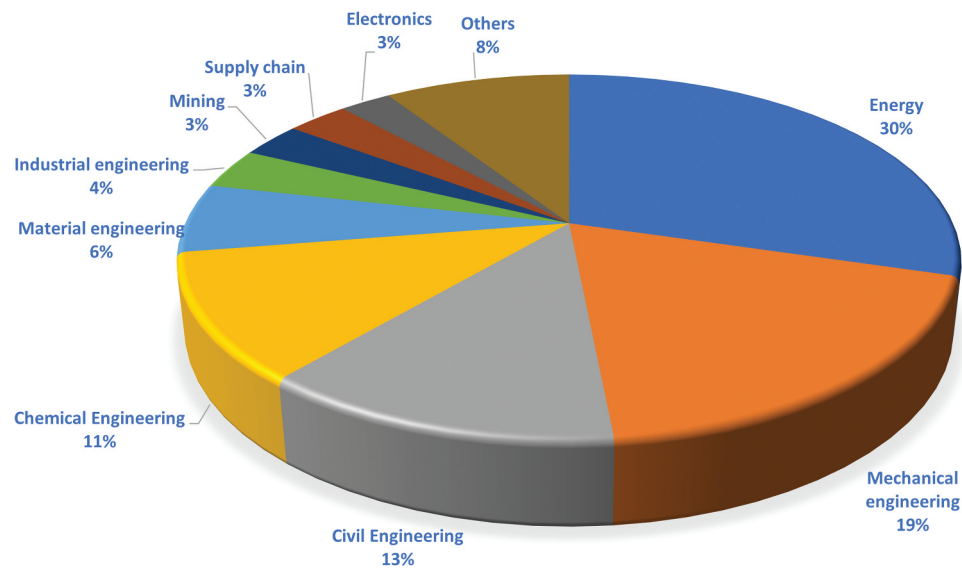


Figure 3. Engineering area distribution of research articles.

number of publications or occurrences. Smaller circles or frames indicate the selected minimum threshold number of publications per author or occurrences of keywords. In comparison, larger circles or frames denote a higher number of publications per author or more frequent keyword occurrences.

The co-authorship visual map, presented in [Figure 4](#), illustrates the relationships and collaborations between different authors within the field of SLCA in engineering applications. The map uses a colour gradient to indicate the timeline of publications, ranging from blue to yellow. Authors with more recent publications are depicted in yellow, while those with earlier publications are shown in blue. Among the 679 authors identified, 50 form the largest set of connected co-authorships, indicating a network of researchers who frequently collaborate on SLCA studies. Marzia Traverso (6) and Matthias Finkbeiner (4) are the authors publishing the greatest quantity of articles within the domain of SLCA in engineering applications. Marzia Traverso, in particular, is more connected to recently published articles, as indicated by the green circles on the map. In contrast, most other authors have published only one or two papers, with only seven authors publishing three articles. The relatively low number of connected co-authorships (50 out of 679) and the limited number of publications per author suggest that many researchers tend to publish on SLCA within the context of their specific engineering disciplines, focusing on the social aspects of their areas of expertise.

The keyword co-occurrence map illustrates the relationships between different research keywords and how frequently they appear within various documents. This visualization helps identify key themes and topics commonly associated with each other in the field of SLCA. For the analysis conducted in this study, the selected articles' titles and abstracts were examined using the settings "All Keywords" and "Full Counting." Out of 5,608 keywords, a map of 265 keywords was generated by setting a minimum occurrence threshold of five. [Figure 5](#) illustrates the visualization map of these keywords. As expected, "SLCA" is the most frequently used keyword, appearing 85 times, followed by "Perspective" (53), "Subcategory" (51), "Social risk" (49), "Score" (48), and "Organization" (43). These frequently occurring terms highlight the ongoing focus on structuring social assessment frameworks, evaluating social risks, and incorporating stakeholder and organizational dimensions into SLCA studies.

A notable trend is the high occurrence of energy-related keywords such as "Biomass" (19), "Bioeconomy" (15), "Fossil fuel" (13), and "Biorefinery" (13), which aligns with that the energy engineering is the most studied field within engineering-focused SLCA.

The visualization also reveals methodological concentrations, particularly within the light blue cluster, which includes keywords such as "aggregation," "assumption," "uncertainty," "hybrid model," "impact pathway," and "weighting factor." These terms reflect the growing emphasis on methodological refinement in SLCA, especially related to data treatment, result interpretation, and model integration. Researchers are

Table 2. Identified articles based on their engineering focus area.

Engineering areas	Source of literature
Energy	(Akhtar et al. 2023), Alidoosti et al. 2021; Atilgan and Azapagic 2017; Aung, Fischer, and Azmi 2021; Azapagic et al. 2016; Baltrocchi et al. 2023; Berridy-Segade et al. 2024; Borri, Zsembinszki, and Cabeza 2024; Buchmayr et al. 2022; Cadena et al. 2019; Campos-Carriedo, Dufour, and Iribarren 2024; Chingono and Mbohwa 2015; Contreras-Lisperguer et al. 2018; Cooper, Stamford, and Azapagic 2018; Corona and San Miguel 2019; Corona et al. 2017; Do Carmo, Margni, and Baptiste 2016, 2017a, 2017b; Egbue 2012; Ekener, Hansson, and Gustavsson 2018; Fattahi, Govindan, and Farhadkhani 2021; Fortier et al. 2019; Gan Yupanqui et al. 2024; Ghaderi, Moini, and Pishvaei 2018; Guarino, Cellura, and Traverso 2020; Hansson et al. 2024; Kaiser et al. 2022; Koese et al. 2023; Kolotzek et al. 2018; Kouloumpis and Azapagic 2018; A. Lehmann et al. 2013; J. Lehmann et al. 2024; Manik, Leahy, and Halog 2013; Martinez-Hernandez et al. 2022; Masilela and Pradhan 2021; Messmann et al. 2023; Nubi, Morse, and Murphy 2021; Osorio-Tejada et al. 2022; Popien et al. 2023; Puentes Bejarano et al. 2024; Reuter 2016; Sadhukhan, Sen, and Gadkari 2021; A. Sánchez et al. 2024; Santoyo-Castelazo and Azapagic 2014; Schlör et al. 2018; Y. Shi et al. 2023; Silva et al. 2024; Souza et al. 2018, 2021; Stougie, Delgado, and Van Der Kooi 2015; Stougie and Van Der Kooi 2016; Thies et al. 2019; van Haaster et al. 2017; Z. Wang, Osseweijer, and Duque 2018; Weldegiorgis and Franks 2014; Werker, Wulf, and Zapp 2019; Y. Wu et al. 2017)
Mechanical engineering	(Agyekum, Fortuin, and van der Harst 2017; Arvidsson et al. 2018; Aschehoug, Schulte, and Bjørnbet 2016; Barke et al. 2020; Baumann et al. 2013; Ben Ruben, Menon, and Sreedharan 2018; Bhanot, Rao, and Deshmukh 2016a, 2016b; Bouillass, Blanc, and Perez-Lopez 2021; Cao et al. 2016; Chang et al. 2015; Chen, Jiang, and Jin 2024; García-Muñia et al. 2021; Haddad et al. 2023; Hadler, Brenner-Fliesser, and Kaltenecker 2023; Islam, Hildenbrand, and Hossain 2018; Jiang et al. 2018; Kluczek and Gladysz 2020; Luthe, Kägi, and Reger 2013; Luthin, Knacksterdt, and Traverso 2024; Ma et al. 2018; Mair-Bauernfeind et al. 2020; Naghshineh et al. 2020; Navarro et al. 2024; Niero and Hauschild 2017; Pack et al. 2020; Pastor et al. 2018; Peruzzini et al. 2017; Pillain et al. 2019; Serra et al. 2022; J. Shi et al. 2024; Singh and Gupta 2018; Soares et al. 2021; Walters and Mirkouei 2020; Weiss et al. 2011; Wilken et al. 2020; Zimmer et al. 2017)
Civil engineering	(Balasbaneh et al. 2021; Balasbaneh, Bin Marsono, and Khaleghi 2018; Bhuiyan, Karim, and Hammad 2024; Del Rosario et al. 2024; Dong and Ng 2016; Evans et al. 2020; Fauzi et al. 2022; Ferrazzo, Tonini de Araújo, and Consoli 2024; Hossain et al. 2018; Hosseinijou, Mansour, and Shirazi 2014; Inti and Tandon 2021; Inti, Sharma, and Tandon 2019; Kayaçetin, Piccardo, and Versele 2023; Liu and Qian 2019; Loreau, Stephan, and Cooper 2024; Mhatre-Shah, Gedam, and Unnikrishnan 2023; Navarro, Martí, and Yepes 2023; Okte, Boakye, and Behrend 2024; Olakitan Atanda 2019; San Vicente-Navarro et al. 2024; Shang et al. 2018; Tighnavard and Ramadan 2024; Vitorio Junior and Kripka 2020; Ying and Yang 2014; Zheng et al. 2019)
Chemical engineering	(M. Hannouf and Assefa 2018; Jungmeier et al. 2015, 2016; Lizasoain-Arteaga et al. 2024; Marting Vidaurre, Lewandowski, and Lask 2022; Orola, Uusitalo, and Levänen 2024; Popovic and Kraslawski 2018; Pucciarelli, Traverso, and Lettieri 2021; Rafiaani et al. 2020; Reinales, Zambrana-Vasquez, and Saez-De-Guinoa 2020; Ren et al. 2015; Serreli et al. 2021; Siebert et al. 2018, 2018a, 2018b; V. Subramanian et al. 2018; Tsalidis 2022; Tsalidis et al. 2020, 2023; Valente, Brekke, and Modahl 2018; Visentin et al. 2022; Xu et al. 2017)
Material engineering	(Ardolino, Palladini, and Arena 2023; Di Giorgio et al. 2024; Haslinger et al. 2024; Krekel, Suer, and Traverso 2024; La Rosa, Valente, and Aradoaei 2024; S. Sánchez et al. 2019; Springer, Wulf, and Zapp 2024; Stoycheva et al. 2022; Traverso et al. 2018; Vavra and Bednarikova 2013; Vavra et al. 2014; Zhang, Bhuiyan, and Zhang 2024)
Industrial engineering	(M. B. Hannouf et al. 2024; Papetti et al. 2020; Popovic et al. 2018; Sandionigi et al. 2024; Sutherland et al. 2016; Walker et al. 2021; P. C. Wang et al. 2011)
Mining	(Cecere et al. 2024; Di Maria et al. 2024; Di Noi et al. 2020; Muller et al. 2021; Roche et al. 2024; S. R. Wu et al. 2019)
Supply chain	(Benoit-Norris, Cavan, and Norris 2012; D'Eusario, Tragnone, and Petti 2022; Hannibal and Kauppi 2019; Mogos et al. 2024; Muñoz-Torres et al. 2023; Norris, Aulisio, and Norris 2012)
Electronics	(Ekener-Petersen and Finnveden 2013; Ekener-Petersen and Moberg 2013; K. Subramanian and Yung 2018; Suckling and Lee 2017; S. W. Wang, Hsu, and Hu 2016)
Environmental engineering	(Foglia et al. 2021; Josa and Garfi 2023; Tsalidis et al. 2024)
SMEs	(Kumar, Rehman, and Phanden 2022; Rehman and Kumar 2023)
Development and application of SOLCA	(Martínez-Blanco et al. 2015)
Marine engineering	(Basurko and Mesbahi 2014)
Organisations	(Tsalis, Avramidou, and Nikolaou 2017)
Service	(Chang et al. 2016)
Not specific	(Bonilla-Alicea and Fu 2021; Chandrakumar, Kulatunga, and Mathavan 2017; Hardadi and Pizzol 2017; Huber and Fröhling 2024; Parent, Cucuzzella, and Revéret 2013; Pelletier et al. 2018; Ramirez et al. 2014; Sakellariou 2018)

increasingly engaging with techniques for managing uncertainty, combining qualitative and quantitative data, and selecting appropriate aggregation methods for multi-criteria decision-making. This suggests a maturing field in which attention is shifting from conceptual exploration toward practical implementation and standardisation of SLCA methods.

3. Content analysis

This section aims to examine the methodologies, frameworks, and social indicators employed in SLCA within engineering applications. Through a content analysis of the existing literature, the section aims to

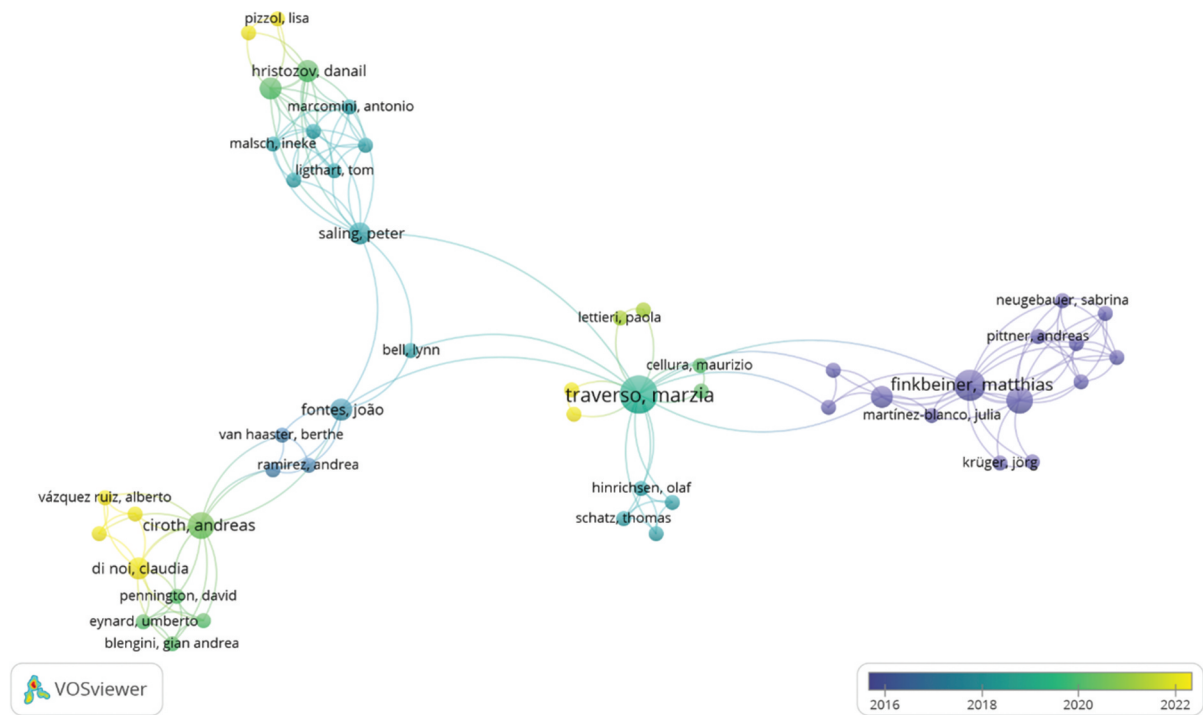


Figure 4. Co-authorship visual map.

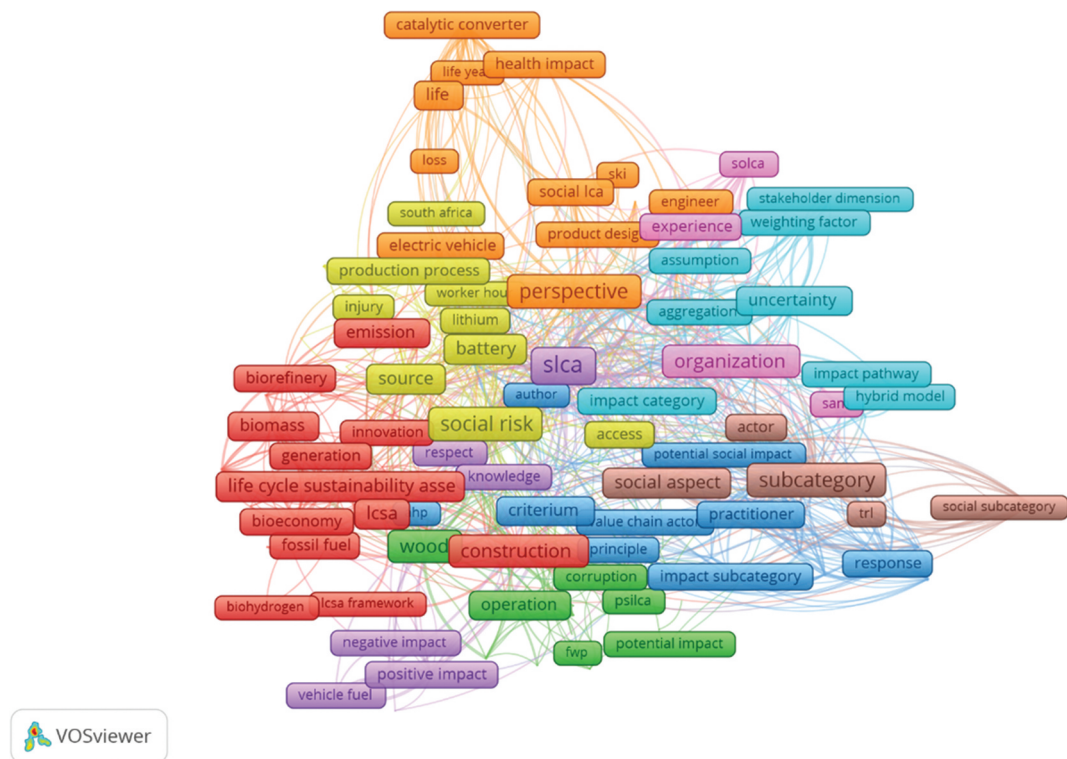


Figure 5. Keyword co-occurrence visual map.

uncover how these methodologies are implemented to address the social impacts inherent in the life cycle of engineering projects and products. Additionally, this analysis identifies key social indicators and evaluates their relevance in engineering contexts while exploring the challenges and limitations associated with conducting SLCA studies in the engineering field. The findings from this content analysis contribute to

a deeper understanding of the current state of SLCA in engineering and offer insights into improving the integration of social considerations into engineering decision-making processes.

3.1. Historical overview of SLCA in engineering

Historically, life cycle assessments have primarily focused on the development and standardisation of environmental and economic assessment methods. However, over the past few decades, the field of SLCA has gained significant momentum, particularly as efforts to standardise SLCA practices have intensified (Buchmayr et al. 2022). The discussion of social impacts from a life cycle perspective has begun with attempts to include health impacts on workers and other groups in LCA (Baumann et al. 2013). The term SLCA was first introduced by O'Brien and colleagues in 1996, marking the beginning of a new dimension in life cycle analysis that integrates social criteria into existing methodologies (O'Brien, Doig, and Clift 1996). In response to the diverse approaches and varying perceptions of SLCA, the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) launched a task force that culminated in the publication of the "Guidelines for Social Life Cycle Assessment of Products" in 2009 (UNEP SETAC 2009). One of the objectives of the working group was to establish a consensus on how social impacts may be best captured and integrated into the existing life cycle assessment framework to move towards the development of the Life Cycle Sustainability Assessment (LCSA) (Benoit-Norris, Cavan, and Norris 2012). These UNEP/SETAC guidelines have since become a cornerstone in the field, establishing a foundation for the standardisation of SLCA practices and significantly shaping its development (Corona et al. 2017). The introduction of the UNEP/SETAC guidelines has significantly expanded the application of SLCA, especially in sectors like energy (A. Lehmann et al. 2013), construction (Hosseinijou, Mansour, and Shirazi 2014), and manufacturing (Zimmer et al. 2017).

The evolution of SLCA frameworks has paralleled the emergence of a broader ideology within engineering that emphasises socio-cultural change alongside technical and environmental considerations. Organisations such as Engineers for Social Responsibility (ESR) and the International Network of Engineers and Scientists for Global Responsibility (INES) played pivotal roles in promoting a more culturally and politically sensitive approach to engineering sustainability, challenging the prevailing values of traditional engineering practices (Sakellariou 2018).

In recent years, Corporate Social Responsibility (CSR) has also become increasingly important as a management tool for promoting social sustainability, particularly in industries (Muller et al. 2021). CSR practices are guided by various normative frameworks, including those established by the International Labour Organisation (ILO), the Global Reporting Initiative (GRI), International Integrated Reporting Council (IIRC) recommendations, the ISO 26000 standardisation (ISO 26000) and the United Nations Global Compact. These frameworks have been instrumental in shaping the integration of SLCA within corporate strategies, underscoring the critical role of social sustainability in contemporary business operations (Bouillass, Blanc, and Perez-Lopez 2021).

On the corporate side, industries with substantial social impacts, are increasingly recognising the strategic value of SLCA. Companies are integrating SLCA into their decision-making processes to address better the social implications of their operations and supply chains. This trend underscores a broader understanding that addressing social sustainability is not only an ethical responsibility but also a strategic imperative in a marketplace that increasingly values corporate responsibility (Martínez-Blanco et al., 2015).

3.2. SLCA methodology

The term SLCA, as defined by the UNEP/SETAC guidelines, refers to a methodology that assesses social and socio-economic aspects of products and their potential impacts along their life cycle (UNEP SETAC 2009). The UNEP/SETAC guidelines have been instrumental in shaping SLCA practices, offering a framework that includes methodological sheets for subcategories of assessment, which help standardise the evaluation process (van Haaster et al. 2017). The primary focus of SLCA is on the consequences have on stakeholders involved in or affected by the product's life cycle (Thies et al. 2019).

SLCA shares a similar framework with LCA, as both methodologies are grounded in the ISO 14040 standards. The phases of SLCA, goal and scope definition, life cycle inventory analysis, life cycle impact

assessment, and interpretation, are aligned with those of LCA (Traverso et al., 2018). However, the phases of SLCA differ in their implementation and content. The goal and scope definition phase in SLCA requires the identification of stakeholders and the relevant social themes, as well as the selection of inventory indicators and impact assessment methods. Stakeholder categories, as suggested by UNEP (2020) (UNEP Life Cycle Initiative and Social LC Alliance 2020), include workers, local communities, consumers, society, value chain actors, and children. Each stakeholder group is associated with specific impact subcategories, which address various social themes such as human rights, working conditions, and cultural heritage (Ardolino, Palladini, and Arena 2023).

Another emerging methodology in the field is Social Organisational Life Cycle Assessment (SO-LCA), which extends the SLCA framework to evaluate the social and socio-economic aspects of an entire organisation, rather than just individual products. Introduced in 2015 (Martínez-Blanco et al. 2015) and further outlined in the UNEP 2020 Guidelines (UNEP Life Cycle Initiative and Social LC Alliance 2020), SO-LCA addresses the activities of an organisation from a life cycle perspective. This methodology combines elements of Organisational Life Cycle Assessment (O-LCA) and SLCA, providing a comprehensive approach to assessing the social impacts associated with an organisation's activities (D'Eusano, Tragnone, and Petti 2022). Although SO-LCA is still relatively underutilised, it represents a significant step forward in the evolution of SLCA, offering a framework for more holistic assessments that consider both organisational and product-level impacts.

3.2.1. Social impact categories and metrics

In SLCA, identifying and selecting appropriate social impact categories, indicators, and metrics are critical for effectively assessing the social impacts associated with the life cycle of a product. SLCA seeks to analyse both positive and negative social impacts across all stages of a product's life cycle, focusing on the effects these activities have on various stakeholders (Ekener, Hansson, and Gustavsson 2018). Sector-specific considerations often guide the selection of social impact categories and indicators, as different industries may prioritise different social impacts based on their unique socio-economic contexts (Bouillass, Blanc, and Perez-Lopez 2021; Fattahi, Govindan, and Farhadkhani 2021). In order to better understand how social impact subcategories are applied across different engineering disciplines, a comprehensive mapping of their usage was conducted and is presented in Table 3. This table illustrates the frequency and distribution of social subcategories across engineering fields including energy, mechanical, civil, chemical, materials, industrial, mining, supply chain (SC), and electronics.

To contextualise the subcategory distribution presented in Table 3, it is useful to recall the number of publications reviewed per field: energy (58), mechanical engineering (37), civil engineering (25), chemical engineering (22), material engineering (12), industrial engineering (7), mining (6), supply chain (6), and electronics (5). Across all engineering domains, there is a clear and consistent emphasis on worker-related subcategories, particularly health and safety, fair salary, working hours, child labour, forced labour, and equal opportunities, as well as on local community subcategories like local employment and safe and healthy living conditions. This aligns with the fact that most SLCA studies in engineering contexts focus on material sourcing, manufacturing, and supply chain operations, where impacts on labour and nearby communities are most pronounced.

Despite these commonalities, several distinctions emerge across engineering fields. Energy, in particular, stands out for its inclusion of energy-specific subcategories that are not addressed in other fields. These include societal-level concerns such as the availability of renewable energy resources, depletion of fossil fuel reserves, and energy security, and consumer-level issues like choices of electricity generation options, bioenergy quality, and inequality of electricity costs. This reflects the sector's systemic role in national infrastructure and sustainability transitions. Mechanical engineering, while also heavily focused on worker well-being, shows a distinct emphasis on operational and organizational aspects, including worker training and education, ergonomic design, and employee satisfaction. Under the consumer dimension, mechanical engineering discusses quality of product and services, product and service labelling, and marketing and communication, suggesting a stronger concern for end-user interaction and product delivery. In civil engineering, the consumer subcategory quality of products and services is more prominent compared to other fields likely due to the nature of infrastructure projects, where service reliability, safety, and usability are central social considerations. Chemical engineering displays a broader distribution of subcategories but

Table 3. Number of papers within each engineering field that address specific social subcategories by stakeholder group, based on SLCA methodological sheets. Note: since individual papers may cover multiple subcategories within the same stakeholder group, the totals may exceed the number of papers reviewed.

Stakeholders	Impact Subcategory	Engineering Areas (# of publications discussed the impact subcategory)
Worker	Working hours	Energy (27), Mechanical (11), Civil (10), Chemical (9), Material (7), Industrial (1), Mining (4), SC (4), Electronics (3)
	Health and Safety	Energy (42), Mechanical (24), Civil (13), Chemical (15), Material (11), Industrial (3), Mining (5), SC (3), Electronics (3)
	Child labour	Energy (29), Mechanical (12), Civil (6), Chemical (10), Material (5), Industrial (1), Mining (5), SC (5), Electronics (2)
	Freedom of Association and Collective Bargaining	Energy (21), Mechanical (8), Civil (7), Chemical (13), Material (6), Industrial (1), Mining (4), SC (5), Electronics (3)
	Forced labour	Energy (30), Mechanical (10), Civil (7), Chemical (8), Material (5), Industrial (1), Mining (2), SC (5), Electronics (2)
	Fair salary	Energy (33), Mechanical (17), Civil (13), Chemical (13), Material (7), Industrial (1), Mining (6), SC (5), Electronics (3)
	Equal opportunities/Discrimination	Energy (32), Mechanical (12), Civil (10), Chemical (14), Material (5), Industrial (3), Mining (4), SC (5), Electronics (3)
	Social benefits/Social security	Energy (18), Mechanical (4), Civil (5), Chemical (8), Material (3), Industrial (3), Mining (3), SC (2), Electronics (2)
	Employment relationship	Mechanical (2), Material (1), Industrial (2), Mining (2)
	Small-holders rights	
	Sexual harassment	Energy (1), Mining (1)
	Training and education	Mechanical (4), Civil (4), Chemical (5), Material (1), Industrial (2), Mining (1)
	Working environment ergonomic design	Mechanical (3), Industrial (1), Mining (1)
	Employee satisfaction	Mechanical (2), Chemical (1), Material (2), Industrial (1)
	Local employment	Energy (30), Mechanical (14), Civil (13), Chemical (12), Material (7), Industrial (1), Mining (4), SC (1), Electronics (2)
Local Community	Respect of local people's life/rights	Energy (16), Mechanical (8), Civil (3), Chemical (5), Material (2), Industrial (1), Mining (4), SC (3), Electronics (1)
	Access to material resources	Energy (12), Mechanical (1), Civil (10), Chemical (7), Material (5), Industrial (2), Mining (3), SC (2), Electronics (2)
	Access to immaterial resources	Energy (7), Mechanical (1), Civil (3), Chemical (2), Mining (1), SC (1), Electronics (2)
	Delocalization and migration	Energy (12), Mechanical (3), Civil (3), Chemical (3), Material (3), Industrial (2), Mining (4), Electronics (2)
	Cultural heritage	Energy (8), Mechanical (1), Civil (4), Chemical (2), Material (1), Industrial (2), Mining (1), SC (1), Electronics (2)
	Safe and healthy living conditions	Energy (25), Mechanical (8), Civil (12), Chemical (11), Material (7), Industrial (3), Mining (5), SC (4), Electronics (2)
	Community engagement	Energy (17), Mechanical (3), Civil (9), Chemical (5), Material (2), Industrial (3), Mining (2), SC (1), Electronics (1)
	Secure living conditions	Energy (7), Mechanical (3), Civil (4), Chemical (2), Material (2), Industrial (1), SC (2), Electronics (2)
	Value added total	Energy (3), Civil (1), Industrial (1)
	Food security	Energy (2), Chemical (2)
Society	Waste management	Mechanical (1), Civil (2), Mining (1)
	Public commitments to sustainability issues	Energy (15), Mechanical (2), Civil (9), Chemical (6), Material (2), Industrial (3), Mining (1), Electronics (2)
	Contribution to economic development	Energy (18), Mechanical (6), Civil (9), Chemical (4), Material (5), Industrial (4), Mining (5), Electronics (2)
	Prevention and mitigation of armed conflicts	Energy (9), Mechanical (4), Civil (1), Chemical (2), Material (2), Industrial (2), SC (1), Electronics (2)
	Technology/development	Energy (11), Mechanical (3), Civil (8), Chemical (4), Material (4), Industrial (3), Mining (1), Electronics (2)
	Corruption	Energy (22), Mechanical (8), Civil (2), Chemical (5), Material (4), Industrial (3), Mining (4), SC (1), Electronics (1)
	Health and Safety	Energy (10), Mechanical (5), Civil (2), Chemical (3), Material (1), Mining (1), SC (1)
	Resource conservation	Energy (5), Mechanical (1), Mining (1)
	External trade	Energy (1)
	Energy Security	Energy (6)
	Ethical treatment of animals	Material (1)
	Poverty alleviation	Energy (4), Mechanical (2), Chemical (2), Mining (1), SC (2)
	Nuclear proliferation	Energy (1)
	Intergenerational equity	Energy (2)
	Depletion of fossil fuel reserves	Energy (1)
	Availability of renewable energy resources	Energy (2)

(Continued)

Table 3. (Continued).

Stakeholders	Impact Subcategory	Engineering Areas (# of publications discussed the impact subcategory)
Consumer	Health and Safety	Energy (5), Mechanical (4), Civil (6), Chemical (3), Material (2), Industrial (3), SC (1), Electronics (2)
	Feedback mechanism	Energy (6), Mechanical (3), Civil (3), Chemical (2), Material (1), Industrial (3), SC (2), Electronics (2)
	Consumer privacy	Energy (3), Mechanical (3), Civil (1), Chemical (1), Material (1), Industrial (1), SC (2), Electronics (2)
	Transparency	Energy (3), Mechanical (1), Civil (2), Chemical (3), Industrial (3), SC (2), Electronics (2)
	End of life responsibility	Energy (2), Mechanical (1), Civil (4), Chemical (5), Material (2), Industrial (2), SC (2), Electronics (2)
	Bioenergy quality	Energy (1)
	Choices of electricity generation options	Energy (2)
	Inequality of electricity costs	Energy (1)
	Quality of product/services	Energy (2), Mechanical (5), Civil (6)
	Product and service labelling	Mechanical (1), Civil (1)
	Marketing and communication	Mechanical (1)
Value Chain	Fair competition	Energy (10), Mechanical (4), Civil (6), Chemical (3), Material (2), Industrial (2), Mining (3), SC (2), Electronics (2)
	Promoting social responsibility	Energy (7), Mechanical (2), Civil (5), Chemical (4), Material (2), Industrial (1), Mining (2), SC (1), Electronics (2)
	Supplier relationships	Energy (7), Mechanical (2), Civil (4), Chemical (1), Material (2), Industrial (2), SC (1), Electronics (2)
	Respect of intellectual property rights	Energy (2), Mechanical (2), Civil (2), Chemical (1), Industrial (1), SC (2), Electronics (1)
	Public sector corruption	Energy (1), Civil (1)
	Contribution of sector to economic development	Energy (1), Mechanical (1)

leans toward worker well-being concerns, including health and safety, freedom of association, fair salary, and equal opportunities.

Fields with fewer studies demonstrate more targeted focus areas. For instance, mining emphasises high-risk subcategories such as forced labour, child labour, and social benefits, reflecting the social sensitivities of extractive operations. Supply chain-focused studies tend to highlight transparency, fair competition, and supplier relationships, centring on upstream governance and social risk. Electronics, despite limited representation, address a broad range of subcategories from each stakeholder.

This analysis shows that while worker and community categories dominate SLCA studies across engineering fields, the selection of subcategories varies contextually shaped by the technical characteristics, stakeholder dynamics, and life cycle stages most relevant to each domain.

Impact subcategories are assessed through corresponding impact indicators that are defined in the UNEP/SETAC methodological sheets (UNEP SETAC 2009). These indicators are directly linked to the life cycle inventory of a product and are selected based on the availability, type, and quality of data (Stoycheva et al. 2022). The application of specific indicators is thus often influenced by the granularity and accessibility of relevant information (Liu and Qian 2019). Indicators can be broadly classified as quantitative, semi-quantitative, or qualitative, depending on how the social issue is defined and measured (Bouillass, Blanc, and Perez-Lopez 2021). For example, a quantitative indicator might report the number of accidents per unit process, whereas a qualitative indicator could describe stress management practices within a company. Semi-quantitative indicators typically involve scoring systems or yes/no responses that categorise qualitative insights into measurable formats (Serra et al. 2022). Beyond data type, indicators are further divided into additive and descriptive forms (Hosseiniyou, Mansour, and Shirazi 2014). Additive indicators are measurable in numeric terms and can be directly related to the functional unit (FU) of a product. For instance, in the “health and safety” subcategory under the “worker” stakeholder group, a typical additive indicator might be the number or percentage of injuries or fatal accidents per unit of product output. These indicators allow direct comparisons across products or processes, supporting more structured and quantitative decision-making in engineering contexts. In contrast, descriptive indicators, while they can sometimes be measured quantitatively, cannot be directly linked to a product’s FU. An example is the “living wage” indicator under the “workers” stakeholder group. Although the living wage can be expressed as a dollar value, it is not typically normalised to a unit of product or service and therefore cannot be

integrated into product-level impact aggregation in the same way. This distinction is particularly relevant in engineering applications, where a balance must be struck between data-driven modelling and the representation of complex, often intangible, social dynamics. Therefore, indicator selection in SLCA must carefully consider not only relevance to stakeholder concerns but also data type, linkage to the FU, and suitability to the goals of the study.

The FU is a measure of the performance of the functional outputs of the product system (UNEP SETAC 2009). Its primary purpose is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure consistency and comparability across product systems. Despite the foundational role of the FU in life cycle methodologies, its application in SLCA presents unique challenges. This is largely due to the qualitative nature of many social indicators, which complicates their direct attribution to product outputs. The challenge is further amplified by the fact that social data are often collected at the organizational or sectoral level, rather than at the product level (Martínez-Blanco et al. 2015). As a result, while most SLCA studies define an FU during the goal and scope phase, they do not always apply it consistently when reporting or interpreting results (Siebert et al. 2018b). In some cases, the FU is considered irrelevant due to the disconnect between product-level analysis and the organizational drivers of social impact. However, according to UNEP/SETAC guidelines, it remains necessary to define the functional unit, as well as the product utility (function), since this provides the essential basis for modelling the product system (van Haaster et al. 2017). Moreover, when additive indicators are used, expressing results per FU becomes critical especially for interpreting social performance against thresholds, benchmarking across systems, or supporting decision-making through multi-criteria assessment methods.

An analysis of FU usage across the reviewed SLCA studies has been conducted, depending on the engineering domain, as shown in Table 4. In the energy sector, the most prevalent FU is defined per unit of generated energy, such as per kWh or MWh, which aligns with the field's emphasis on evaluating the social implications of energy generation performance. Some energy studies also use alternative FUs, such as per unit of product or labour-hours, while a notable proportion (23 out of 58) do not define an FU. In mechanical engineering, there is a broader variety of FU types, including per unit of product, annual production, unit output, or even saved time for an employee. However, more than half of the mechanical studies reviewed did not specify an FU. Civil engineering studies often define the FU based on unit structure, such as per bridge or building, which is appropriate given the sector's service-oriented outputs. Similar trends are observed in chemical and material engineering, where studies employ various FU types such as per unit of product, monetary output, or annual operations, but almost half of the reviewed papers omit FU reporting. In fields such as mining, supply chain, and electronics, FUs are mostly defined per unit of product or monetary value, yet several studies still report no FU. These findings highlight the lack of standardisation in FU definition and application within SLCA studies.

3.2.2. Data collection methods, challenges and databases

The inventory phase of SLCA is critical for gathering the necessary data to model systems and obtain life cycle impact assessment (LCIA) results. This phase directly follows the initial stages of defining the goals and boundaries of the study and is foundational in evaluating the social impacts of products throughout their life cycle. The data collection process in SLCA is multifaceted and can be broadly categorised into primary (site-specific) and secondary (generic) data (Hosseiniyou, Mansour, and Shirazi 2014). Site-specific data provide detailed, context-specific information directly from the case study. Generic data refers to data not collected on-site (with interested parties). Even data collected from other producers of the same product type in the same country as that of the life cycle stage under study is still considered generic as it may not be representative of the impacts of the particular supply chain (Serra et al. 2022).

The effectiveness of SLCA in engineering largely depends on the robustness of the data collection methods used. Accurate and comprehensive data collection is crucial for accurately assessing social impacts and ensuring that the findings are reliable and actionable. In SLCA, data collection typically involves a combination of qualitative, quantitative, and semi-quantitative approaches, each tailored to capture different dimensions of social impacts within engineering projects.

Quantitative data collection methods in SLCA often include existing databases, government reports, and industry statistics to measure social indicators (Serra et al. 2022). Qualitative data collection involves the use of interviews, focus groups, and surveys (Aschehoug, Schulte, and Bjørnset 2016). These methods are

Table 4. Analysis of fu usage across engineering fields.

Engineering Area	Functional unit	
Energy	Per unit of generated energy	(Alidoosti et al. 2021; Atilgan and Azapagic 2017; Aung, Fischer, and Azmi 2021; Azapagic et al. 2016; Berridy-Segade et al. 2024; Buchmayr et al. 2022; Cooper, Stamford, and Azapagic 2018; Corona and San Miguel 2019; Corona et al. 2017; Do Carmo, Margni, and Baptiste 2016, 2017a, 2017b; Ekener, Hansson, and Gustavsson 2018; Fattahi, Govindan, and Farhadkhani 2021; Hansson et al. 2024; Koese et al. 2023; Masilela and Pradhan 2021; Popien et al. 2023; Puentes Bejarano et al. 2024; van Haaster et al. 2017)
	Per unit of product	(Campos-Carriedo, Dufour, and Iribarren 2024; Egbue 2012; Guarino, Cellura, and Traverso 2020; Kolotzek et al. 2018; Schlör et al. 2018; Y. Shi et al. 2023; Silva et al. 2024; Thies et al. 2019; Weldegiorgis and Franks 2014; Werker, Wulf, and Zapp 2019)
	Labour-hours	(Gan Yupanqui et al. 2024; Martinez-Hernandez et al. 2022; Sathukhan, Sen, and Gadkari 2021; Stougie and Van Der Kooi 2016; Stougie, Delgado, and Van Der Kooi 2015)
	No FU	(Akhtar et al. 2023; Alidoosti et al. 2021; Atilgan and Azapagic 2017; Aung, Fischer, and Azmi 2021; Azapagic et al. 2016; Baltrocchi et al. 2023; Berridy-Segade et al. 2024; Borri, Zsembinski, and Cabeza 2024; Buchmayr et al. 2022; Cadena et al. 2019; Campos-Carriedo, Dufour, and Iribarren 2024; Chingono and Mbohwa 2015; Contreras-Lisperguer et al. 2018; Cooper, Stamford, and Azapagic 2018; Corona and San Miguel 2019; Corona et al. 2017; Do Carmo, Margni, and Baptiste 2016, 2017a, 2017b; Egbue 2012; Ekener, Hansson, and Gustavsson 2018; Fattahi, Govindan, and Farhadkhani 2021; Fortier et al. 2019; Gan Yupanqui et al. 2024; Ghaderi, Moini, and Pishvaei 2018; Guarino, Cellura, and Traverso 2020; Hansson et al. 2024; Kaiser et al. 2022; Koese et al. 2023; Kolotzek et al. 2018; Kouloumpis and Azapagic 2018; A. Lehmann et al. 2013; J. Lehmann et al. 2024; Manik, Leahy, and Halog 2013; Martinez-Hernandez et al. 2022; Masilela and Pradhan 2021; Messmann et al. 2023; Nubi, Morse, and Murphy 2021; Osorio-Tejada et al. 2022; Popien et al. 2023; Puentes Bejarano et al. 2024; Reuter 2016; Sathukhan, Sen, and Gadkari 2021; A. Sánchez et al. 2024; Santoyo-Castelazo and Azapagic 2014; Schlör et al. 2018; Y. Shi et al. 2023; Silva et al. 2024; Souza et al. 2018, 2021; Stougie, Delgado, and Van Der Kooi 2015; Stougie and Van Der Kooi 2016; Thies et al. 2019; van Haaster et al. 2017; Z. Wang, Osseweijer, and Duque 2018; Weldegiorgis and Franks 2014; Werker, Wulf, and Zapp 2019; Y. Wu et al. 2017)
Mechanical Engineering	Per unit of product	(Arvidsson et al. 2018; Aschehoug, Schulte, and Bjørnbet 2016; Ben Ruben, Menon, and Sreedharan 2018; Haddad et al. 2023; Islam, Hildenbrand, and Hossain 2018; Jiang et al. 2018; Luthe, Kägi, and Reger 2013; Luthin, Knacksterdt, and Traverso 2024; Navarro et al. 2024; Pastor et al. 2018)
	Annual production of product	(Baumann et al. 2013; Kluczek and Gladysz 2020)
	Per unit process	(Bhanot, Rao, and Deshmukh 2016a; Chang et al. 2015; J. Shi et al. 2024)
	Unit output of the product system	(Bouillass, Blanc, and Perez-Lopez 2021; Chen, Jiang, and Jin 2024; Pillain et al. 2019; Serra et al. 2022)
	Saved time for one employee	(Walters and Mirkouei 2020)
	No FU	(Agyekum, Fortuin, and van der Harst 2017; Bhanot, Rao, and Deshmukh 2016b; Hadler, Brenner-Fliesser, and Kaltenegger 2023; Mair-Bauernfeind et al. 2020; Naghshineh et al. 2020; Peruzzini et al. 2017; Singh and Gupta 2018; Soares et al. 2021; Zimmer et al. 2017)
Civil	Per unit structure	(Balasbaneh et al. 2021; Balasbaneh, Bin Marsono, and Khaleghi 2018; Dong and Ng 2016; Evans et al. 2020; Fauzi et al. 2022; Hosseinijou, Mansour, and Shirazi 2014; Inti and Tandon 2021; Inti, Sharma, and Tandon 2019; Kayaçetin, Piccardo, and Versele 2023; Liu and Qian 2019; Navarro, Marti, and Yepes 2023; Shang et al. 2018; Vitorio Junior and Kripka 2020)
	Per unit product	(Ferrazzo, Tonini de Araújo, and Consoli 2024; Loreau, Stephan, and Cooper 2024; San Vicente-Navarro et al. 2024)
	No FU	(Hossain et al. 2018; Mhatre-Shah, Gedam, and Unnikrishnan 2023; Ying and Yang 2014; Zheng et al. 2019)
Chemical Engineering	Per unit product	(Lizasoain-Arteaga et al. 2024; Marting Vidaurre, Lewandowski, and Lask 2022; Tsalidis 2022; Tsalidis et al. 2023; Valente, Brekke, and Modahl 2018; Visentin et al. 2022)
	Annual production of product	(Pucciarelli, Traverso, and Lettieri 2021; Serreli et al. 2021; V. Subramanian et al. 2018)
	Unit operation plant	(Tsalidis et al. 2020)
	Per unit monetary output of the system	(Orola, Uusitalo, and Levänen 2024)
	No FU	(M. Hannouf and Assefa 2018; Jungmeier et al. 2015, 2016; Lizasoain-Arteaga et al. 2024; Marting Vidaurre, Lewandowski, and Lask 2022; Orola, Uusitalo, and Levänen 2024; Popovic and Kraslawski 2018; Pucciarelli, Traverso, and Lettieri 2021; Rafiaani et al. 2020; Reinales, Zambrana-Vasquez, and Saez-De-Guinoa 2020; Ren et al. 2015; Serreli et al. 2021; Siebert et al. 2018, 2018a, 2018b; V. Subramanian et al. 2018; Tsalidis 2022; Tsalidis et al. 2020, 2023; Valente, Brekke, and Modahl 2018; Visentin et al. 2022; Xu et al. 2017)
Material Engineering	Per unit product	(Di Giorgio et al. 2024; Krekel, Suer, and Traverso 2024; S. Sánchez et al. 2019; Springer, Wulf, and Zapp 2024; Traverso et al. 2018)
	Annual operation	(Ardolino, Palladini, and Arena 2023; Zhang, Bhuiyan, and Zhang 2024)
Industrial Engineering	No FU	(Haslinger et al. 2024; La Rosa, Valente, and Aradoaei 2024; Stoycheva et al. 2022)
	Work hour per unit product	(P. C. Wang et al. 2011)
	No FU	(M. B. Hannouf et al. 2024; Papetti et al. 2020; Popovic et al. 2018; Sandionigi et al. 2024; Sutherland et al. 2016; Walker et al. 2021; P. C. Wang et al. 2011)

(Continued)

Table 4. (Continued).

Engineering Area	Functional unit	
Mining	Per unit product	(Muller et al. 2021; Roche et al. 2024; S. R. Wu et al. 2019)
	Per unit monetary output of the system	(Cecere et al. 2024; Di Maria et al. 2024)
Supply Chain	No FU	(Di Noi et al. 2020)
	Per unit product	(Muñoz-Torres et al. 2023)
	Per unit monetary output of the system	(Benoit-Norris, Cavan, and Norris 2012; Norris, Aulisio, and Norris 2012)
	No FU	(Benoit-Norris, Cavan, and Norris 2012; D'Eusano, Tragnone, and Petti 2022; Hannibal and Kauppi 2019; Mogos et al. 2024; Muñoz-Torres et al. 2023; Norris, Aulisio, and Norris 2012)
Electronics	Per unit product	(Ekener-Petersen and Finnveden 2013; K. Subramanian and Yung 2018)
	No FU	(Ekener-Petersen and Finnveden 2013; Ekener-Petersen and Moberg 2013; K. Subramanian and Yung 2018; Suckling and Lee 2017; S. W. Wang, Hsu, and Hu 2016)

particularly effective for capturing the nuanced perspectives of stakeholders, including workers, community members, and local authorities (Cadena et al. 2019).

Despite the availability of data collection methods, SLCA faces several challenges, particularly concerning the quality and representativeness of the data. One of the primary challenges is the difficulty in linking social indicators and impacts directly to specific products. This challenge is exacerbated by the complex and often opaque nature of global supply chains, where the social impacts of production activities can vary widely depending on the geographic and socio-economic context. Additionally, the lack of standardised procedures for addressing data gaps and ensuring data completeness further complicates the SLCA process. For instance, while highly detailed, site-specific data are often difficult to obtain in sufficient quality and quantity, especially for products with extensive and complex supply chains, this limitation necessitates the use of generic data, which, while useful, may not fully capture the specific social risks associated with individual supply chains (Fauzi et al. 2022).

To support data collection in SLCA and address some of the challenges, two databases have been developed: the Social Hotspots Database (SHDB) and the Product Social Impact Life Cycle Assessment (PSILCA).

The SHDB is a comprehensive global database identifying potential social risks or “hotspots” within supply chains (Benoit-Norris, Cavan, and Norris 2012). It is particularly valuable for practitioners needing to prioritise site-specific data collection in areas where social risks are highest. The SHDB provides contextual information. Contextual data represent the typical social situation in a country and economic sector/industry. Once the selection of countries as possible suppliers for each of the inputs is completed, the SHDB is used to collect the risk levels relating to each country and to the specific industrial sector (Serra et al. 2022). The SHDB uses a multi-regional input-output model based on the Global Trade Analysis Project (GTAP) and includes data on 6,441-unit processes across 113 regions and 67 industry sectors. The database categorises social risks into qualitative levels—low, medium, high, and very high—allowing users to aggregate these risks across different processes to identify critical hotspots within the supply chain. (Thies et al., 2019).

The PSILCA database, developed by GreenDelta, is another database for SLCA. PSILCA provides comprehensive social impact data, utilising the EORA multi-regional input/output database as its foundation (Di Noi et al. 2020). PSILCA is a country-specific sector (CSS) database (Koese et al. 2023). It covers 189 different countries, for which a wide range of sectors are attributed, with around 15,000 different sectors. Both inputs (materials and products provided by other sectors) and outputs (generated products) of a CSS are expressed in USD (Bouillass, Blanc, and Perez-Lopez 2021). The database includes both qualitative and quantitative social indicators across various stakeholder categories, including workers, local communities, society, and value chain actors. Regarding these indicators, data is provided as risks, with a scale ranging from no/very low risk to very high risk. A positive evaluation in terms of opportunities is also available. PSILCA quantifies social risks using an activity variable, typically worker hours, and scales these risks according to their severity, expressed in medium-risk hour equivalents (Di Noi et al. 2020).

While both SHDB and PSILCA offer extensive resources for conducting SLCA, they also come with certain limitations. For instance, SHDB’s reliance on the GTAP model means that its granularity is limited

to the sector and country level, which may not fully capture the specific social dynamics within individual supply chains (Schlör et al. 2018). Similarly, PSILCA, while more detailed in its sector-specific data, often relies on generic indicators that may not reflect the nuanced social conditions of particular industries or regions. Despite these challenges, these databases represent significant advancements in the field of SLCA, providing essential tools for identifying and assessing social risks across global supply chains (Bouillass, Blanc, and Perez-Lopez 2021).

SLCA has an inherently site-specific and geographically sensitive nature. Whether through direct comparison of site-specific data with national policies or the use of country- or sector-level databases, geographic context plays a critical role in shaping social impact outcomes. Table 5 presents the countries where the reviewed SLCA studies were conducted across each engineering discipline. Among them, the energy field exhibits the highest number of cross-country comparisons, particularly in studies assessing different energy sources. This reflects the globalised nature of energy systems and the importance of regional variations in social, environmental, and economic conditions. Many of these multi-country studies in the energy sector rely on SHDB or PSILCA to incorporate location-based differences in social risks. These databases enable researchers to compare national contexts and embed geographic variability into SLCA interpretations, thereby enhancing the relevance and robustness of sustainability decision-making.

Table 5. Geographic distribution of reviewed SLCA studies across engineering fields.

Engineering Area	Geographic Location
Energy	Africa (Masilela and Pradhan 2021), Australia (Weldegiorgis and Franks 2014), Bolivia (Baltrocchi et al. 2023), Brazil (Souza et al. 2018, 2021; Z. Wang, Osseweijer, and Duque 2018), Canada (Do Carmo, Margni, and Baptiste 2016, 2017b), Chile (Egbue 2012), China (Y. Wu et al. 2017), EU (Buchmayr et al. 2022; Campos-Carriedo, Dufour, and Iribarren 2024; Ekener, Hansson, and Gustavsson 2018; Hansson et al. 2024; Messmann et al. 2023; van Haaster et al. 2017), France (J. Lehmann et al. 2024), Germany (Gan Yupanqui et al. 2024; Popien et al. 2023), Indonesia (A. Lehmann et al. 2013; Manik, Leahy, and Halog 2013), Iran (Fattahi, Govindan, and Farhadkhani 2021; Ghaderi, Moini, and Pishvae 2018), Italy (Guarino, Cellura, and Traverso 2020; Kaiser et al. 2022), Jamaica (Contreras-Lisperguer et al. 2018), Mexico (Martinez-Hernandez et al. 2022; Santoyo-Castelazo and Azapagic 2014), Myanmar (Aung, Fischer, and Azmi 2021), Netherlands (Cadena et al. 2019; Stougie and Van Der Kooi 2016; Stougie, Delgado, and Van Der Kooi 2015), Nigeria (Nubi, Morse, and Murphy 2021), South Africa (Chingono and Mbohwa 2015), Spain (Berridy-Segade et al. 2024; Corona and San Miguel 2019; Corona et al. 2017; A. Sánchez et al. 2024), Sweden (Puentes Bejarano et al. 2024), Turkey (Atilgan and Azapagic 2017), UK (Azapagic et al. 2016; Cooper, Stamford, and Azapagic 2018; Kolotzek et al. 2018; Sadhukhan, Sen, and Gadkari 2021), China-Germany (Koeset et al. 2023), Argentina-Malaysia-USA-Canada (Do Carmo, Margni, and Baptiste 2017a), USA-Chile-South Africa-Saudi Arabia-Oman-China-Australia (Akhtar et al. 2023), Colombia-Spain-Malaysia (Osorio-Tejada et al. 2022), Congo-China-Zambia-Australia-Canada (Reuter 2016), Australia-Malaysia-USA-China (Schlör et al. 2018), China-Japan-South Korea (Y. Shi et al. 2023), Germany-Austria-Spain (Werker, Wulf, and Zapp 2019), Germany-Austria-Spain-Italy-Greece-UK-Switzerland-Japan (Borri, Zsembinski, and Cabeza 2024), Brazil-Chile-Mexico (Silva et al. 2024)
Mechanical Engineering	Austria (Mair-Bauernfeind et al. 2020), Canada (Walters and Mirkouei 2020), China (Jiang et al. 2018), EU (Peruzzini et al. 2017), France (Bouillass, Blanc, and Perez-Lopez 2021; Pillain et al. 2019), Germany (Chang et al. 2015; Luthe, Kägi, and Reger 2013; Luthin, Knacksterdt, and Traverso 2024; Zimmer et al. 2017), Ghana (Agyekum, Fortuin, and van der Harst 2017), India (Ben Ruben, Menon, and Sreedharan 2018; Singh and Gupta 2018), Italy (Serra et al. 2022), Norway (Aschehoug, Schulte, and Bjørnset 2016), Spain (Navarro et al. 2024), UK (Haddad et al. 2023; Naghshineh et al. 2020), Belgium-China-USA (Hadler, Brenner-Fliesser, and Kaltenegger 2023), China-Germany-South Africa (Pastor et al. 2018), China-Japan-South Korea (Chen, Jiang, and Jin 2024)
Civil Engineering	Belgium (Kayaçetin, Piccardo, and Versele 2023), Brazil (Vitorio Junior and Kripka 2020), China (Shang et al. 2018; Ying and Yang 2014; Zheng et al. 2019), Hong Kong (Dong and Ng 2016; Hossain et al. 2018), India (Mhatre-Shah, Gedam, and Unnikrishnan 2023), Iran (Hosseinijou, Mansour, and Shirazi 2014), Malaysia (Balasbaneh et al. 2021; Balasbaneh, Bin Marsono, and Khaleghi 2018), Singapore (Liu and Qian 2019), Spain (San Vicente-Navarro et al. 2024), USA (Evans et al. 2020; Inti and Tandon 2021; Inti, Sharma, and Tandon 2019), Canada-China (Fauzi et al. 2022), China-Italy-Czechia (Loreau, Stephan, and Cooper 2024)
Chemical Engineering	Belgium (Lizasoain-Arteaga et al. 2024; Rafiaani et al. 2020), Canada (M. Hannouf and Assefa 2018), China (Ren et al. 2015), Croatia (Marting Vidaurre, Lewandowski, and Lask 2022), EU (Jungmeier et al. 2016; Pucciarelli, Traverso, and Lettieri 2021), Germany (Siebert et al. 2018, 2018a, 2018b), Italy (Serrelli et al. 2021; Tsalidis et al. 2023), Netherlands (Tsalidis 2022), Norway (Valente, Brekke, and Modahl 2018), Netherlands-Spain-Poland-Turkey (Tsalidis et al. 2020), Brazil-Canada-China-the Czech Republic-Germany-India-Japan-Switzerland-UK-USA (Visentin et al. 2022), Finland-Congo-Indonesia-Australia-South Africa-China (Orola, Uusitalo, and Levänen 2024)
Material Engineering	Australia (Zhang, Bhuiyan, and Zhang 2024), Cuba (S. Sánchez et al. 2019), EU (Haslinger et al. 2024; La Rosa, Valente, and Aradoaei 2024; Stoycheva et al. 2022), Germany (Krekel, Suer, and Traverso 2024; Springer, Wulf, and Zapp 2024), Italy (Di Giorgio et al. 2024), US (Traverso et al. 2018)
Industrial Engineering	Italy (Papetti et al. 2020), Italy-Netherlands (Walker et al. 2021), France-Germany (P. C. Wang et al. 2011)
Mining	Bosnia and Herzegovina (Muller et al. 2021), Chile (Roche et al. 2024), EU (Cecere et al. 2024; Di Noi et al. 2020), Finland (Di Maria et al. 2024), USA (S. R. Wu et al. 2019)
Supply chain Electronics	USA (Benoit-Norris, Cavan, and Norris 2012; Norris, Aulisio, and Norris 2012) Taiwan (S. W. Wang, Hsu, and Hu 2016)

In contrast to energy field, SLCA studies in other engineering fields tend to focus on single-country case studies and less frequently incorporate explicit geographic comparisons. In many cases, particularly when the objective is framework development or the evaluation of design alternatives within the same region, geographic information is either briefly mentioned or entirely absent. This underlines a missed opportunity to integrate contextual social factors, especially when local conditions can significantly influence SLCA outcomes.

3.2.3. *Social life cycle impact assessment*

The impact assessment phase of SLCA is critical for evaluating the social impacts identified during the data collection phase. This phase involves applying specific methodologies designed to measure and interpret the social impacts associated with engineering projects. Two primary approaches are commonly used in SLCA impact assessment: the reference scale approach (Type I) and the impact pathway approach (Type II) (UNEP Life Cycle Initiative and Social LC Alliance 2020).

The reference scale approach (Type I) is one of the most widely utilised methods in SLCIA. This approach involves comparing the social performance of a product or project against predefined benchmarks or standards, often derived from international conventions, such as those set by the International Labour Organisation (ILO) and the Organisation for Economic Co-operation and Development (OECD) (Marting Vidaurre, Lewandowski, and Lask 2022). Type I methods assess social impacts based on ordinal scales, where results are expressed regarding risk, performance, or the degree of management of social issues (Benoît-Norris et al. 2011).

A key characteristic of Type I methods is the use of Performance Reference Points (PRPs), which serve as thresholds to evaluate the extent to which an organisation or activity meets internationally recognised social norms (UNEP SETAC 2009). These PRPs help translate qualitative, quantitative, and semi-quantitative data into standardised scores, which can then be aggregated into impact categories or stakeholder categories (M. Hannouf and Assefa 2018). The Subcategory Assessment Method (SAM), a widely applied framework within Type I methods, exemplifies this process by converting diverse data types into semi-quantitative forms and comparing them against PRPs to assess organisational performance at multiple levels (Tsalidis 2022).

Type II method in social LCIA, known as the impact pathway approach, traces the causal relationships between activities and their social outcomes. This approach involves developing characterization models that establish cause-effect chains, linking inventory indicators to social impact subcategories and ultimately to broader impact categories (Souza et al. 2021). UNEP/SETAC (2009) has listed three endpoints impact categories: human capital, cultural heritage, and human well-being (UNEP SETAC 2009).

The impact pathway approach is particularly valuable in assessing the complex and multifaceted nature of social impacts, especially in contexts where these impacts are influenced by various factors beyond the immediate activities of a project. For example, the social effects of a large infrastructure project may depend not only on the direct outcomes, such as job creation or displacement, but also on broader contextual elements like local governance and socioeconomic conditions. By mapping these cause-effect relationships, Type II methods provide a deeper understanding of how social impacts arise and how they can be effectively mitigated (Pillain et al. 2019).

However, the implementation of SLCIA based on cause-effect chains are very limited. Establishing accurate cause-effect chains requires detailed, context-specific data, which can be difficult to obtain and analyse. This complexity often makes the approach more time-consuming and resource-intensive (Siebert et al. 2018).

Given the inherent complexities of evaluating social impacts, Multi-Criteria Decision-Making (MCDM) techniques are increasingly being integrated into SLCIA to determine the relevance of each indicator in the final social score (Navarro, Martí, and Yepes 2023). MCDM methods facilitate the comparison and weighting of different social impact indicators, allowing for more informed decisions when faced with multiple criteria.

One of the most commonly used MCDM techniques in social LCIA is the Analytic Hierarchy Process (AHP), which supports decision-making by structuring complex problems into a hierarchy of criteria and alternatives (Kolotzek et al. 2018). AHP involves pairwise comparisons of criteria to establish their relative importance, which is then used to determine the overall weightings for each

criterion in the decision-making process (Zimmer et al. 2017). The comparisons are typically conducted using Saaty's fundamental scale, which translates qualitative judgments into numerical values, enabling the construction of a square comparison matrix $A_{n \times n}$ where n is the number of criteria involved in the decision-making process (Navarro, Martí, and Yepes 2023). This structured approach allows for the integration of both qualitative and quantitative data types, accommodating additive indicators as well as descriptive ones. AHP is particularly advantageous in SLCA contexts because it enables decision-makers to synthesise both positive and negative social impacts across alternatives. Through the pairwise comparison process, positive effects (which should be maximized) and negative effects (which should be minimized) are transformed into relative preference scores, facilitating their inclusion in a unified scoring system (Hosseinijou, Mansour, and Shirazi 2014).

Despite its strengths, AHP has also been criticized for its sensitivity to inconsistency in human judgment, especially as the number of criteria increases. In complex SLCA applications involving numerous and diverse indicators, maintaining consistency in pairwise comparisons becomes increasingly difficult, potentially compromising the robustness of the results (Navarro, Martí, and Yepes 2023).

To address some of the limitations of AHP, alternative MCDM methods such as the Decision-Making Trial and Evaluation Laboratory (DEMATEL) and the Best-Worst Method (BWM) have been proposed. DEMATEL effectively analyses the interrelationships among criteria, classifying them into cause-and-effect groups, and is particularly useful for identifying key factors in complex systems (Kumar, Rehman, and Phanden 2022). One of DEMATEL's strengths lies in its ability to reduce the number of judgments required from experts, thereby simplifying the comparison process and improving the consistency of results, especially when used alongside AHP (Navarro, Martí, and Yepes 2023). Furthermore, DEMATEL can accommodate uncertainty and ambiguity in expert opinions through its fuzzy extension, making it a suitable tool for addressing complex social sustainability issues (Kumar, Rehman, and Phanden 2022).

On the other hand, BWM simplifies the decision-making process even further by relying on only the best and worst criteria for pairwise comparisons, significantly reducing the cognitive burden on decision-makers (Alidoosti et al. 2021). As it requires just $2n-3$ comparisons (compared to $n(n-1)/2$ in AHP), BWM is less data-intensive while still delivering stable and reliable outcomes due to its consistent structure. This makes it particularly useful in contexts with limited expert availability or when rapid decision-making is required.

Beyond isolated SLCA applications, MCDM techniques have also been widely adopted for the integration of SLCA with LCA and LCC assessments in holistic life cycle sustainability assessment frameworks. AHP has again been extensively applied in these settings to support the aggregation of results across sustainability dimensions. The method helps translate stakeholder or expert preferences into weights for social, environmental, and economic indicators, allowing for the derivation of an overall sustainability score. However, since weighting is inherently value-based, it requires to analyse the sensitivity of outcomes to different weighting scenarios before drawing final conclusions (Corona and San Miguel 2019).

Other MCDM approaches have also emerged to support integrated sustainability assessment. Multi-Attribute Value Theory (MAVT), for example, calculates a global sustainability score by developing partial value functions for each criterion. First, the value function is estimated for each scenario and indicator, typically based on a ranking scale. The sustainability score is then calculated using the value functions. Scenarios are ranked again according to their total scores, allowing decision-makers to determine the most sustainable option based on a consolidated metric. As with AHP, the robustness of MAVT outcomes should be tested using sensitivity analysis to assess how changes in indicator weights affect the scenario rankings (Santoyo-Castelazo and Azapagic 2014).

To address this uncertainty and imprecision in sustainability assessments, the FELICITA (Fuzzy Evaluation for Life Cycle Integrated Sustainability Assessment) model has been proposed (Kouloumpis and Azapagic 2018). This model employs fuzzy inference systems, which are well-suited for handling ambiguous or linguistically defined information. Unlike purely mathematical models that rely on precise numerical inputs, fuzzy inference allows for the use of verbal IF-THEN rules, which stakeholders and decision-makers often find more intuitive and relatable. In this context, fuzzy logic captures the "degrees of truth" associated with imprecise variables, enabling assessments where input values cannot be defined with certainty. This makes FELICITA particularly valuable for integrating SLCA with LCA and LCC in real-world engineering scenarios where subjective judgments and qualitative data are frequently encountered.

Another approach for dealing with uncertainty in multi-criteria assessments is the application of the PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) method. PROMETHEE is an MCDM technique that ranks alternatives based on a combination of criteria values, preference functions, and weighting schemes. It is particularly useful in contexts where subjective judgment needs to be minimized or excluded. For instance, in one study, stakeholder involvement was deliberately omitted to reduce bias and enhance feasibility (Wilken et al. 2020). Instead, the researchers applied six distinct weighting scenarios and nine preference scenarios, each representing different levels of sensitivity and performance thresholds across criteria. This structure allowed for a comprehensive exploration of how changes in assumptions or weights can affect the overall ranking of alternatives, thus offering a robust mechanism to handle variability and uncertainty in decision-making processes.

In addition to fuzzy inference and scenario-based methods, Monte Carlo simulation has also been applied in integration of the SLCA with LCA and LCC to address uncertainty in sustainability results. In one study (Visentin et al. 2022), a discrete probability distribution was used, and a 10,000-iteration Monte Carlo simulation was performed to evaluate the variability of the sustainability index under probabilistic conditions. The simulation was conducted at a 95% confidence level. While the sustainability rankings remained consistent with those derived from traditional evaluation methods, the simulation revealed only minor variations in index values, with a low standard deviation (ranging from 0.009 to 0.032). Nevertheless, this application illustrates how incorporating uncertainty analysis, particularly through probabilistic tools like Monte Carlo simulations, can enhance the credibility and robustness of LCSA results by quantifying the range and likelihood of possible outcomes.

3.3. Challenges and limitations in SLCA for engineering applications

The implementation of SLCA in engineering projects offers significant benefits in assessing the social impacts of these projects, but it also presents numerous challenges and limitations. These challenges can impede the effectiveness of SLCA and must be addressed to enhance its application in engineering. This section outlines the main challenges and limitations associated with conducting SLCA in engineering applications, with a focus on methodological difficulties, data availability and quality, and the integration of SLCA into decision-making processes.

3.3.1. Methodological challenges

One of the most significant challenges in SLCA is the complexity and diversity of the methodologies used. Unlike LCA, which benefits from relatively standardised methodologies, SLCA lacks a universally accepted framework. This lack of standardisation makes comparing results across different studies and developing consistent best practices difficult (Ekener-Petersen and Finnveden 2013). In addition, there is no agreed-upon framework for assessing the social sustainability of different technologies, leading to a wide range of approaches that vary significantly depending on the context and the specific social issues being examined (Buchmayr et al. 2022). This lack of a systematic and quantitative methodology further complicates the application of SLCA, leaving practitioners without clear guidance on effectively implementing the assessment (Cadena et al. 2019).

A particularly challenging aspect of SLCA is the absence of generally accepted characterization models that link subcategories to impact categories. This gap is partly due to the underdevelopment of causal models in social sciences, which makes it difficult to establish clear cause-effect relationships between social activities and their impacts. Consequently, the indicators used in SLCA are often qualitative or semi-quantitative, complicating the aggregation of results and rendering comparisons between different systems problematic (Cadena et al. 2019).

The selection and weighting of social indicators in SLCA also present significant methodological challenges (Azapagic et al. 2016). With no standardised framework to guide the selection process, practitioners often rely on common sense or subjective judgment rather than practical experience. This can result in inconsistent choices of indicators that may not adequately capture the most relevant social impacts for a given project (D'Eusano, Tragnone, and Petti 2022). Furthermore, the qualitative and subjective nature of many social issues complicates the decision on which impact categories should be included in an assessment, leading to further discrepancies in how SLCA is applied (Hardadi and Pizzol 2017).

Another unresolved challenge is the aggregation of positive and negative social impacts. Determining what constitutes a positive impact can be context-dependent and subjective. For instance, a production facility with no child labour might be considered a positive impact in regions where child labour is prevalent, but in areas where this risk is negligible, the same feature might not be seen as a significant positive impact. This raises questions about whether such attributes should be universally considered as positive impacts, further complicating the aggregation of results in SLCA (Ekener, Hansson, and Gustavsson 2018).

3.3.2. Data availability and quality

Data availability and quality are critical challenges in SLCA, significantly affecting the accuracy and reliability of assessments. Unlike environmental or economic data, social data are often less readily available and harder to quantify, which complicates the assessment process (Cadena et al. 2019). This lack of systematic data collection is particularly pronounced in developing countries and industries with limited transparency, where information on key social impacts. Reliable assessment of social conditions within a company's supply chain often depends on obtaining specific supplier information, which is not always readily available (Kolotzek et al. 2018). The social circumstances in supply chains are strongly influenced by individual participants, meaning that even identical products can have different social impacts depending on the supply chain involved. While assessing social hotspots at the country or sector level can provide initial insights, this approach may not capture the full extent of social impacts at a more granular level (Fauzi et al. 2022).

Additionally, the qualitative nature of much of the social data available for SLCA poses significant challenges. The scarcity of numerical databases means that much of the analysis relies on subjective interpretations, which can vary widely between different studies. This subjectivity introduces a degree of uncertainty into the assessments, making it difficult to draw consistent conclusions (Chingono and Mbohwa 2015).

The quality of the available social data further complicates SLCA. In many cases, the data may be outdated, incomplete, or biased, which can lead to inaccurate or misleading assessments of social impacts. This issue is particularly acute in regions with weak governance structures or in sectors where social concerns are not prioritised. For example, labour practices in informal sectors or small-scale enterprises are notoriously difficult to monitor, resulting in unreliable data that complicates accurately assessing social impacts in these contexts (Kayaçetin, Piccardo, and Versele 2023).

3.3.3. Integration into decision-making processes

Integrating SLCA findings into engineering decision-making processes presents another significant challenge. While SLCA can provide valuable insights into the social impacts of engineering projects, translating these insights into actionable decisions is not always straightforward. One of the main barriers to integration is the perceived complexity and subjectivity of SLCA results, which can make it difficult for decision-makers to interpret and apply them effectively (van Haaster et al. 2017).

Moreover, the integration of SLCA into decision-making is often hampered by the lack of clear guidance on how to balance social, environmental, and economic considerations. In many cases, decision-makers may prioritise environmental or economic outcomes over social ones, particularly when the social impacts are less tangible or more difficult to quantify. This prioritisation can lead to the underrepresentation of social issues in engineering project planning and implementation, reducing the overall effectiveness of SLCA (Stoycheva et al. 2022).

Another challenge is the need for stakeholder engagement in the SLCA process. Effective integration of SLCA into decision-making requires input from a wide range of stakeholders, including local communities, workers, government agencies, and non-governmental organisations. However, engaging these stakeholders can be challenging, particularly in large or complex engineering projects where interests may conflict. Moreover, stakeholders may have differing views on which social impacts are most important, further complicating the decision-making process (García-Muiña et al. 2021).

3.3.4. Integration with environmental and economic assessments

Integrating SLCA with environmental Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), presents significant challenges within the engineering context. Traditionally, LCA has focused on

quantifiable environmental impacts, while LCC evaluates economic aspects. However, as the understanding of sustainability evolves to encompass its multidimensional nature, there has been a growing effort to integrate SLCA with LCA and LCC to provide a more holistic evaluation of engineering projects (Buchmayr et al. 2022).

A key challenge in this integration lies in the inherently different data types used across these methods. LCA and LCC benefit from numerical, well-structured, and often standardized data. In contrast, SLCA frequently relies on qualitative or semi-quantitative information related to stakeholder groups, societal expectations, and localized social conditions (García-Muiña et al. 2021). This discrepancy makes it difficult to directly compare or aggregate environmental, social, and economic impacts.

The definition and application of the FU further illustrate these differences. While environmental LCA uses the FU as a consistent, quantifiable reference to compare environmental impacts per unit of product or service, SLCA lacks a universally accepted FU due to its broader social focus and qualitative data orientation (Cadena et al. 2019). Instead, SLCA often shifts toward an organizational or stakeholder-centred assessment model, evaluating company practices or supply chain behaviours in relation to social criteria, rather than directly linking them to product outputs (García-Muiña et al. 2021).

Another challenge in integrating SLCA with LCA and LCC is the subjectivity inherent in assessing social impacts. Unlike environmental impacts, which can often be measured objectively through scientific metrics, social impacts are influenced by cultural, social, and political contexts, making them more subjective and variable. For instance, community satisfaction or perceptions of fairness may differ widely depending on local norms and values, complicating efforts to standardise social impact assessments across different contexts. This subjectivity further complicates the integration of SLCA into a unified sustainability assessment framework, as it introduces a level of uncertainty that is less prevalent in LCA or LCC (Josa and Garfi 2023).

To mitigate these issues, MCDM methods have been employed to support integration. These tools allow for the structured comparison, weighting, and aggregation of social, environmental, and economic criteria, thereby offering a systematic approach to manage conflicting indicators. However, as noted in *Data availability and quality*, these methods are not without limitations. Techniques such as AHP, PROMETHEE, MAVT, and fuzzy inference systems rely on expert judgments or stakeholder input to derive weights and preferences. This introduces value-based decisions that can bias outcomes, particularly if inconsistent or unrepresentative input is used.

3.4. Future directions

As SLCA continues to evolve, its application within engineering disciplines presents numerous opportunities for growth and improvement. Future developments in SLCA can enhance its effectiveness, address current limitations, and expand its use across a broader range of engineering projects. This section explores key areas for future research and practice, including the standardisation of methodologies, data collection and analysis advancements, deeper integration with environmental and economic assessments, and increased focus on stakeholder engagement and ethical considerations.

One of the most critical needs for the future of SLCA in engineering is the standardisation of methodologies. As discussed, the lack of a universally accepted framework for SLCA creates challenges in comparing results across different studies and developing consistent best practices. Future research should aim to establish flexible yet harmonised guidelines that can be adopted across various sectors and contexts. This includes aligning impact subcategories, indicator selection, weighting methods, and result aggregation processes. Structured, multi-level frameworks such as the one proposed by Groib Furtner et al. (2023) (Groiß-Fürtner, Mair-Bauernfeind, and Hesser 2023), advocate for nested levels of assessment that scale based on data availability and decision-maker needs. In addition, sector-specific modules should be developed to reflect distinct stakeholder concerns and risk typologies. These should be supported by internationally aligned protocols, such as those under the EU taxonomy and Sustainable Development Goals (SDGs), to enhance relevance and policy alignment.

Another methodological approach that has not been widely adopted in SLCA within the engineering context is system thinking. The complex and often implicit interrelationships among social and engineering variables can be more effectively captured using system thinking tools such as system dynamics (SD) simulation. SD, through utilising causal loop and stocks and flows diagrams, can effectively capture the emerging behaviour of, and the interchange between, social and engineering systems in a quantitative manner. The prospects of systems thinking in SLCA have been thoroughly discussed in McCabe and Halog (2018) (McCabe and Halog 2018) where the authors, in addition to proposing a framework for utilising systems thinking in SLCA, suggest agent-based modelling (ABM) as another powerful tool to employ in SLCA studies, particularly when integrating individual choices. Future work should explore hybrid modelling strategies that incorporate causal relationships between social indicators and performance outcomes to support more dynamic and predictive social assessments.

Advancements in data collection and analysis will also play a critical role in the future development of SLCA. Traditional SLCA has relied heavily on static and retrospective datasets, which are often outdated or lack geographic specificity. Recent research has begun to explore dynamic and digital approaches, such as integrating Industry 4.0 tools to transform SLCA into a more responsive and real-time methodology. For instance, GarcíaMuiña et al. (2021) (García-Muiña et al. 2021) present a pioneering study integrating SOLCA with Industry 4.0 technologies. This blended approach employs realtime digital data collection from manufacturing environments to generate sitespecific social indicators and indexes. This enables continuous monitoring of social performance against key stakeholder categories, with particular emphasis on metrics associated with circular economy transitions.

Another key future direction involves the integration of SLCA with LCA and LCC to support more holistic sustainability assessments. Despite methodological progress, full integration remains difficult due to the diverse nature of data used in each approach. Environmental and economic impacts are often quantifiable and model-based, whereas social impacts remain largely qualitative and context-specific. Future work should focus on creating integrated assessment tools that can handle the complexity of combining social, environmental, and economic data. These may involve the use of unified ontologies, interoperable data platforms, and MCDM methods capable of combining additive and descriptive indicators across domains. Such integration would provide a more holistic view of sustainability, enabling decision-makers to better understand the trade-offs between different dimensions of sustainability and to make more informed choices (Buchmayr et al. 2022).

Furthermore, applying SLCA to emerging engineering domains, such as digital technologies, circular economy, and advanced manufacturing, requires extending current methodologies to account for novel social risks and opportunities. Tsalis et al. (2022) (Tsalis, Stefanakis, and Nikolaou 2022) propose a comprehensive framework designed to evaluate social impacts across the life cycle of circular economy products. Their model synthesises circular economy principles with SLCA, enabling consideration of aspects like job creation, stakeholder engagement, and supply chain complexity within circular systems. The transition to circular and digital systems introduces new forms of labour, evolving supply chain governance, and stakeholder interactions that traditional SLCA frameworks struggle to encapsulate. There is a growing need for SLCA methodologies to evolve in parallel with these technologies to maintain their relevance and decision-making value in future sustainability assessments.

In response to the identified future steps to address the challenges in applying SLCA within engineering applications and align it with LCA and LCC, a structured roadmap has been developed, as illustrated in Figure 6. This roadmap reflects these future directions across three core pillars: Methodology Standardisation, Data Availability & Quality, and Integration with LCA and LCC. Each pillar contains specific action areas informed by current research and industry developments. Actions range from piloting transparency tools and machine learning-driven data validation, to building causal characterisation models and integrating SLCA metrics with dynamic decision-making platforms. These steps are designed to guide the evolution of SLCA into a more robust, evidence-based, and actionable tool that supports comprehensive sustainability decision-making across engineering sectors.



Figure 6. Structured roadmap to enhance the application of SLCA.

4. Conclusion

The purpose of this review was to shed light on the increasing relevance of SLCA within the engineering domain, underscoring its role in evaluating the social impacts of engineering projects alongside traditional environmental and economic assessments. The results highlight the diverse applications of SLCA across engineering fields, particularly in sectors like energy, manufacturing, and chemical engineering.

In response to the first research question, this review identified that the current methodologies and frameworks employed in SLCA of engineering applications are primarily based on the UNEP/SETAC guidelines, which provide a structured approach for assessing social and socio-economic impacts across product life cycles. Additionally, methodologies such as SO-LCA have emerged, extending the focus to organisational-level impacts. These frameworks address social impacts by evaluating stakeholder categories, including workers, local communities, consumers, society and value chain actors, and by employing both qualitative and semi-quantitative indicators to capture a broad range of social themes such as human rights, working conditions, and cultural heritage.

For the second research question, the key social indicators used in SLCA studies of engineering applications include both quantitative and qualitative indicators. Common indicators assess factors such as labour rights, health and safety, governance, and socio-economic contributions. These indicators are applied across all stages of a product's life cycle to ensure a comprehensive evaluation of social impacts. The review highlights that while some indicators are standardised, the selection often depends on sector-specific considerations, which influences how social aspects are defined and prioritised in engineering projects.

Addressing the third research question, the main challenges and limitations associated with conducting SLCA studies in engineering applications include the lack of standardised methodologies, difficulties in data availability and quality, and challenges in integrating SLCA with LCA and LCC assessments. Methodological inconsistencies hinder the comparability of studies, while the qualitative nature of social data complicates the assessment process. To overcome these challenges, the review suggests standardising the assessment methodologies, advancing data collection methods, and developing integrated assessment tools that combine environmental, social, and economic factors. Efforts to standardise social indicators and impact categories will also be essential for enhancing the consistency and reliability of SLCA outcomes, thereby facilitating better integration into engineering decision-making processes.

Despite these challenges, the growing body of research suggests a promising future for SLCA in engineering. Advancements in data collection methods, greater emphasis on stakeholder engagement, and the development of integrated assessment tools that combine environmental, social, and economic factors will be crucial to enhancing the utility of SLCA. Moreover, standardisation efforts, particularly in defining social indicators and impact categories, are essential to ensure consistent and meaningful

assessments across different engineering applications. By addressing these challenges, SLCA can become an even more effective tool for promoting socially responsible and sustainable engineering practices in the future.

In addition, there is a pressing need for SLCA studies to better document and communicate the downstream impacts of their findings, such as design changes, procurement decisions, or policy shifts, to demonstrate the practical value of SLCA. Bridging this gap between assessment and implementation will be key to ensuring that SLCA serves as an actionable tool.

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Author contribution

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Yousef Haddad: Data curation, Writing- Original draft preparation

Rylan Cox: Data curation, Writing- Original draft preparation

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Konstantinos Salonitis is the head of Sustainable Manufacturing Systems Centre. His current research focus is on the sustainability of manufacturing systems and processes, the design and optimization of manufacturing systems, and the use of lean and green approaches for managing manufacturing.

Data availability statement

Data supporting this study are openly available from CORD at <https://doi.org/10.57996/cran.ceres-2761>.

PRISMA 2020 checklist

Prisma 2020 checklists are openly available from CORD at <https://doi.org/10.57996/cran.ceres-2761>.

Registration and protocol

Th review was not registered.

Konstantinos Salonitis

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