Università Ca'Foscari Venezia

Master's Degree

In Environmental Humanities

Final Thesis

Assessment of innovative technologies of non-stick coatings in a Social Life Cycle Assessment perspective

Supervisor
Prof. Daniele Brombal

Assistant supervisors
Prof. Elena Semenzin, Dr. Lisa Pizzol, Phd fellow Arianna Livieri

Graduand
Sarah Devecchi
Matriculation number 88336

Academic Year

2021 / 2022

Index

Abstract

Sustainability is a multi-disciplinary and integrated concept, accounting for the environmental, social, and economic aspects. To properly quantify the environmental, social, and economic impacts and thus to provide a comprehensive sustainability profile, Life Cycle Assessment methodologies can be applied. They include (Environmental) Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA). These are standardized procedures aimed at evaluating the environmental, social, and economic impacts of activities or organization based on ISO standards 14040 and 14044 which define the stages and elements to be included in a study to assess the entire life cycle of a defined system, *"from cradle to grave".* Specifically, the topic of the thesis is to apply Social-Life Cycle Assessment (S-LCA) as a tool to measure the implementation of these goals for socio-economic matters, helping companies and consequently countries to keep the pace with the established targets. Indeed, this thesis aims at producing an in-depth analysis of the S-LCA methodology and presents its application to a case study,Since this topic can be considered rather new in comaparison with LCA and LCC application, it could resutls to be quite precious for practitioners. This work presents the research developed during a period of curricular internship within the company GreenDecision Srl and was performed in the context of the Horizon2020 SUNSHINE project, which developed an approach of Safe and Sustainable by Design (SSbD) to be applied in the design stage of materials and products considering each stage of product development from a lifecycle perspective. The SSbD is achieved via a tiered approach that uses screening-level qualitative (Tier1) and semi-quantitative (Tier2) methodologies in the early stages of innovation and quantitative (Tier3) assessment methods for the later stages. To support the implementation of the SSbD approach, the Life Cycle Sustainability Assessment (LCSA) methodology was analysed, along with each of its components (LCA, S-LCA, LCC), focusing on the interdisciplinarity and potentiality for the integration of these three aspects. The activities performed in this thesis is twofold. First, the alignment of social aspects assessed in Tier1 and Tier2, and partially in Tier 3 was performed to support the monitoring of these aspects along the material/product development stages. Following, the S-LCA was applied to a multi component nanomaterial produced by a partner of the SUNSHINE project as part of the quantitative (Tier3) assessment proposed in SUNSHINE. The product selected for the case study is a nanomaterial-based not-sticking paint applied as a coating on industrial baking trays. The study was performed following thoroughly the official procedure provided by the UNEP/SETAC guidelines. The aim of this work was to analyse in depth the

methodology and, through a case study, highlighting the promising aspects and the weaknesses observed in the application. One relevant result of the thesis is the alignment of the social aspects assessed in Tier1, Tier2 and partially Tier3 of the SSbD approach. This work supported the development of new questions which have been incorporated in the Tier1 questionnaire with the goal of tackling the most relevant social issues for nanomaterials and provide specific information for the further assessment levels. Moreover, the application of S-LCA to a nanomaterial-based product pointed out the main social hotspots of the nano-based product assessed, and the stages of the life cycle contributing the most. Specifically, the raw materials (i.e.; SiC 60nm and SiC 500nm) are those contributing the most on the total share of social potential impacts. This is due to their extraction phase, which happens in China. Moreover, the application showed how the limited coverage of social database is an obstacle for real case studies, where availability of data, especially from supply chain, is limited.

Purpose

Implementing sustainability is a complex task. The shift toward a model of sustainable development is a worldwide shared goal that is calling for suitable methodologies and tools for properly incorporating objectives addressing the whole spectrum of sustainability, namely the environmental, social, and economic dimensions. These practical tools and rational methods should support companies, decision makers and regulators in measuring the sustainability of new products, technologies, projects, and in monitoring the results of implementing sustainable practices at company level. The Life Cycle Thinking approach has proved to be an effective way to assess and reduce product's resource use and emissions to the environment as well as to improve product's socio-economic performance through the entire life cycle. Life Cycle Sustainability Assessment (LCSA) is a method that can provide an integrated description of impacts, of a product or service, covering all aspects of sustainability. LCSA is a combination of three methodologies, one for each sustainability dimension: (Environmental) Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC). This thesis specifically focuses on the S-LCA methodology, since the interest in social sustainability matters has risen in the recent years and the methodology is still at early stages of development (Herrera Almanza & Corona, 2020). Indeed, the practical application of the methodology to real case studies, as reported in this thesis, is an effective way to produce new knowledge and increase expertise in a novel field of research as the one on Social Life Cycle Assessment. Moreover, the approach developed in the SUNSHINE project, which is the context of this thesis, is composed of 3 different assessment levels (qualitative, semi-quantitative, and quantitative), creating more opportunities for companies to assess their sustainability performances based on the availability of data and the level of stakeholders' engagement.

Specifically, the European Horizon2020 SUNSHINE project, coordinated by the Department of Environmental Science, Informatics and Statistics of the University Ca' Foscari of Venice, aims at facilitating the transition to Safe and Sustainable by Design approach for advanced materials and provided the case study information that supported the application of the research developments of the thesis. The case study application was carried out during the collaboration with GreenDecision Srl, a Ca' Foscari *spin off* and a partner of SUNSHINE.

The case study product under assessment falls into the category of Multi-Component Nano Material (MCNM) which have been defined as key technologies for the transition to more sustainable innovations. MCNM can offer technological benefits both in performance and functionality, and through a SSbD approach they can play a crucial role for the European Green Deal goal of a zero-pollution economy and toxic-free environment. However, before placing these new products on the market, it is needed to assess their potential environmental and socio-economic threats, since their development faces challenges regarding the health and safety of users and the environment.

Studying the role and potentialities that a life cycle approach, and more specifically the S-LCA, has in the engineered nanomaterials and nano-enabled products context is a fundamental step to achieve socio-economic goals and it is the main purpose of this thesis work.

Objectives and structure

The main goal of this work is to study in detail and apply the Social LCA methodology as a part of the development of an integrated sustainability assessment framework for innovative processes, products, and services. Since the SSbD approach developed in SUNSHINE is achieved via a tiered approach that uses screening-level qualitative (Tier1) and semi-quantitative (Tier2) methodologies in the early stages of innovation and quantitative (Tier3) assessment methods for the later stages, one specific goal of this thesis is to align the criteria used in the three different tiers in order to have a coherent approach.

Finally, to better understand how to apply the S-LCA methodology, since literature implementations in case studies is still not adequate, a second specific goal of this thesis is to apply the S-LCA methodology to a real case study. The relevant case study was selected among those made available by the partners of the European Horizon2020 SUNSHINE project, specifically from a company producing a novel PFAS-free anti-sticking coating paint used in the baking industry.

The thesis is structured in five chapters. In the first chapter it is provided an overview on the history and development of the sustainability concept, declined in its three dimensions. The second chapter introduces the concept of Life Cycle Sustainability Assessment, including a detailed description of each of the three life cycle methodologies: (Environmental) LCA, S-LCA, and LCC. Special attention is paid to S-LCA, being it the less known methodology and the one applied in the case study. The third chapter is dedicated to the outline of the context of the case study, the SUNSHINE project, and the Safe and Sustainable by Design concept in a life cycle perspective. The first part of the fourth chapter presents an alignment work carried out as a precedent step to the S-LCA, aimed at improving the prior level of assessment (Tier1). It explains how the assessment at a qualitative level integrates and enriches the later application of the S-LCA methodology (Tier3) to a relevant case study, topic of second part of chapter four. Finally, chapter five, is dedicated to the discussion of the results obtained from the case study interpretation. The chapters are followed by the Conclusions, in which results, challenges and relevant knowledge to the case study context are discussed.

1 Introduction to sustainability

In 1972, the publication of the book *The Limits to Growth* introduced formally the idea of the unsustainability of environmental, economic, and societal trends (Meadows et al., 1972). The authors (scientists, educators, economists, humanists, industrialists, and national and international civil servants) selected five variables characterizing the society that at the time showed a steady growth trend (population, food production, industrialization, pollution, and consumption of non-renewable natural resources) and modelled their predicted development through computational tools to generate future scenarios, according to different assumptions about the approaches that could have been adopted to tackle the related problems. Business-as-usual resulted ineffective to reverse the unsustainable pattern that would have eventually led to the worst scenario: overshoot and collapse. For the first time, thanks to the book's release, the debate was open about the until then unquestioned approach to growth. Shortly after, the concept of "sustainable development" was theorized in the context of the World Commission on Environment and Development, that in 1987 produced the document *Our Common Future*, which states:

"Humanity has the ability to make development sustainable
to ensure that it meets the needs of the present without compromising
the ability of future generations to meet their own needs."

Bruntland report, 1987

The issues to be faced were identified as part of a net not only concerning the management of the natural resources, but also the development of society and economy. Consequently, integrated sustainability must consider all three dimensions to be in line with the definition. Environmental, social, and economic sustainability stay in a relationship that can be represented through different models, in which it prevails respectively interdependence and intra-dependence. In the first case (Figure 1-1), the three aspects are sets intersected one to the other; sustainability lies in the section created by the simultaneous overlap of all.

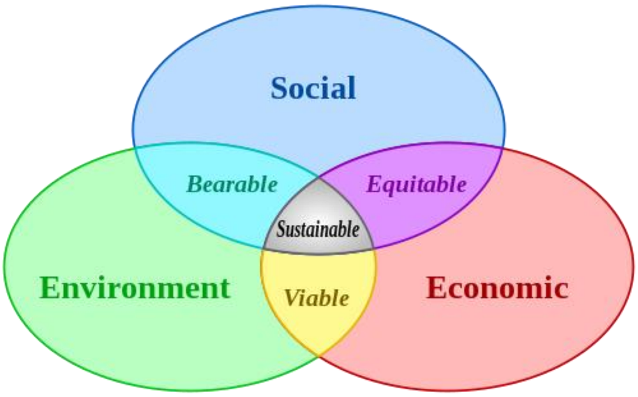

Figure 1-1 Sustainability dimensions as intersected sets

Intra-dependence is instead visualized through sets nested one into the other, in which the environment forms the basis of the scheme (Figure 1-2). It is evident, in this second representation, that environmental health is an essential condition for societal and economic prosperity, hierarchically a step further in respect of the other two.

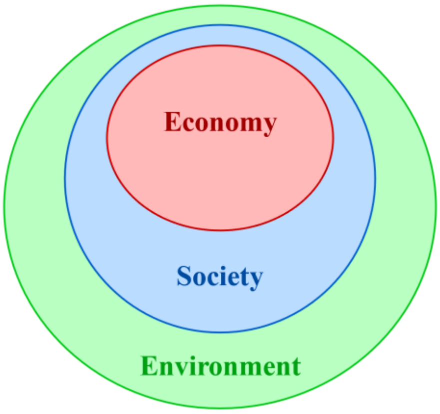

Figure 1-2 Sustainability dimensions as nested sets

In the following paragraphs a definition of the three pillars of sustainability previously mentioned is provided.

1.1 Environmental sustainability

The health of the planet is strictly connected to the health of human society. Air, water, land, minerals, and ecosystem resources are the natural capital whose protection and preservation are crucial to avoid shortages that would compromise future generations. A development that is sustainable and environmental-wise, falls within the planetary boundaries that natural resources define. It means, as visualized in the second model for sustainability representation, that sustainable development has to occur in between the limits of the environmental circle. It must respect the maximum carrying capacity of the earth to sustain and regenerate biotic and abiotic systems. Therefore, environmental sustainability requires a conscious use of this capital, where the rate of usage does not exceed the renovation one and the waste production is aligned with the biogeochemical cycles for their assimilation into the ecosystem.

1.2 Social sustainability

Social sustainability is about preserving and maintaining social capital, including both the material and immaterial services provided by society to its members. The United Nations highlight the role that businesses play in social impact matters, both positively and negatively (*Social Sustainability | UN Global Compact*). Managing this impact and the relationships between different stakeholders is at the basis of the social dimension of sustainability. Ensuring the respect of human rights across the world is one of the major goals of integrated sustainability, threatened by inequalities, violence and social decline, still characterizing nowadays societies. While dealing with social sustainability, it is of utmost importance to identify and define all the involved social groups and the diversity of issues and needs they might face, to better understand which contribution would improve their lives. Health, well-being, good quality education, and opportunities are the main challenges brought into the debate on social sustainability.

1.3 Economic sustainability

The economist Roger Perman, tracing back the origin of the (economic) sustainability problem in his book *Natural Resource and Environmental Economics*, claims that since the 1950s economic growth started to be identified as the ultimate solution to poverty (Perman, 1996). However, the publication of *Limits to Growth* raised questions about the option of an unlimited growing trend in a resource-limited context. Economic activities occur within the natural environment and draw material from the earth system, becoming part of the cause and consequences of the environmental crisis. An ecosystem deprived of its element or overcharged out of its carrying capacity would no longer be able to provide the environmental services needed for growth, revealing the unsustainability of this approach. Decoupling environmental pressure from economic growth is considered less and less feasible, while new theories about prosperity instead of growth arise among scholars. Indeed, prosperity and well-being do not have to be necessarily dependent on economic growth, if included within societies that consume less and grow in non-material dimensions

(*Growth without Economic Growth — European Environment Agency*). Green growth, doughnut economics, degrowth and post-growth are the main alternative currents in the debate, that however fall outside the aims of this work.

1.4 Towards Sustainable Development

The guidelines to boost sustainably in all dimensions are shared worldwide through the *2030 Agenda for Sustainable Development*, a document produced in the context of the Conference of Parties held in Paris in 2015 (COP21). The representatives for the 193 ONU Member States organized the actions envisioned for sustainable development in 17 goals (Figure 1-3), each representing a crucial aspect to be tackled by all countries through global partnership. These goals include all the elements implied in the three pillars of sustainability, separately defined, but still very much related to each other. Social sustainability virtually encompasses all the SDGs, since it aims at protecting individual and societal wellbeing. More specifically it contributes to the achievement of SDG1-6 (No Poverty, Zero Hunger, Good Health and Wellbeing, Quality Education, Gender Equality, Clean Water and Sanitation) through the assessment of fair working conditions; to SDG8 encouraging a sustainable growth and adequate employment; to SDG10 by evaluating the potential risk for inequalities; to SDG 12 by promoting responsible consumption and production; to SDG16 aiming at the goal of Peaceful And inclusive societies, access to justice and accountable institutions and to SDG17 by strengthening the global partnership for the goals (UNEP, 2020).

Figure 1-3 Sustainable Development Goals (un.org)

Within the European context, the Green Deal is an integral part of European Commission's strategy to implement the United Nation's 2030 Agenda and the sustainable development goals. The European Green Deal is a set of proposals and guidelines to "transform the EU into a modern, resource-efficient, and competitive economy, ensuring:

- no net emissions of greenhouse gases by 2050;
- economic growth decoupled from resource use;
- no person and no place left behind".

Member States had to prepare a plan of investments which is aimed at taking action according to the SDGs and Green Deal targets, in order to achieve a sustainable future while ease the transition out of the Covid-19 pandemic, seizing the opportunity of starting by a sustainable by the design approach. The plan of investments was implemented through the Next Generation EU Recovery Plan, which includes monetary support to cope with the social and economic post-pandemic damages (A European Green Deal, 2021).

2 LCSA

As already presented in the previous Chapter, the goals set by Agenda 2030 *for Sustainable Development* imply that Member States will have to commit to achieve the objectives determined by the agreement, by actively involving companies and organizations in the assessment of their sustainability and the sustainability of their products. Measuring progress in sustainable development is of utmost importance to keep the alignment with the pursued objective, as well as providing a mean to trace the level of improvement. However, when dealing with sustainability, the complexity of including all the variables and parameters can lead to results that are partial and/or not representative. As comprehensive is the concept of sustainability, so it must be the approach to assess it. Measuring sustainability implies going beyond traditional methodologies, that usually focus on one specific process or activity related to the object of study. By broadening the perspective, it is possible to consider services, organizations, and products in their whole timeline of existence, meaning from their design phase to the disposal one, to produce results that virtually account for every possible considerable aspect. One of the approaches considering all these requirements is the Life Cycle Thinking model, which describes the item under assessment during its whole utility life, from "cradle to grave". The objectives of this method are to assess and consequently reduce products' resource use and emissions to the environment as well as to improve their socio-economic performance through the life cycle, by highlighting impacts related to each phase or process (Life Cycle Initiative). Life cycle thinking is implemented by applying a series of tools that have been developed according to these principles. Life Cycle assessment tools can provide standardized and effective ways to keep track of the achievement and to orient decision making, Operationally, the methodology of "Life Cycle Sustainability Assessment" (LCSA) can be adopted to obtain an integrated analysis of sustainability performance, considering simultaneously the three pillars: Environmental, Social, and Economic. Indeed, performing a LCSA requires to combine the three available Life Cycle methodologies addressing the three pillars of sustainability: (Environmental) Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC). These are all based on the same series of ISO standard 14040, meaning that integration of them into one comprehensive analysis is possible in an efficient and effective way. The series of ISO 14040 was originally developed for the (Environmental) LCA only. Thanks to the standardization and the rising environmental concerns, the methodology was the privileged one in the sustainability field of research. Recently, however, the European context is conveying more and more attention on the social and economic aspects of sustainability, meaning that the focus shifted from a mere environmental concern to a broader analysis. LCSA allows to better understand and address the impacts of products and services along their life cycles, acknowledging the need for tackling sustainability from a holistic perspective (Towards a life cycle sustainability assessment, Life Cycle Initiative 2011). On a more practical level, the advantages of performing a LCSA cover various aspects of impact mitigation and involve different stakeholders, from businesses to consumers. It is a mean to organize in a more structured way information and data, identifying the trade-offs between the environmental, economic, and social factors, it promotes awareness and foster improvements in the life cycle processes. Moreover, it can support decision makers toward more sustainable choices, or consumers towards conscious purchasing. In conclusion, LCSA provides a clear and precise way to measure and communicate the sustainability of products and services in a thorough and comprehensive way, broadening the rooster of potential actors interested in an effective and straightforward tool to engage in sustainability thinking.

As previously mentioned, the series of ISO 14040 provides a framework to orient the practitioner during the analysis; however, the standard leaves some choices to the individual and therefore it is required a further level of guidance to support consistency and quality assurance (International Reference Life Cycle Data System, Handbook 2010).

In the following paragraph it will be presented the UNEP/SETAC Life Cycle Initiative, a project operating on the international level with the goal of developing a series of guidelines to create a solid background on which to base LCA studies.

"The Life Cycle Initiative is a public-private, multi-stakeholder partnership enabling the global use of credible life cycle knowledge by private and public decision makers."

Life Cycle Initiative 2017-2022 Strategy document

The UNEP/SETAC Life Cycle Initiative provides expertise for life cycle users to allow public and private decision makers to have the tools to ease the transition to sustainability thinking. Hosted by the UN Environmental Program (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC), the goal of the Life Cycle initiative is to produce knowledge and know-how on life cycle approaches to implement actions in line with the Sustainable Development Goals and Nationally Determined Contributions established by the Paris Agreement. The underlying idea is that constructing a partnership between these three methodologies, LCA, LCC and S-LCA, would be an effective tool to reach the objective concerning sustainability that the international community set. To reach this goal they engage in different activities aiming at making Life Cycle thinking a mainstream tool for measuring and assessing sustainability. They identified three areas of intervention:

1. Technical and Policy Advice, and Stewardship for Life Cycle Approaches;
2. Life Cycle Capacity Development;
3. Life Cycle Knowledge Consensus and Platform.

The information retrieved from LCA studies are becoming more and more used while pursuing sustainable development, both by private businesses and the public sector. More specifically, concerning the European context, the EU Commission's platform on Life Cycle Assessment listed some of the functions that LCA performs.

For private businesses:

- reducing the environmental burdens of businesses;
- improve the competitiveness of products;
- improve communication with governmental bodies;
- improve product design;
- improve decision-making of purchasing and technology investments;
- highlight the trade-offs associated with the endpoint categories.

For the public sector:

- stakeholders' consultation;
- policy improvement and implementation;
- trade-offs identification;
- environmental performances analysis.

In the context of this work, I will give an overview of the three Life Cycle Assessment techniques, later focusing on the Social-LCA, as the methodology under analysis in the case study presented in paragraph 2.2.

2.1 LCA

2.1.1 Definition

The Life Cycle Assessment is a methodology aimed at quantifying the pressures of goods and services on the environment, following the life cycle thinking approach that includes an assessment from the extraction of raw materials to the disposal of the final product. Among the impacts, it is counted both the direct and indirect emissions and their relative contribution to specific impact categories, according to data regarding input of energy and materials, and outputs of substances into the air, soil, and waters. Figure 2-1 shows an example of the life cycle phases of a product.

Figure 2-1 Life Cycle phases. Readapted from BibLud-net

The assessment methodology is defined by the international ISO standards 14040-14044, providing the fundamentals elements on which the analysis is based:

- life cycle approach;
- environmentally concerned;
- relative approach and functional unit;
- iterative approach;
- transparency;
- completeness;
- scientific approach based on natural sciences.

A LCA finally provides the users with results that allow to draw conclusions on the interaction between a product's environmental intervention and its impacts on Human Health, Resource Depletion and Ecosystem Quality, later defined as Endpoint categories, which allows to use the information for the scopes listed in the previous paragraph.

2.1.2 Structure

The framework of LCA was developed by SETAC in 1990, later modified and standardized through ISO standards. It is organized according to four phases, to be approached through an iterative procedure for the sake of coherence and completeness. Figure 2-2 provides a visual representation of the phases of an LCA. The arrows represent the iterative approach of the methodology. The description of each phase is provided in the next paragraphs.

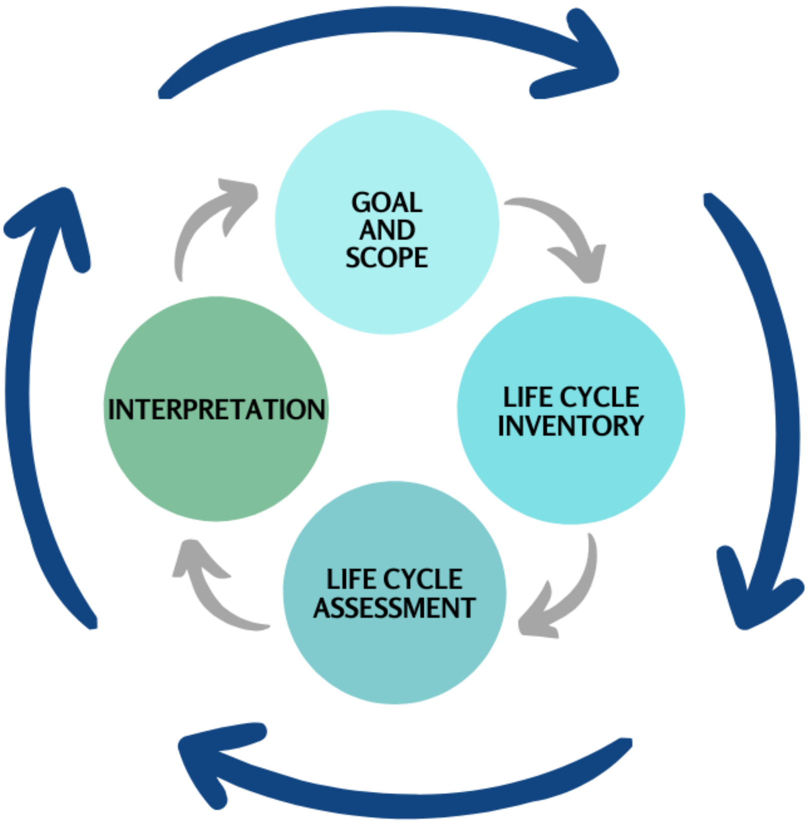

Figure 2-2 Life Cycle Assessment phases. The arrows symbolize the iterative approach of the process

Goal and Scope definition

In this phase it is defined the aim of the study, the functional unit, the borders of the system, data availability, assumptions and limitations of the approach adopted. The goal must include the intended application of the study, the motivation to undertake it and the targeted public for the result dissemination. The scope must specify the functions of the system being studied, including some essential element to be reported from this early phase:

- attributional/consequential thinking. Define if the study aligns with attributional or consequential thinking. The choice will determine methodological choices in subsequent phases (UNEP, 2011). The attributional approach is also known as the "accounting" or "descriptive" one. The aim is to provide information on the share of global impacts that the life cycle of the specific product has, worldwide. The consequential or "change-oriented" approach aims at providing information on the environmental burdens related, directly or indirectly, to a decision, namely its consequences. The process analyses are only the ones affected by a cause-effect relationship that originates from that decision. Figure 2-3 shows the conceptual differences between the two visually. The two circles represent the total environmental burdens. On the left, the section defined by the discontinuous lines represents the share attributable to the specific product. On the right, the shaded region represents the environmental burden changes as a result of a decision;

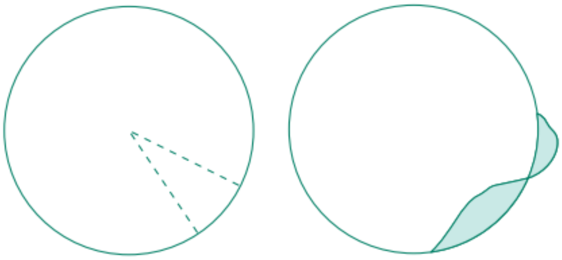

Figure 2-3 Visualization of attributional and consequential thinking

- functional unit. It is a metric that is chosen coherently with the goal and scope of the study, allowing to process and present data from LCA. More specifically, it is a reference measure to which connect input and output fluxes of energy and materials. Moreover, it is crucial because it grants the possibility of comparison between different LCA studies;
- reference flow. It translates FU into a product flux. The results must be scaled according to the inputs needed for the chosen functional unit. However, the study can decide to not perform the scaling for either a shortage of data or conceptual reason when scaling would not affect the results. The decision must be reported, justified and discussed;
- product system. It is the collective of all the unitary processes that concurs to the life cycle of the selected product. It is usually represented through a flowchart;

- system boundaries. The system must be described thoroughly in all its components, from physical environment, operation and production processes that will be included into the analysis. It is usually organised in three parts: upstream, core and downstream module. The upstream section includes those processes having place before the product system subgroup, as raw material sourcing and elaboration. The product system is the core module, while downstream processes accounts for the use and end of life phases. Ideally, it should follow the product from cradle to grave. It is usually represented through a flow chart in which all relevant life cycle stages and their relative components are represented and connected to better organize the data collection. Figure 2-4 provides a visual example of flow chart. As every phase, also the system boundaries definition is an iterative process since it depends on data availability. Changes must be noted and justified;

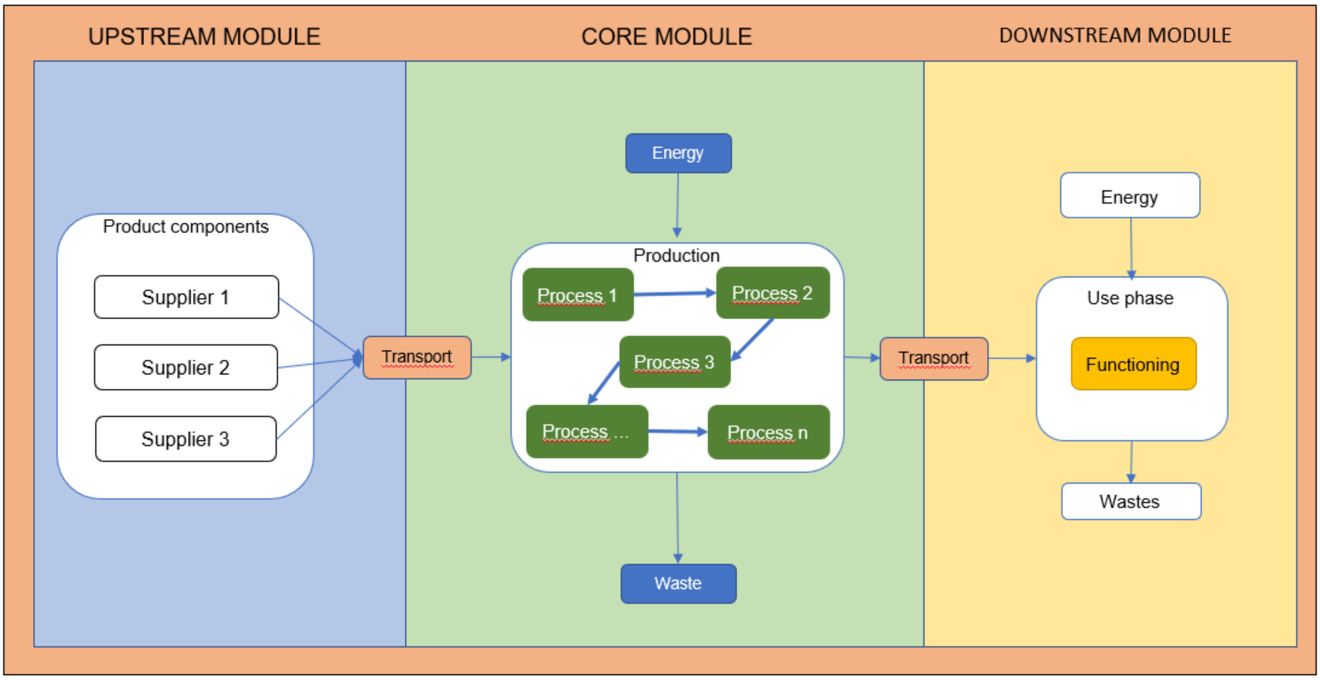

Figure 2-4 Example of flowchart including the upstream, core and downstream modules

- data quality requirements. Data can be either primary or secondary, depending on the source from which they're retrieved. Primary data are collected directly from the company through interviews and questionnaires, while secondary data are found in publication and databases. The quality of data affects the reliability of results; therefore, it is important to measure and keep monitored these data through some criteria:
    - accuracy;

    - completeness;
    - representativity;
    - consistency;
    - replicability.
- assumptions and limitations. It may be the case when information is lacking that the work team assumes some connections or data from literature review or previous knowledge. It is important to report all the reasoning behind these decisions to help the targeted public with understanding the results. It is possible to undergo a sensitivity analysis to verify how the assumptions affect the final result.

Life Cycle Inventory (LCI)

In this phase input and outputs of energy and material, from all processes, are quantified. According to the iterative nature of LCA, during the development of the study it can emerge the need for more specific data or for the inclusion of new limitations to the scope phase due to lack of information. The inventory can be updated accordingly, along with the data collection procedures. The flux diagram drafted in the previous section is enriched with the quantitative data gathered, reporting the source, time, and nature of the datum (primary or secondary). It might be necessary in this context to carry out an allocation procedure, distributing the inward and outward fluxes according to the system boundaries established. This might be done by referring to the physical properties of products, their economic value or narrowing down the original system boundaries.

Life Cycle Impact Assessment (LCIA)

During this phase, it is performed the evaluation of impacts according to the data collected in the previous stage of the study.

According to the ISO standard, this phase develops through four steps:

1. classification – results from the inventory are assigned to the relative impact categories. Different assessment methods include a different selection of impact categories, always related to resource consumption and emissions into the environment;
2. characterization – results from the inventory are transformed through a characterization factor into measures of the category indicators, representative for the impact categories contributions;

3. normalization – data are further elaborated to obtain relative parameters, based on a benchmark value, that help the quantitative representation of the results;
4. weighting – the impact categories are evaluated based on the criticality of the impact and its importance. Indicators are multiplied for a numeric factor according to these considerations. However, due to this passage the stage is affected by the subjectivity of the operator, creating results that cannot be utilized to address the public but only for internal use.

The first two phases are compulsory elements to carry out an LCA study, while the second two are optional and debated, since they are more subjected to potential biases.

Each phase can be carried out according to different methods; the following list presents some of the most used in Europe:

- Eco-indicator 99;
- CML-IA;
- EDIP 97;
- EPS 2000;
- Impact 2002+.

Another of the most used methods is ReCiPe, which has the objective of transforming the results of the life cycle inventory into specific indicators to make the visualization of final result clear and comparable. ReCiPe considers two indicators, respectively “midpoint” and “endpoint”. At the midpoint level, 18 impact categories are defined, which at the endpoint level are aggregated into 3 categories to evaluate the damage to human health, ecosystems, and resources.

Life Cycle Interpretation

In this last phase, results from LCI and LCIA are combined to produce a final assessment organized according to the goals and scope defined in the first phase. Results, conclusions, limitations, and recommendations must be presented in a way that allows to evaluate impacts and proceed accordingly. ISO 14044 standard comprises three elements:

1. identification of the significant issues based on the results of the LCI and LCIA phases of LCA;
2. an evaluation that considers completeness, sensitivity, and consistency checks;
3. conclusions, limitations, and recommendations.

Figure 2-5 shows how this phase connects and interacts with the other steps of a LCA.

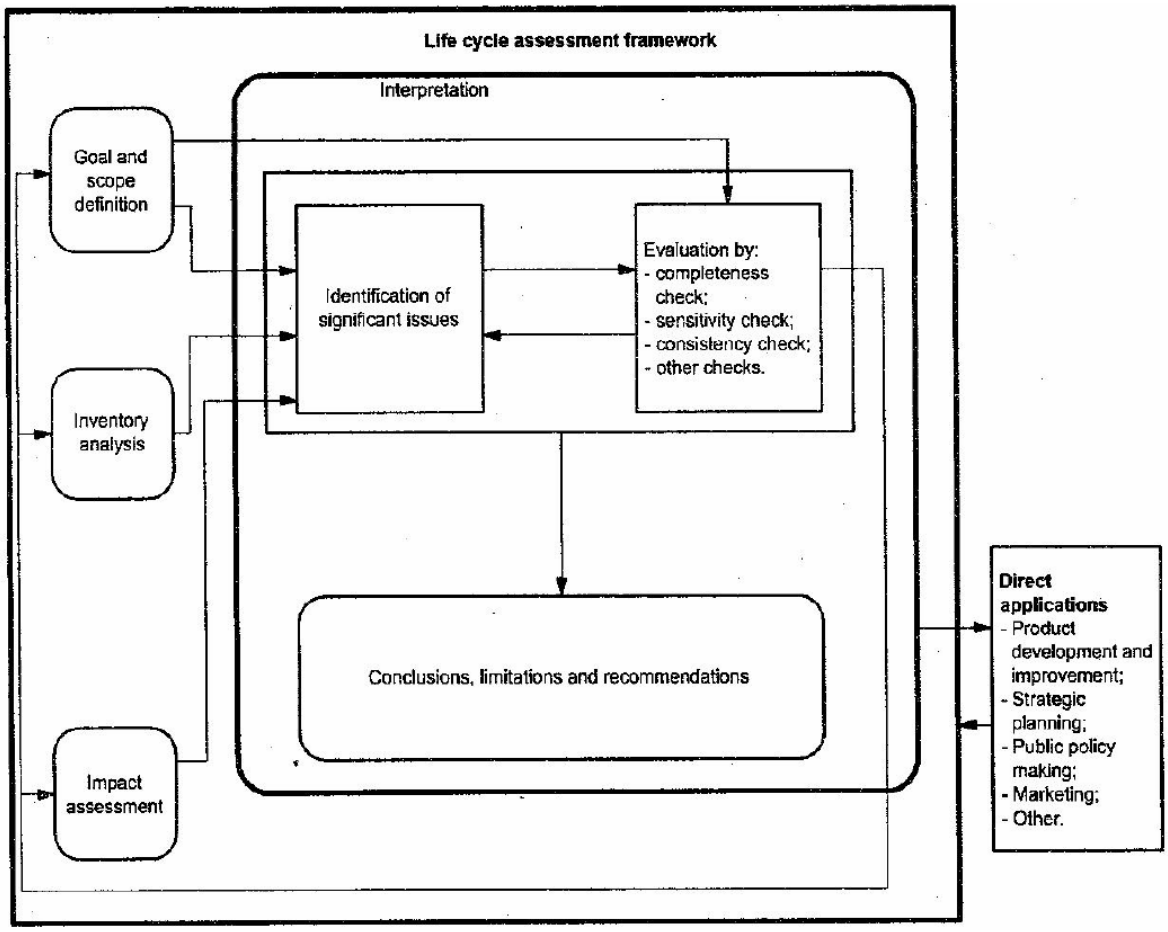

Figure 2-5 Relationship between elements within the interpretation phase with the other phases of LCA (ISO 14044: 2006)

2.1.3 Software

Few softwares are available to carry out an LCA analysis. A software is required during the LCIA phase, to elaborate data by allocating energy and material flows to the impact categories. In the European context the more consolidated are the following:

- SimaPro (The Netherlands);
- Gabi and Umberto (Germany);
- OpenLCA.

Along with the softwares, databases have been developed to support the inventory phase, either specifically for one software or independently. In the context of this thesis, the SimaPro software will be presented, both because it is widely used in the LCA research and application field and because it is also relevant for the case study presented in the next chapters. Indeed, the SimaPro software is also available with the Social Hotspot DataBase extensions, a S-LCA tool that will be presented in paragraph 2.2.20.

SimaPro (System for Integrated Environmental Assessment of Products) is developed by PRé Consultant (Product Ecology Consultant) in the Netherlands, released for the first time in 1990. It is a professional tool used to collect, analyse, and monitor the sustainability performance data of products and services. It offers great flexibility in the application and modelling of complex systems, for a variety of applications, such as sustainability reporting, carbon and water footprint, product design, etc. It supports various databases, to be selected based on specific case study needs.

2.2 S-LCA

2.2.1 Definition

In line with (Environmental) LCA, the Social Life Cycle Assessment methodology is organized according to the series of ISO standards 14044 and 14040. Therefore, the structure of a study results to be the same, a four-step iterative procedure aimed at providing an evidence-based decision-making tool to highlight trade-offs in sustainability issues (UNEP, 2020). In the 1990s, when social issues started to be at the centre of the sustainability debates, it was considered necessary to develop a parallel LCA methodology, separated from the environmental one. This was mainly due to the challenges encountered in data collection, purely quantitative in (Environmental) LCA, and the complexity of merging social and environmental indicators in one analysis. The implementation of specific guidelines stalled until 2006, when UNEP and SETAC entrusted a taskforce for the development of the first edition of the “Guidelines for social life cycle assessment of product”, released in 2009 (Pollok et al., 2021).

The first version of S-LCA defined by the UNEP/SETAC guidelines of 2009 was the product S-LCA. However, in literature, a parallel line trying to assess the social performance of companies as a whole started to emerge. This trend is reflected in the updates of the last released version of the UNEP/SETAC Guidelines, where Social Organizational Life Cycle Assessment is presented as an alternative social assessment. Developed through the merging of the S-LCA and Organizational (Environmental) LCA frameworks, it is considered a valid tool for internal assessment, while comparative objectives cannot be pursued through the implementation of this technique due to the lack of consistent basis for comparison and to the variability between different companies products portfolios (D’Eusanio et al., 2022; UNEP, 2020).

Nowadays, companies concerned about sustainability face the challenge of ensuring traceability and control of their supply and production chain during a product or organisation life cycle, both environmentally and socio-economically wise. S-LCA was designed to support decision-making by helping to understand better the social impacts and human rights in the supply chain and life cycles. It is a tool for measuring the share of social impacts on various *stakeholder categories* through a multi-criteria, multi-stakeholder and multi-step analysis assessing the performance of a product through its entire life cycle (ScoreLCA, Executive summary, 2018). Its foundation is the Universal declaration for human rights. It is also related to other available tools, such as ISO 2600 or the human right principles (SimaPro, 2019). According to the UNEP/SETAC Guidelines of 2020, S-LCA can produce different outcomes, or either an integrated result from the combination of them:

- assessment of potential social impacts;
- evaluation of social risks;
- measurement of the social performance.

In S-LCA, impacts are organized into subcategories, which in turn are grouped into six categories, corresponding to the six stakeholder types identified in the last version of the S-LCA guidelines (UNEP, 2020*)*. Stakeholders are defined as the actors that are involved in the product value chain and might be affected positively or negatively by the activities implemented during its life cycle stages (Bouillas et al. 2021). Therefore, performing a S-LCA, includes the selection of concerned stakeholder for the specific case study, which can be approached through a participatory approach, by including representatives of one or more stakeholder's categories in the selection process. Figure 2-6 provides a visualization of the hierarchy of grouping mentioned above. To each stakeholder category corresponds a variable number of impact subcategories, each characterized by indicators to help data collection. Impact subcategories can be aggregated into impact categories to support a further assessment or interpretation. Figure 2-7 provides the complete list of impact subcategories, organized by stakeholder, from which the practitioner selects the relevant issues. The process of inclusion or exclusion of subcategories must be justified, and the process of selection needs to be described (UNEP, 2020). The newly released version of the guidelines modified the original list of five stakeholder categories by adding the sixth, namely "Children". Workers, Local community, Society, Consumers, Value chain actors and the newly added Children category aim at representing virtually every possible target actively or passively involved in the system under assessment. The inclusion or exclusion of one or more stakeholders' categories should be promptly justified in the scope of the study. Moreover, the impact subcategories related to each stakeholder can be modified and adjusted accordingly, if deemed by the practitioner, previous justification. The S-LCA brought about the innovation that is the stakeholder approach, introducing a novelty in comparison to the (Environmental LCA). The focus on social matter begins with this change of perspective of the methodology, which redefines the centre of the study as the affected subjects instead of the impacted indicators. More and more studies took advantage of this approach to underline the positive impacts of specific activities by performing a study in which only one stakeholder category is considered, which resulted in a new sub-area of research to specifically highlight the positive side of activities.

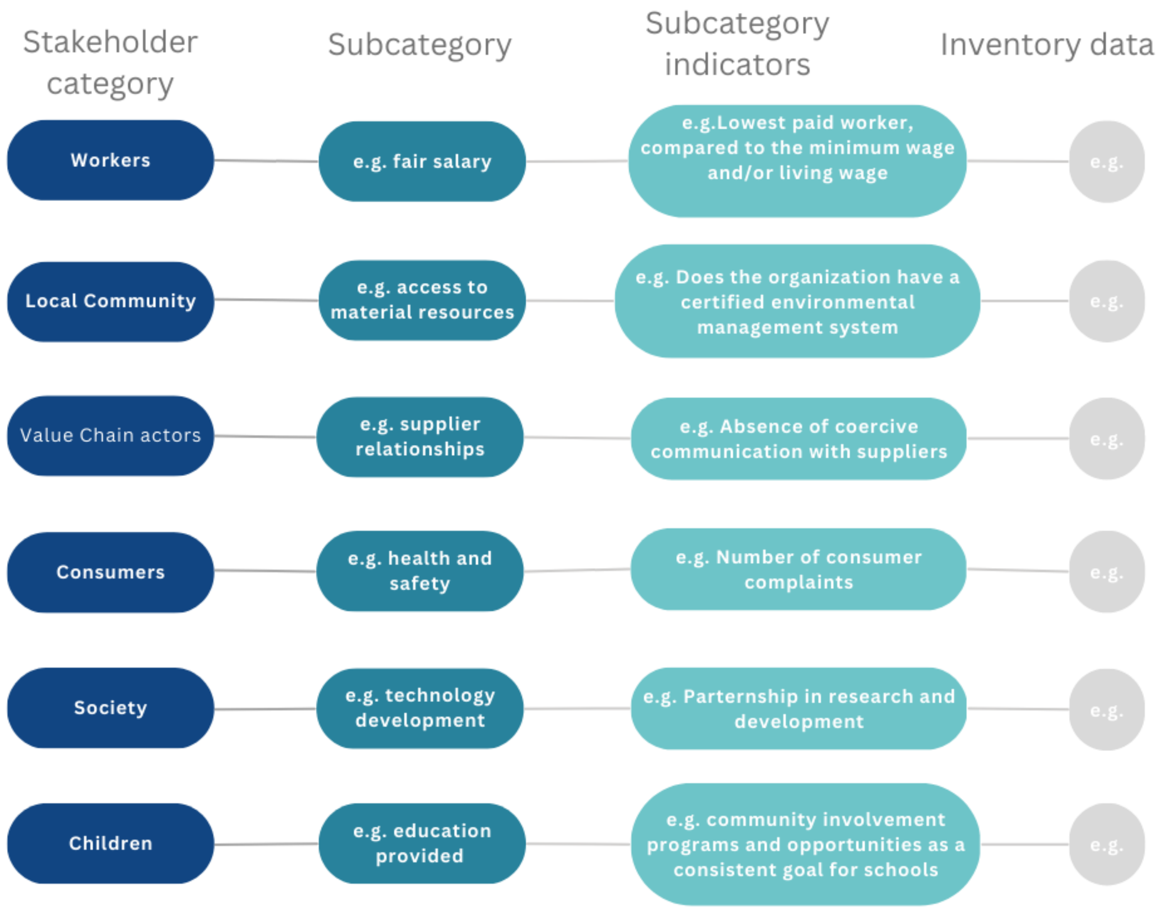

Figure 2-6 Visualization of the relationship between stakeholder categories and data collection for impact assessment

Stakeholder categories	Worker	Local community	Value chain actors (not including consumers)	Consumer	Society	Children
Subcatego-ries	1. Freedom of association and collective barganing 2. Child lbor 3. Fair salary 4. Working hours 5. Forced labor 6. Equal opportu-nities/discri-mination 7. Health and safety 8. Social bene-fits/social security 9. Employment rela-tionship 10. Sexual haras-sment 11. Smallholders including farmers	1. Access to material re-sources 2. Access to immaterial resources 3. Delocalization and migra-tion 4. Cultural heri-tage 5. Safe and healthy living conditions 6. Respect of indigenous rights 7. Community en-gagement 8. Local employ-ment 9. Secure living conditions	1. Fair competi-tion 2. Promoting so-cial responsi-bility 3. Supplier rela-tionships 4. Respect of intellectual property rights 5. Wealth distri-bution	1. Health and safety 2. Feedback mecha-nism 3. Consumer privacy 4. Transparen-cy 5. End-of-life res-ponsibility	1. Public com-mitments to sustainability issues 2. Contribution to economic de-velopment 3. Prevention and mitigation of armed conflicts 4. Technology de-velopment 5. Corruption 6. Ethical treatment of animals 7. Poverty allevia-tion	1. Education provided in the local commu-nity 2. Health issues for children as consumers 3. Children concerns regarding marketing practices

*Figure 2-7 List of impact subcategories by stakeholder (*UNEP, 2020*)*

A social LCA study can assess the likelihood of occurrence of an impact, also called a *potential* social impact. Seldom it may produce results of *actual* impacts if the company was able to provide qualitative primary data. Social impacts measured through S-LCA can contribute either positively or negatively on the final results, according to the double nature of a social impact itself. Contrarily to environmental impacts, measured according to their negative impact on the natural resources, "*social conditions do not merely need to be protected from deterioration, but also need to be actively improved"* (UNEP, 2020).

Improvement in people well-being and social conditions are macro categories of positive impacts, understood as beneficial outcomes from an activity of the life cycle. It is important to consider them separately from negative impacts resulting from the analysis, since offsetting is not functional in S-LCA (UNEP, 2020). Indeed, positive impacts cannot be considered as a mend of a social issue, that by itself poses a threat to human well-being and can therefore only be avoided or solved in its specificity.

The UNEP/SETAC guidelines for S-LCA have listed three possible types of positive impacts:

1. type A – positive social performance[1] going beyond business as usual;
2. type B – positive social impact through presence (product or company existence);
3. type C – positive social impact through product utility.

Type A

Business as usual can includes both compliance to national and international standards and conducts below this level. Actions and practices going beyond the minimum requirements produces a positive impact on the society at all stakeholders' level, ensuring improved condition and healthy working environment.

Type B

Companies' presence in specific locations and contexts can produce positive impacts on employment, infrastructure improvement, capacity building and in general creates more opportunity for workers and local communities.

Type C

This category of positive impacts can be assessed in the use phase, since it depends on the intrinsic properties of the product, for examples medical treatments, water management systems, etc.

However, the assessment of positive impacts is not yet properly developed due to the complexity of including that into an analysis that borrows the framework from ISO 14044 and 14040. Practitioner are developing tools to measure those impacts and provide a more comprehensive picture of social sustainability. In the context of this work, a case study developed according to the guidelines' instruction will be presented, which will highlight both positive and negative impacts.

[1] Social performance refers to the principles, practices, and outcomes of businesses' relationships with people, organizations, institutions, communities, and societies in terms of the deliberate actions of businesses toward these stakeholders as well as the unintended externalities of business activity measured against a known standard (UNEP, 2020 citing Wood, 2016). It usually measures the distance from a known benchmark status, often times defined as the business-as-usual scenario. A higher score stands for a performance beyond the standard, therefore implementing some good practices; a lower score indicates non-compliance with the set of basic requirements defined.

As mentioned above, S-LCA primarly assesses *potential* social impacts. To do so, the likelihood of adverse social effects on stakeholders is estimated through the assessment of social risks, meaning the probability of a social issue to arise due to the product company activities. Social risks are indicators of potential social impacts based on knowledge about a specific activity/sector/trade usually measured at country, sector, or company level. Where social risk has a high probability to occur, a social hotspot can be identified. Potential social risk assessment is a practice supported by databases, such as the Social Hotspot Database, presented later on. Database sectors data, by country, point out at risks or opportunities for social wellbeing and development depending on the sector and the geographical area, thanks to the data collected from the ILO, world bank, laborsta, etc. (UNEP, 2020; SHDB). When time and resources allow a further development of the study, the collection of primary qualitative data through interviews and questionnaires provides the means of verifying the *actual* presence of impacts to confirm the identified social hotspots.

2.2.2 Structure

The Social Life Cycle Assessment standardized procedures draws its bone structure from the ISO 14040 and ISO 14044, concerning the (Environmental) LCA. A specific ISO - ISO/CD 14075 Principles and frameworks for social life cycle assessment is under way and will be released in the next years (14075, ISO standard). Therefore, a S-LCA study is organized into the four phases described for (Environmental) LCA:

1. Goal and Scope Definition;
2. Life Cycle Inventory – LCI;
3. Life Cycle Impact Assessment – LCIA;
4. Life Cycle Interpretation.

However, specificities of each phase and diversity of data required distinguish the two methodologies and calls for further explanations, provided in the next paragraphs.

Goal and Scope Definition

Goal definition

The objective of this phase is to provide information about:

- the reason why the study is carried out;
- the envisioned use of the results;

- the target to which it is destined;
- who will need the result (internal or external use);
- the assessed system;
- the selected relevant stakeholders and subcategories;
- the eventual improvement opportunities envisioned by the client and the practitioner(s).

The process is usually iterative, as the study itself. Therefore, the new information collected and/or processed in the following phases can provide new insights that would consequently require an adjustment of the goal defined in the very beginning of the assessment.

Scope definition

In this phase, the object of the study and the methodological framework is defined on the basis of the same elements previously listed in paragraph 2.1.2 for (Environmental) LCA, such as:

- functional unit (FU). It defines quantitatively the object of the study. In line with (Environmental) LCA, in S-LCA it is possible to adopt a product or an organization perspective, defining the FU accordingly. In the case of a product S-LCA, beside the product's description and technical utility, must state its social utility. This element will help to explicit the type C of positive impact further on in the study. While the definition of FU, and therefore of the product or organization perspective, is a mandatory step of S-LCA according to the guidelines, scholars approaching the methodology application are reporting the choice of FU as one of the main challenges for S-LCA feasibility. The discussion concerns the representativeness of a FU for the measurement of social aspects, in an assessment where the performance to be evaluated regards more the relation between the company and the stakeholder rather than the product flow itself. The result of the study should provide a perspective of the company as a whole, linking the socioeconomic impacts to its behaviour, and therefore be decoupled from the limitation of a system circumscribed to the FU (Zamagni et all, 2011; D'Eusanio et al. 2019; Martínez-Blanco et al. 2014);
- product system. In S-LCA, it is of utmost importance to specify the location of the activity and the involved companies. Indeed, S-LCA studies are location dependent, since the available databases are organized by country and retrieve information

through statistics accounting for the national laws concerning labour and workers' rights;

- system boundaries. The definition will establish which processes are going to be included in the assessment. In S-LCA, instead of applying a traditional physical perspective for the choice of the system boundaries, an effect perspective could prove to be more useful in underlining the relationship between stakeholders. Indeed, the first one draws relations between technological processes and economic flows, helping the definition for the production cycle and life cycle stages, while the effect perspective's attempt has the aim to represent interactions between companies and stakeholders ensuring the inclusion of all the concerned ones;
- activity variable (optional). It is a measure of the relevance of each unit process in the final system. It allows to account for different share of impacts, based on the importance every process has. The most common activity variable is "working-hours" (Bouillas, 2021), corresponding to the hours necessary for a worker to complete a production activity or unity process (UNEP, 2020);
- stakeholders. The selection of relevant stakeholders is a crucial part of a S-LCA. According to the guidelines, this choice is at the discretion of the practitioner, as well as the addition of a new category or the subdivision of a group of stakeholders into more specific ones. Stakeholders' participation in the indicators' selection process (public participation e.g., focus groups) is highly recommended, either to obtain more details or to guarantee that the selected indicators reflect their values;
- impact assessment method. To perform S-LCA, two methods can be selected: Reference Scale or Impact Pathway as described in Table 2-1. In both methods, relevant stakeholders and subcategories are selected, along with indicators, type of data, and data collection strategy;
- data collection strategy. In the *Scope* phase it is important to define which indicators would be adopted to assess each impact subcategory, per stakeholder type. This information will guide the process of data collection (inventory), that should also be describe.

Table 2-1 Impact assessment methods for S-LCA

REFERENCE SCALE APPROACH (RS)	IMPACT PATHWAY APPROACH (IP)
It aims at assessing the impact of a system based on its social performances or risks. It	This method assesses social consequences linking them in cause-effect

evaluates the data according to a defined benchmark taken as a reference in the scale of possible performances. To every behaviour adopted, a value is assigned; this would be above the reference if the performances is beyond standard and therefore generates positive impacts, below the reference if it results as non-compliant. This method is preferred when the goal is to obtain results on the present situation of the activity, since due to its approach it does not provide a long-term projection on the potential impacts. Moreover, since the most used databases align with the RS method, it results more convenient for practitioners to select it as the preferred approach (Bouillass et al., 2021).	relations. The objective is to predict the impacts related to the product system by establishing relationship between the product system itself and the potential impacts, in a process defined as "characterization". This approach reflects the need for an analysis that looks at the long-term scale that considers future implication of present performances, in a E-LCA fashion. However, its use is still limited since it proved to be valid only to assess the potential social and socio-economic impacts of the *workers* category, and for a restricted number of impact subcategories. (Bouillass et al., 2021)

Life Cycle Inventory

This phase is about collecting all the data required for the assessment. The required data and the collection strategy listed in the *Scope definition* phase are gathered for all the unit processes included within the system boundaries. As in the (Environmental) LCA, the process is carried out in an iterative fashion, adjusting accordingly to the development of the study. However, in S-LCA, data collection results more complex compared to (Environmental) LCA. Data and results are much more context and location dependant, making it a challenge to use database derived information. Indeed, collecting specific data by stakeholder is considered the most time-consuming phase of Life Cycle Inventory (UNEP, 2020). As in all Life Cycle studies, in S-LCA primary data collection is highly preferable, since database data could distort a specific company result significantly. Nonetheless, it is the availability of the information and the opportunity to obtain in-hand data, both qualitative and quantitative, that finally would lead the decision of which approach is to be adopted. To optimize the process and allocate efforts efficiently, it is suggested to adopt an approach to prioritize data collection, among the following (UNEP, 2020):

1. literature review. Are there background studies on the assessed system already providing information on which key social aspect are to be considered?;
2. identify the most intensive activities, based on the activity variable;
3. hotspot identification. The selection can be based on countries, envisioned risks, controverse products, etc.

Methodological sheets are provided among the material released by the UNEP/SETAC life cycle initiative, where practical examples of sources are proposed to help collection of data (Zanchi et al., 2018). The methodological sheets also provide a definition of the categories, the unit of measure, indicators, and other information to orient the inventory process.

It is highly suggested to collect qualitative primary data through interviews and questionnaires, to support a Reference Scale assessment or to validate the results of an Impact Pathway assessment carried out with the support of a dedicated software and the correspondent database. However, in the circumstances in which primary qualitative data are missing, S-LCA practitioners can rely on a number of databases that collected a significant amount of socio-economic data, enriched and update along with the development of specific S-LCA applications. It is important to notice that when only database information is used, the obtained results on *potential* social impacts provide company with a map of the social hotspots of their product life cycle.

Below, I will briefly present the Social Hotspot Database (SHDB) and the Product Social Impact Life Cycle Assessment (PSILCA). These databases have been the main sources for generic social data in S-LCA up to now and they are the ones more closely related to the S-LCA methodology, since they were developed in compliance with the Guidelines for Social Life Cycle Assessment (Pollok et al., 2021, UNEP, 2020). Moreover, they can be used in the same (Environmental) LCA software, increasing their convenience especially in cases of integrated studies.

Social Hotspot DataBase (SHDB)

The SHDB is a sector specific database developed by NewEarth B, available both in Simapro and as a separate tool. The first public version was launched in 2013, later updated in 2016 and in 2019. The database uses an economic Global Trade Input Model (GTM), therefore it requires input data as “purchases by country”, in dollars. If the country of origin is not provided as primary data, the GTM will provide estimate from through the software. Results includes information on the supply chain, a model for that product system including countries and sectors involved, worker hours information. From the latter, it is possible to obtain estimates of the work intensity of every production activity, providing information on which processes of the system are identified as social hotspots. Results can also be expressed in medium hours equivalent, describing the social footprint or the overall social risk associated with the product system (by impact category or by impact subcategory).

The SHDB 2019 is organized in 6 impact categories, 26 subcategories, 160 indicators and 244 countries.

Product Social Impact Life Cycle Assessment (PSILCA)

The PSILCA Database is a tool developed by GreenDelta. Since 2016, 3 versions have been released and the fourth is currently under development. The database is based on the model of the Eora database, using a multi-regional input/output approach. It covers 14 838 sectors for 189 countries. According to the characteristics of the databases currently on the market, it is considered to be the most comprehensive one available. It is organized into 4 stakeholder categories, 19 subcategories, and 69 qualitative and quantitative social aspects indicators. The goal for the fourth version is to address more social aspects that reflect society most discussed issues nowadays. (Psilca.Net).

Life Cycle Impact Assessment (LCIA)

In this phase, the data collected are elaborated to provide results for the understanding and evaluation of the potential social impacts of the product system. The potential impacts can be either referred to the present, past, or future of the system. The data are assigned to subcategory indicators and aggregated into the subcategories. The results provided reflect the impact of the specific subcategory on the stakeholder category to which it refers.

As described in Table 2-1, the impact assessment stage in the context of S-LCA can be performed according to two different approaches: Reference Scale Assessment (RS S-LCA) and Impact Pathway Assessment (IP S-LCA). RS S-LCA aims at assessing the impact of a system based on its social performances or risks, while IP S-LCA assesses social consequences linking them in cause-effect relations. In the following part I will present the main elements characterizing the two approaches.

Reference Scale approach

When implementing a study through the RS approach, Reference Scales are to be established during the inventory phase, for each indicator selected. They must comprise a number of levels corresponding to different levels of performance, indicated by number or in non-numerical terms, as letters or colours. Performance is qualitatively assessed through performance reference points (PRP) referring to one of the levels indicated, often coupled with a performance indicator elaborating on the requirement for a data to be associated to the specific level. The number of levels can vary from 2 (presence or absence of an impact) to 5, according to the case studies implemented up until now.

I will present two RS developed in the context of S-LCA: The Subcategory Assessment Method (SAM) by Ramirez et al. (Ramirez et al., 2014) and a semi-quantitative S-LCA based framework for the assessment of sustainability at early stages in the context of Safe and Sustainable Design of Engineered Nanomaterials and Nano-Enabled Products by Stoycheva et al. (Stoycheva et al., 2022). The first was chosen due to the popularity it gained since its first implementation; the second due to its relevance for the application in the case study presented in chapter 3 and chapter 4.

SAM

The method proposed, developed by Ramirez et al. (2014), aims at providing an evaluation approach for all S-LCA subcategories during the S-LCIA phase. The unit process has to be set as the manufactory organization itself, since it was considered the direct responsible for the processes involved in the product life cycle. For each subcategory a benchmark was defined on which to measure performance, named "basic requirements (BR)", defined according to the methodological sheets' indications. BR correspond to one of the four levels included in the scale, each identified with a letter and associated with different levels of compliance.

Level	A	B	C	D
Scale Score	4	3	2	1

Figure 2-8 Scale levels and score (Ramirez et al., 2014)

According to Figure 2-8, Level A corresponds to the better performance, going beyond compliance of BR. Level B accounts instead for companies fulfilling the BR, while performances not complying falls into level C if operating in a positive context and D if operating in a negative context. Then a questionnaire was developed for the inventory phase, with at least one question for each subcategory. The questionnaire target must be a minimum of one representative for each stakeholder category. To obtain more reliable information it is suggested to approach more actors as possible, for a triangulation of data. The result is a semi-quantitative social product profile, modelled on international standards that provides companies the knowledge required to implement proactive social responsibility behaviours.

Socio-Economic Life Cycle-Based Framework for Safe and Sustainable Design of Engineered Nanomaterials and Nano-Enabled Products

The tool developed by Stoycheva et al. (2022), combines S-LCA with a multi-criteria decision analysis, in order to semi-quantitatively self-assess the social impacts along the life cycle of a nanomaterial or nano-enabled product. The assessment is considered an initial screening due to the amount of information required, and therefore the previous step towards a full S-LCA. Since the aim was to create a nano-specific tool, only 19 of the 40 impact subcategories were considered relevant and selected to be included in the tool sheet. Then, a survey targeting every subcategory was developed to provide a data collection strategy for practitioners. Data were retrieved from the SHDB and the 2021 methodological sheets for S-LCA, by country of origin. The questions are constructed with three possible answers: (i) below national average, (ii) in line with national average, (iii) above national average. The results of the survey are then elaborated to obtain scores from indicators, then aggregated into subcategories, categories, and single score to compare the significance of social impacts.

Impact Pathway approach

If implementing an IP S-LCA assessment, the stakeholder focus loosens to give space to social mechanisms. They link activities included in the system to their social consequences. In line with (Environmental) LCA, they are represented by social impact categories, impact category indicators and characterization models. A visual representation is provided in Figure 2-9. The analysis provides results at midpoint and endpoint levels. In the first case, impacts calculated refers to the mid part of the cause-effect chain, while endpoints refer to the final impacts.

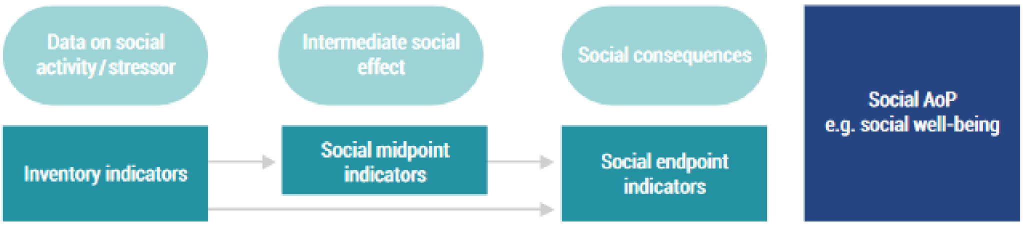

*Figure 2-9 social impact pathway scheme (*UNEP, 2020*)*

Life Cycle Interpretation

In this final phase, results are analysed in depth, summarized, and discussed to produce a final assessment providing conclusions, recommendations, and information for decision-making steps. In line with (Environmental) LCA, the interpretation of result is modelled from the requirements of ISO 14044 (2006). It must include information deriving from:

- completeness check: all the relevant issues indicated in the Goal and Scope have been addressed, which objectives have been achieved and which remain unsolved. If the results are not tuned with the goals, the Goal and scope should be revised and adapted, accordingly to the iterative nature of S-LCA;
- consistency check: the methodology applied has been implemented consistently throughout all the study and no evident contradiction can be find between the choice of indicators, method, and results obtained;
- sensitivity and data quality check: how the assumptions affected the results of the study. Different scenarios can be modelled to understand the contribution of the practitioner assumptions under different conditions;
- materiality assessment: it provides a tool to further interpret results, based on the share of impact associated with life cycle phases, processes or stakeholders;
- Conclusions, limitations, and recommendations.

Weaknesses

Due to its relative recent gain of interest in sustainability studies, S-LCA is still considered to be at an infancy level (Stoycheva et al., 2022). However, its implementation in published paper is showing a rising trend, as shown in Figure 2-10. Nonetheless, due to its applicability immaturity, it counts with a few barriers related to its implementation in case studies. Practitioners who have been dealing with social assessments point out the obstacle they encountered in their work, showing shared patterns. Although documents providing guidelines, UNEP/SETAC Guidelines for Social Life Cycle Assessment of Product between them, studies often differ for the lack of standardization and contradictions of the methodology (Pollok et al., 2021).

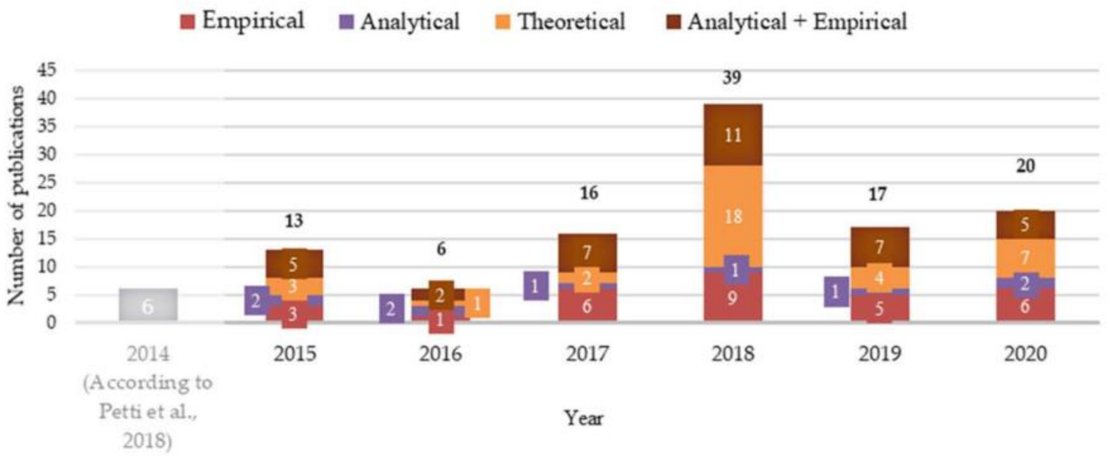

Figure 2-10 Trend of S-LCA publications between 2015 and 2020 (Pollok et al., 2021)

In the following part I will provide an overview of the most common issues and gaps that relates to S-LCA methodology, retrieved from a literature review based on bibliographic databases. The paper selected vary from step-by-step case studies to review paper on S-LCA state of art. A list of the findings is presented below:

- <u>functional unit (FU)</u>. As described in the paragraph (goal and scope), the definition of a functional unit is crucial to develop a study comparable to others concerning the same field of application. It is also fundamental in a context of LCSA, where the same FU would allow the alignment of the three methodologies. However, when attempting to measure social impacts, it becomes complex to find a unit originally designed to normalize data for quantifiable physical flows. Many social issues are not relatable to a functional unit but concern the company as a whole. Moreover, a company having a non-compliant performance only in production lines not inherent to the FU established would escape the share of bad impacts coming from those specific processes. Practitioners dealt differently with the challenge, resulting in a collection of studies hardly comparable. (Pollok et al., 2021; Zamagni et al., 2011);
- <u>definition of social impacts.</u> According to the guidelines definitions, social impacts cover a broad spectrum of impacts, including socioeconomic processes and social capital. Although theoretically various societal dynamics could be covered, having a look at the subcategories the company perspective results to be the privileged one. The

performance of a company on social matters is the main subject of assessment, while the consequences on the societal structure of the introduction of a product does not appear in the results. (Zamagni et al., 2011);

- product vs organization S-LCA. Practitioners claimed that the distinction between Product and Organization cannot be translated from (Environmental) LCA to S-LCA, since most of the times social impacts are inherent to the overall behaviour of the company more than to the specific product life cycle processes. On the other hand, a S-LCA adopting only an organization perspective would face the risk ignoring all the phases of a life cycle, losing the connection with the original methodology itself. (Pollok citing others);
- activity variable. The choice of using an activity variable as working hours could lead to a inappropriate weighting of negative impacts, if relegated to a non-significant amount of hours;
- data collection. According to the guidelines and to many research papers, this phase is the most time-consuming and complex of a S-LCA study. S-LCA requires context specific data, that can be provided either in a qualitative, semi-quantitative or qualitative form. Primary data are recommended to understand better the context and obtain more veritable depiction of the social situation (Petti et al., 2018). Only in the last couple of years databases started to provide data of an adequate level to evaluate social impacts, a quality that was lacking in the previous versions and therefore in virtually all the case study produced up to now (Tokede & Traverso, 2020). Therefore, the S-LCA assessment already published relied mainly on primary data, encountering challenges as the lack of resources, time (both of practitioners and companies), and willingness to collaborate, resulting in a less reliable outcome of the study. More specifically, in a study dealing with the S-LCA of a jar of honey, it was pointed out how the corporate culture is the main obstacle to a comprehensive assessment, since it lacks the understanding of the opportunities arising from such an assessment and it doesn’t perceive the whole supply chain as fundamental part of a product system. On the other hand, also micro-company could challenge the data collection at the supply chain level, since they are more likely to lack human and economic resources. (D’Eusanio et al., 2018);
- evolution of the society. Societies are inevitably dynamic systems. This represents a challenge for S-LCA, that does not provide a method on how to predict the evolutions and how to take account of them (Tokede & Traverso, 2020);

- communication strategies. S-LCA still misses strong communication strategies to reach the targeted public. Companies could be more prone to engage in such assessment if there was a clear opportunity to spend the result on the market. Zamagni et al. suggested the creation of a social label, inspired by the one related carbon footprint (Zamagni et al., 2011);
- subcategories indicators. The first version of the methodological sheets for subcategories in S-LCA, released in 2013, was considered not adequate to guide practitioners in the first phases of S-LCA. The lack of standard indicators and methods to select and collect data for their assessment, lead to a not homogeneous development of S-LCA studies, since the criteria to select relevant indicators was left to the practitioners judgment. The lack of theoretical foundations and empirical expertise did not provided a ground solid enough for the methodology to thrive (Kühnen & Hahn, 2017). However, the new updated version of the methodological sheets, following the release of the 2020 version of the Guidelines, is available since December 2021. Literature is still poor in case studies produced in the last couple of years, leaving as an open question if the new version has evolved to adapt better to practitioners need.

2.2.3 Software

Among the software available for S-LCA, most coincide with the software already presented for (Environmental) LCA, such as SimaPro, OpenLCA, and Gabi. For the purpose of this thesis, SimaPro will be described along with its SHDB extension.

The software is the most widely used among LCA practitioner and it supports the SHDB extension. It is developed by PRé Consultants (Product Ecology Consultants) and for this specific assessment it was used its 9.4.0.2 version. The tool provides a professional way to collect analyse and monitor sustainability performances through company data on products and services.

Data in the SHDB are organized by country. Each country provides a list of processes aligned with the Global Trade Analysis Project (GTAP) sectors; the country/process invoice is formed by a series of inputs of social issues from the GTAP network input-output. Every social issue is associated with the cost through a working hours relation, meaning that each dollar is linked with a certain amount of working hours. Each social issue has different levels of risk associated: Very High (VH), High Risk (HR), Medium Risk (MR), Low Risk (LR), Non Determined (ND). These levels of risk correspond to a specific characterization factor to which the working hours are multiplied to obtain the impacts in medium risk hour equivalent (mrheq). The result represents the probability of the specific risk to happen (SimaPro, 2019).

The software provides three impact assessment methods:

1. Social Hotspot 2016 Category Method w Weights. It weights the impact categories equally. We don't have the same number of subcategories for each impact category, so the subcategories will consequently be weighted not equally;
2. Social Hotspot 2016 Subcategory Method w Weights. Viceversa, it weights the subcategories equally;
3. Social Hotspot 2016 Subcat & Cat Method w Damages. It combines both approaches.

Due to the recent release of fourth and last updated version of the SHDB, the study was carried out with the former to last version, resulting in a slightly different subcategory selection. While the version three includes 5 category and 25 subcategories, the new version was enriched of one category and one more subcategory, going towards a more and more complete assessment (Grant, 2019; C. Norris et al., 2014; Norris et al., 2019). The impact assessment included in the SimaPro software is the Type II or Impact Pathway, which aims at assessing and model the relations between the social activities and their effects. It does so by creating impact pathways, linking the company activity to intermediate social impact level (midpoint), then to social damage and benefit levels (endpoints), and finally to an Area of Protection (AoP). AoP is usually identified as the Social or human wellbeing. Social Midpoint and Endpoint are usually defined according to the expertise of the impact pathway developing team, often times merging knowledge both from disciplines of the social and natural sciences to account for all kind of interrelations between social indicators and the damage or impact categories. The SHDB defined a set of five Endpoint, or categories, and 25 Midpoints, or subcategories. All share the same unit of measure, medium risk hour equivalent (mrheq). The list is provided below.

Categories (Endpoints), and related Subcategories (Midpoints):

1. Labour Rights & Decent Work
    a. Wage
    b. Poverty
    c. Child Labour
    d. Forced Labour
    e. Excessive Work Time

f. Freedom of Association
g. Migrant Labour
h. Social Benefits
i. Labour Laws/Conventions
j. Discrimination
k. Unemployment

2. Health & Safety
    a. Occupational Toxicity & Hazards
    b. Injuries & Fatalities
3. Human Rights
    a. Indigenous Rights
    b. Gender Equity
    c. High Conflict Zones
    d. Non-Communicable Diseases
    e. Communicable Diseases
4. Governance
    a. Legal System
    b. Corruption
5. Community
    a. Access to Drinking Water
    a. Access to Sanitation
    b. Children out of School
    c. Access to Hospital Beds
    d. Smallholder v Commercial Farms

2.3 LCC

2.3.1 Definition

The Life Cycle Costing is a methodology to assess and measure the cost associated with a product or a service during its whole life cycle. The goal is to provide decision-makers with a tool to include in the decisional process not only costs associated with the initial investment but also costs inherent to the operational processes, the maintenance, and the end-of-life or disposal phase. It is mainly used for the construction industry, production and use of energy, transportation sector (mainly aerospace), and military equipment. However, it's still missing a general standardization on the methodology that developed differently in specific application contexts. The available ISO standards are the following:

- ISO 15663:2021 Petroleum, petrochemical, and natural gas industries — Life cycle costing;
- ISO 15686-5:2008 Buildings and Constructed Assets. Service Life Planning;
- ISO 20468-8:2022 Guidelines for performance evaluation of treatment technologies for water reuse systems — Part 8: Evaluation of treatment systems based on life cycle cost.

There are three types of LCC, namely the conventional, the environmental, and the societal. The Conventional LCC (C-LCC) is the first type developed and it is a tool for a merely economical assessment. It is instead targeted to the market, often carried on before the system assessed is released into the market itself. The second type is represented by Environmental LCC (E-LCC), a methodology that aims at including in the analysis the externalities or the indirect costs in the environment, health and safety of stakeholder. The costs are therefore combined with the environmental through the internalization of the externalities deriving from the processes included in the system boundaries. The result is a match between the LCC and the LCA methodologies that provides a more comprehensive evaluation and an environmental accounting tool. LCC can also be adapted to include all the stakeholders involved in the life cycle, resulting in a third typology, the Societal LCC (S-LCC). This last type includes the assessment of economic, environmental, and social impacts, resulting in the most complete one. However, as in S-LCA, the complexity of measuring qualitative parameters has slowed down its application in real case studies. Nonetheless, in the last years, the trend in sustainability assessment methodology is making E-LCC and S-LCC the privileged decision-making tools, pointing toward a gradual replacement of C-LCC (*Associazione Rete Italiana LCA* 2022). Performing a E-LCC is, at the state of art, the most successful approach to guide technological progress and optimizing the trade-offs between the environment and the economic interest. Figure 2-11 provides a visual representation of the relationship between the three types of LCC.

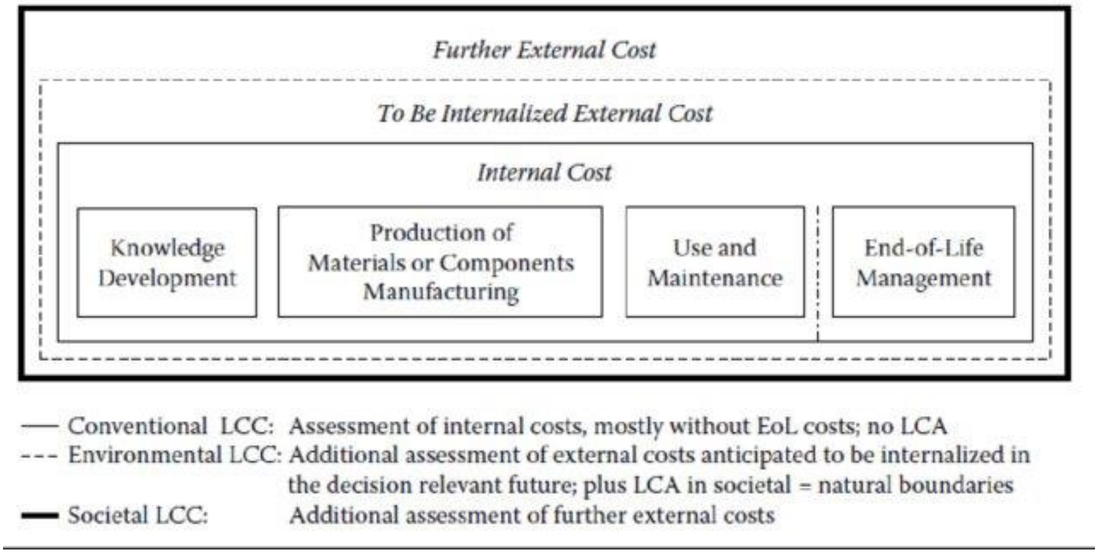

Figure 2-11 Three types of LCC. Figure by Fabio De Menna

In the following paragraphs it will be present the structure of an E-LCC study, since its standardization provide a measure of its coherence and reliability.

2.3.2 Structure

According to the SETAC Working Group, an E-LCC study aligns with the LCA framework defined by ISO 14040. Therefore, it develops in four phases, adaptable according to the specific case study:

1. Goal and Scope definition;
2. Economic life cycle inventory;
3. Interpretation;
4. Reporting and review.

Goal and Scope Definition

In this phase, the aim, the objective, the perspective, and the target of the study are defined. The most common objectives to develop a LCC study can be to identify the total cost of a product system, to evaluate a product competitivity on the market or to communicate the internal costs in a company. The perspective adopted can vary from the production company to the consumer or the supply chain. In line with LCA, also the functional unit and the system boundaries are selected in this phase. The functional unit will provide the reference to which all the cost and benefits are related. Specific for LCC is instead a Cost Breakdown Structure

(CBS). It would consist of a document in with all the costs incurrent in a project are detailed and whose development is recommended to facilitate the latter data collection (Valdivia & Lie, 2011). It must comprise the fundamental elements of an LCC analysis:

- initial investment (raw materials, research and development costs, transportation, installing);
- time frame considered (it is preferred to create different time frame scenarios to account for a more comprehensive analysis);
- discount rate;
- operational and maintenance costs;
- disposal costs.

Economic Life Cycle Inventory

All the costs inherent to the life cycle are listed and quantified on a unit process level (Valdivia & Lie, 2011). Data are retrieved from on-site interviews, company reports, or databases. It is necessary to collect direct, indirect, contingent costs and the externalities that will be internalised. Direct costs refer to the production phase; indirect costs account for external services payments, waste treatment costs, compensation of pollutants; contingent costs are the risk for uncertain future environmental damages; externalities that will be internalized are the costs associated to the environmental damages that is assumed will be paid for and therefore included in the final counting. The first two, direct and indirect costs, must be allocated according to the selected functional unit. The allocation is carried on based on a cost driver parameter, that can be, for instance, the working hours or the working cost associated to the specific activity. Contingent costs and externalities are to be actualized into present values, even if they represent eventual future expenses, in a process named *discounting*. The discount rate must be selected by the practitioner and justified in the assessment. It is warmly encouraged to perform a sensitivity analysis to evaluate different discount rate scenarios (Associazione Rete Italiana LCA, 2022).

Interpretation

This phase covers the evaluation of the results obtained after the data elaboration. Data must be checked in accuracy, quality, and relevance according to the goal and scope established in the first phase. This phase can also include uncertainty and sensibility analysis.

Reporting and Review

At the end of the study, results are collected in a report and revised according to the target established in the Goal and Scope phase. Unlikely traditional economic evaluation tools, E-LCC provides a more comprehensive assessment, focusing more on the supply chain effects rather than financial management aspects. This reflects the trend in public procurement and business sustainability reporting of requiring more holistic and comprehensive reports (De Menna, 2016). In line with (Environmental) LCA, it is recommended to implement an uncertainty, consistency, and completeness check.

3 Case Study

In the following chapters, it will be briefly presented the context in which the S-LCA methodology will be applied for the assessment of a nano-product developed by a European company. The company is one of the partners of the European Horizon2020 (H2020) project **Safe and sUstainable by design Strategies for HIgh performance multi-component NanomatErials** (*SUNSHINE).* Within the project, I worked with the partner GreenDecision, participating in the working group in charge of “industrial scale case studies”. In this context, I focalised on S-LCA as it is one of the more challenging sustainability assessments tool due to its relatively low implementation in on-field case studies. As will be explained in detail later, the approach developed by SUNSHINE includes three tiers of assessment for each sustainability pillar, each reaching a higher level of detail. Life Cycle Assessment corresponds to the last level, or Tier3. After obtaining results through the three methodologies – (Environmental) LCA, S-LCA, LCC – an integration of the data would allow the alignment from an LCSA perspective.

The following paragraphs will present (i) the relevant detail of the H2020 European project SUNSHINE for this case study, focusing on the main objectives envisioned, (ii) the Safe and Sustainable by Design (SSbD) concept on which it is based, (iii) the specific objective to which this work is contributing.

3.1 SUNSHINE

In the context of the European Green deal, it has been set the goal for a zero-pollution economy for a toxic-free environment. The implementation strategy includes the Chemical Strategy for Sustainability (CSS) and the Zero Pollution Action Plan, that through the transition to SSbD aims at preventing the risks associated with chemicals and advanced materials. Indeed, many industrial sectors are engaging in research and development to implement new technologies based on multi-component nanomaterials (MCNMs), technologies that offer unprecedented benefits both in performance and functionality, but simultaneously create concerns regarding the health and safety of users and the environment.

SUNSHINE is an industry-oriented project which aims at tackling these specific issues through the development of an overarching SSbD approach for advanced materials and practically test it on industrial MCNMs. MCNMs are considered key technology to transition to more sustainable innovations, and therefore the SUNSHINE success is a crucial step towards a more sustainable future. The precautionary principle on which it is based stems from the SSbD approach applied in a lifecycle perspective, that allows the risks and threats to be identified before the market release. The SSbD approach will be detailed in the next paragraph.

3.2 Safe and sustainable by design in a lifecycle perspective

The CSS describes the SSbD as: “a pre-market approach to chemicals design that focuses on providing a function (or service), while avoiding volumes and chemical properties that may be harmful to human health or the environment, in particular groups of chemicals likely to be (eco) toxic, persistent, bio-accumulative, or mobile. In this context, the overall sustainability should be ensured by minimising the environmental footprint of chemicals in particular on climate change, resource use, ecosystems and biodiversity from a life cycle perspective” (European Commission, 2020). Also, ”the SSbD approach addresses the safety and sustainability of the material/chemical/product and associated processes along the whole life cycle, including all the steps of the research and development (R&D) phase, production, use, recycling and disposal” (OECD, 2022).

The is a strong relation between SSbD and LCA. Indeed, Life Cycle Assessment is a comprehensive tool to measure and manage sustainability. It generally supports decision making processes in a retrospective perspective, meaning that it is applied ex-post to organizations and products already at the market level. While traditionally an LCA study does not explore the future scenarios explicitly, the analysis is anyway characterized by a future-oriented approach since the consequences triggered by the results would only be evident in the future (Buyle et al., 2019). According to the ISO standards 14040 and 14044, providing the framework for LCA, a study can be performed to assess impacts in an attributional or consequential fashion. Both approaches refer to an existing system, the former concerning the environmental footprint and the latter environmental consequences due to a change in the system (Tsalidis & Korevaar, 2022). However, according to Cucurachi et al. (Cucurachi et al., 2018), LCA practical application is evolving beyond the standards, producing more and more opportunities for the application of the cradle-to-gate framework in a more future-concerned way. Ex-ante LCA is one result of this process stemmed from the traditional “ex-post LCA”, referring to studies applied to systems already on the market. More specifically, it complements LCA approach by promoting the assessment from early stages, where changes are easier, more impactful in a long-term perspective, and less costly to implement. Interest on the topic is rising particularly in the field of emerging technologies, read – in technologies still at early stage of development, for which studies are focusing specifically on future states (Buyle et al., 2019). Our interest concerns emerging nanomaterials that, according to the European chemical strategy for sustainability (EC, 2020a), must be envisioned safe and sustainable from their design. The task bears the challenge of measuring the potential impacts through an approach that uses data at a lab or bench scale, producing preliminary results that allow to evaluate potential impacts in a LCA perspective. This strategy has been implemented in many works (e.g., NanoReg2022), since it is more and more demonstrating its potential to "lower uncertainty on the risks, higher ecological and economic value, increased stakeholder confidence and increased preparedness for future regulation" (Jiménez et al., 2022). Indeed, the iterative fashion of the LCA approach proposed allows to distribute costs and risks gradually through the development process, making each step proportional to the level of quality that the emerging technology has proven.

3.3 Life Cycle Sustainability Assessment of green and innovative solutions

Within SUNSHINE, a SSbD working group has been set up, which I contributed to, with the aim of developing, validating and implementing SSbD strategies along the product supply chain and the life cycle stages of assessed MCNMs. To this end, a tiered approach was developed, including screening-level qualitative (Tier1) and a semi-quantitative (Tier2) methodologies to be applied in the early stages of innovation and a quantitative (Tier3) assessment methods for the later stages. All the tiers include in the assessment the three sustainability dimensions, namely the environmental, social and economic one.

In details, the three tiers will be presented at their state of development as follows:

Tier1 consists in a qualitative self-assessment analysis at the Research and Development stage. The choice of focusing on early stage of the life cycle addresses the need to identify hotspots or possible safety and/or sustainability issues to tackle before the product is released to market. By doing so, it prevents the waste of resources that can be redirected to the further development of the product. The analysis is structured as a questionnaire including questions for the pre-evaluation of safety, sustainability and functionality. The questionnaire can theoretically be applied to possible design alternatives to inform the selection of the best option. As a life cycle thinking approach is adopted, the safety, sustainability and functionality assessment is carried out by considering all life cycle stages, from raw materials acquisition to the end of life.

Tier2 is a semi-quantitative analysis carried out through a scoring procedure aimed at understanding if the issues identified in Tier1 have been resolved or new issues arose.

Overall, the development of this tier is still at early stages, while it is already available a tool for the social sustainability assessment part (Stoycheva et al., 2022).

Tier3 covers the quantitative assessment level, evaluating safety and sustainability of the design alternatives that were selected in the prior tiers. This more detailed analysis involves, among other safety-related assessments, the Life Cycles' methodologies: (Environmental) LCA, S-LCA, and LCC (confront paragraphs 2.1; 2.2; 2.3).

The work performed for this thesis concerns the alignment of socio-economic aspects/indicators among the three tiers described above and the application of S-LCA in the Tier3, focusing the attention on Multi Components Nano Materials (MCNMs) and specifically on one case study which develop and innovative MCNM for non-sticking coating.

4 Application of the Social LCA to an innovative technology for non-sticking coating

The application of the Social LCA was conducted for a relevant case study from the SUNSHINE project, with the aim of understanding how to improve safety and sustainability of MCNMs in early stages of development. The purpose of this S-LCA study is to apply the S-LCA methodology to a nano-enabled product, more specifically a novel PFAS-free anti-sticking coating used in the baking industry. The coating is processed in a paint that is then used to cover baking trays.

The company selected for the case study specifically develops, produces and markets microencapsulated active ingredients and functional coatings based on nanomaterials. The material provided by the company and assessed for this case study is a nanocomposite coating composed of silica carbide and titanium dioxide (SiC@TiO_2) which provides non-stick properties on its application in bread baking trays. This innovative material is a substitute for Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS)-based non-stick coatings, such as Teflon (Polytetrafluoroethylene or PTFE). Indeed, it is well known that exposure to high levels of some PFAS may cause adverse health effects including reduced antibody responses to vaccines, increased cholesterol levels, low infant birth weight, and increased risk of high blood pressure (Pizzol et al., 2022). Therefore, industries are currently searching for ways to substitute Teflon-based coatings for safer and more sustainable alternatives.

The opportunity to avoid the use of toxic and carcinogenic substances such as PFAS is a promising step towards safer alternatives to the current market options. The innovative product has been realised using Sol-Gel-Derived Silicon-Containing Hybrids modified with SiC@TiO_2 which enhances anti-sticking properties when applied on baking trays. The presence of SiC in the core of the MCNM increases the mechanical and thermal properties, the durability, and improves the anti-sticking properties of the surface on which it is placed. The material main ingredients are two components, a 60nm SiC@TiO_2 and a 500 nm SiC@TiO_2.

The specific case study was selected due to its advanced stage in the SUNSHINE project. Indeed, for this case study the application of the Tier1 of the SSbD approach is already available.

4.1 Description

The Social LCA study was developed according to the 2020 version of the UNEP/SETAC Guidelines. The document suggests the assessment of social impacts for six stakeholder categories, each associated with a set of subcategories covering relevant matters for the specific social group. The stakeholder categories are the basis of the assessment since their selection in the scope has to be justified mandatorily (Stoycheva et al., 2022). Indeed, although it is strongly encouraged an assessment including all six of them, many scholars have developed case studies whose focus encloses one of few stakeholders' category. This was due either to poor data availability or to produce a work able to provide a more detailed focus on all kinds of impacts related to one specific stakeholder. In some cases, efforts were concentrated to contrast the complexity and the time required to produce a full assessment with primary data, still considered one of the main obstacles to a reliable S-LCA study.

For this study, the following categories of stakeholders were included in the assessment: Workers, Local community, Value chain actors, Consumers, and Society. The choice is in line with the paper developed by Stoycheva and colleagues (Stoycheva et al., 2022) for the development of socio-economic assessment of (advanced) engineered nanomaterials and nano-enabled products (NEPs) to support safe-and-sustainable-by-design (SSbD) decision making by industries in the early stages of product development. The paper presents a S-LCA scoring methodology which fits within Tier2 of the SSbD approach described above and provides a list of relevant subcategories for MCNMs. The list includes a spectrum of nineteen subcategories covering all the stakeholder categories but children, because it was developed before the release of the updated version of the UNEP/SETAC Guidelines. This theoretical background was also considered for the choice of relevant stakeholders and subcategories to include in the qualitative questionnaire developed for Tier1. Tier1 results were then used to discuss the case study results of the S-LCA, according to the primary qualitative data collected throughout the questions submitted to the production company.

The list of subcategories selected in the Tier2 was used to tune the first qualitative level, Tier1, with the second, Tier2, with the aim of creating a stronger base for the Tier3 S-LCA. By doing so, the most relevant subcategories for MCNMs assessment have been covered more in detail for the latter S-LCA assessment. Even though Tier1 comes before Tier2 both conceptually and operationally, the latter was used to perform an ex-post alignment, after a first testing in the case study of SUNSHINE project. Tier1 consists in a first screening assessment, based on the implementation of a qualitative analysis through a self-assessment questionnaire addressing safety, functionality, and sustainability of advanced materials. The questionnaire is structured in five sections, one for each life cycle stage: raw materials and resources production, production (material), manufacturing, use, end of life. In each section, the sustainability part was organized to cover all dimensions of sustainability, in order to provide a comprehensive tool for this first step of sustainability assessment. The work of tuning was performed for the questions concerning the socioeconomic aspects of sustainability, in line with the topic developed in this thesis.

Tier1 questions concerning social sustainability where initially not organized according to the stakeholders and subcategories associated with the S-LCA methodology, being it the first assessment level developed in the project. Moreover, the first version was not aligned with aspects to be considered in Tier2 and Tier3. Therefore, the first step was to match the questions from Tier1 to the stakeholders and subcategories, both provided in the methodological sheets and selected by the study in which Tier2 was developed (Stoycheva et al., 2022; UNEP, 2020). A table for each stakeholder was structured, organized by subcategories, including the methodological sheet indicators provided by UNEP/SETAC document and the Tier2 related questions. Then, questions prepared in the first version of Tier1 were associated to the relevant rows. If a match was not found, the column was left blank. Following, the list of the relevant subcategories selected for Tier2, by stakeholder category is reported:

- workers: child labor, fair salary, working hours, forced labor, equal opportunities/discrimination, health and safety;
- local community: access to material resources, delocalization and migration, safe and healthy living conditions, respect of indigenous right, local employment;
- value chain actors: supplier relationships;
- consumers: health and safety, end-of-life responsibility;
- society: contribution to economic development, prevention and mitigation of armed conflicts, technology development, corruption, ethical treatment of animals.

Figure 4-1 present schematically the reasoning behind the tuning work; Table 4-1 shows the original Tier1 questionnaire; Table 4-2 is the one created after the first step of the tuning.

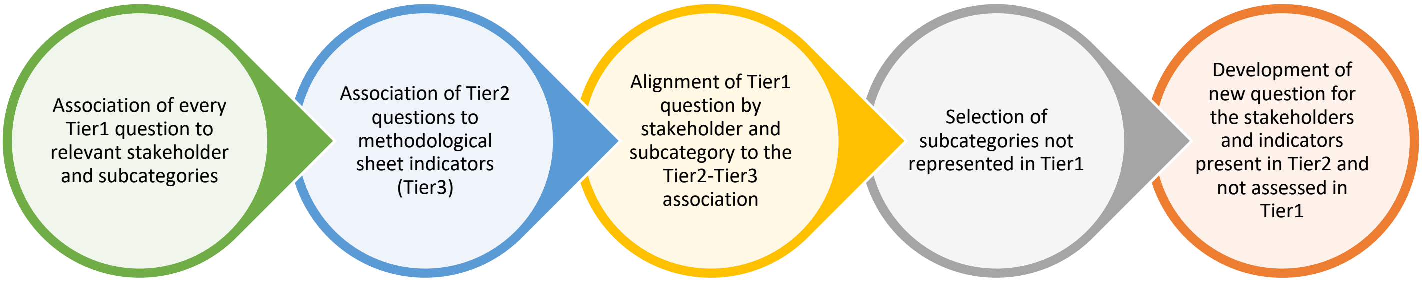

Figure 4-1 Step-by-step tuning procedure for Tier1 and Tier2

Table 4-1 First version of Tier1 questionnaire developed for SUNSHINE project

Aspects	Ambition	Objectives/ criteria	Indicators	Questions	Stakeholder	Subcategory
Life Cycle Stage: Raw materials and resources-Production						
Social sustainability	**Improvement of the social aspects**	**Traceability**	Traceability of raw materials	Are there policies in place to allow traceability of your raw materials?	Value chain actors	Supplier relationships
			Raw materials coming from underdeveloped, developing or third world countries	Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?	workers	Child labor, health and safety, equal opportunities/discrimination
Life Cycle Stage: Production of the MCNM						
Social sustainability	**Improvement of the social aspects**	**Traceability**	Promotion of regional products	Are supplies used during the production process promoting regional products?	Local community	Cultural heritage
			Assessment of suppliers	Are suppliers socially responsible (e.g., if they implement CSR principles)?	Value chain actor	Supplier relationships
		Increase in value	Technological development, economic impact, education opportunities	Did you consider if the production process results in technological development, additional education opportunities?	Society	Technology development
Life Cycle Stage: Production of the product						
Social sustainability	**Improvement of the social aspects**	**Traceability**	Promotion of regional products	Are supplies used during the manufacturing promoting regional products?	Local community	Cultural heritage
			Assessment of suppliers	Are suppliers socially responsible (e.g., if they implement CSR principles)?	Value chain actor	Supplier relationship
		Increase in value	Technological development, economic impact, education opportunities	Did you consider if the manufacturing process results in technological development, additional education opportunities?	Society	Technology development
Life Cycle Stage: Use						
Social sustainability	**Improvement of the social aspects**	**Traceability**	Promotion of regional products	Is the product promoted regionally?	Local community	Cultural heritage

Table 4-2 First step of tuning of Tier1, Tier2, and partially Tier3

WORKERS		
1. Child Labor		
Tier1	Tier2	Methodological sheet indicator (Tier3)
Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?	Self-evaluation of the risks of child labour in their own operation and their suppliers as above, below or equal to the national average (SHDB)	Percentage of working children under the legal age of 15 years old (14 y for developing economies)
		Children are not performing work during the night
		Records on all workers stating names and ages or dates of birth are kept on file
		Working children younger than 15 and under the local compulsory age are attending school
2. Fair salary		
Tier1	Tier2	Methodological sheet indicator (Tier3)
Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?	Evaluation of the risks of wage and poverty levels in their own operation and their suppliers as below or equal to the national average (SHDB)	Lowest paid worker, compared to the minimum wage and/or living wage
		Number of employees earning wages below poverty line
		Presence of suspicious deductions on wages
		Regular and documented payment of workers
3. Working hours		
Tier1	Tier2	Methodological sheet indicator (Tier3)
	Operationalized in terms of excessive working time using data from the SHBD	Number of hours effectively worked by employees (at each level of employment)
		Number of holidays effectively used by employees
		Respect of contractual agreements concerning overtime
		The organization provides flexibility
4. Forced labor		
Tier1	Tier2	Methodological sheet indicator (Tier3)

Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?	Self-evaluation of the risks of forced labor in their own operation and their suppliers as above, below or equal to the national average (SHDB)	Workers voluntarily agree upon employment terms. Employment contracts stipulate wage, working time, holidays and terms of resignation. Employment contracts are comprehensible to the workers and are kept on file
		Birth certificate, passport, identity card, work permit, or other original documents belonging to the worker are not retained or kept for safety reasons by the organization neither upon hiring nor during employment
		Workers are free to terminate their employment within the prevailing limits
		Workers are not bonded by debts exceeding legal limits to the employer

5. Equal opportunities/discrimination

Tier1	Tier2	Methodological sheet indicator (Tier3)
Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?	Evaluation of the risks of the levels of gender inequity and discrimination in their own operation and their suppliers as below or equal to the national average (SHDB)	Total numbers of incidents of discrimination and actions taken
		composition of governance bodies and breakdown of employees per category according to gender, age group, minority, group membership and other indicators of diversity
		Ratio of basic salary of men to women by employee category
		presence of formal policies on equal opportunities
		Announcements of open position happen through national/regional newspaper, public job databases on the internet, employment services, or other publicly available media ensuring a broad announcement

6. Health and safety

Tier1	Tier2	Methodological sheet indicator (Tier3)
Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?	Evaluation of the risks of occupational toxics and hazards and cases of injuries and fatalities at their own operation (SHDB)	Number/percentage of injuries or fatal accidents in the organization by job qualification inside the company
		Hours of injuries per level of employees
		Number of (serious/non-serious) Occupational Safety and Health Administration (OSHA) violation reported within the past 3 years and status of violation
		Presence of a formal policy concerning health and safety
		Adequate general occupational safety measures
		Preventive measures and emergency protocols existing regarding accidents and injuries
		Preventive measures and emergency protocols existing regarding pesticide and chemical exposure
		Appropriate protective gear required in all applicable situations
		GRI lab: education, training, counselling, prevention, and risk control programs in place to assist workforce members, their families, or community members regarding serious disease

LOCAL COMMUNITY

7. Access to Material Resources

Tier1	Tier2	Methodological sheet indicator (Tier3)
	Users are asked (i) if they assess the impacts their operation has on the local community or (ii) if they have a certified environmental management system (Generic)	Has the organization developed project-related infrastructure with mutual community access and benefit
		Strength of organizational risk assessment with regard to potential for material resource conflict
		Does the organization have a certified environmental management system

8. Delocalization and migration

Tier1	Tier2	Methodological sheet indicator (Tier3)
	Evaluation of the risks to migrant workers in their own operation and their suppliers as below or equal to the national average (SHDB)	Number of individuals who resettle (voluntarily and involuntarily) that can be attributed to the organization
		Strength of organizational policies related to resettlement (e.g. due diligence and procedural safeguard)
		Strength of organizational procedures for integrating migrant workers into the community

9. Safe and healthy living conditions

Tier1	Tier2	Methodological sheet indicator (Tier3)
	Evaluation of (i) communicable diseases, (ii) non-communicable diseases, (iii) access to drinking water and (iv) access to sanitation at their suppliers' (SHDB)	Management oversight of structural integrity
		Organization efforts to strengthen community health (e.g. through shared community access to organization health resources)
		Management effort to minimize use of hazardous substances

10. Respect of Indigenous Right

Tier1	Tier2	Methodological sheet indicator (Tier3)
	Evaluate the overall risk of indigenous rights being infringed (SHDB)	Number of reported and/or documented illegal activities
		Strenght of Policies in Place to Protect the rights of Indigenous Community Members
		Annual Meetings Held with Indigenous Community Members
		The organization committed to accepting indigenous land rights

		Response to Charges of Discrimination against Indigenous Community Members

11. Local Employment

Tier1	Tier2	Methodological sheet indicator (Tier3)
	Operationalized in terms of the unemployment rate in local communities using SHDB data	Percentage of workforce hired locally
		Percentage of spending on locally based suppliers
		Strenght of policies on local hiring preferences

VALUE CHAIN ACTORS

12. Supplier Relationships

Tier1	Tier2	Methodological sheet indicator (Tier3)
Are there policies in place to allow traceability of your raw materials?	First, users are asked if they provision a social assessment of their suppliers in their procurement process. Next, a full assessment of all relevant impact categories applicable for suppliers is conducted. Indicators 1-6; 8-11, 18-19. (Generic)	Absence of coercive communication with suppliers
		Sufficient lead time
		Reasonable volume fluctuation

CONSUMERS

13. Health and Safety

Tier1	Tier2	Methodological sheet indicator (Tier3)
	Users should report whether they assess the hazard, social and ecological impacts their products might have on consumers (Generic)	Number of consumer complaints
		Number of defects detected per production batch
		Presence of Management measures to assess consumer health and safety
		Quality of labels of health and safety requirements
		Presence of a Quality and/or Product Safety Management System such as ISO 9001:2015, British Retail Consortium (BCR), Halal, International Food Standard (IFS), ISO 10377:2013, etc.

14. End-of-life responsibility		
Tier1	Tier2	Methodological sheet indicator (Tier3)
	Users should assess whether they (i) have incidents of non-compliance with regulatory labelling requirements, (ii) do not have incidents of non-compliance with regulatory labelling requirements or (iii) have systems in place to ensure that clear information is provided to consumers on end-of-life options (Generic)	Annual incidents of non-compliance with regulatory labelling requirements
		Do internal management system ensure that clear information is provided to consumers on end-of-life options (if applicable)?

SOCIETY		
15. Contribution to Economic Development		
Tier1	Tier2	Methodological sheet indicator (Tier3)
Did you consider if the the manufacturing process results in technological development, additional education opportunities?	Users need to assess whether their innovative (nano-enabled) product is creating more value for society compared to their conventional product (Generic)	Proportion of informal employment in non-agricultural employment, by sex
		Average hourly earnings of female and male employees, by occupation, age, and persons with disabilities
		Contribution of the product/service/organization to economic progress (e.g., annual growth rate of real GDP per employed person)
16. Prevention and mitigation of armed conflicts		
Tier1	Tier2	Methodological sheet indicator (Tier3)
	Users are asked whether they are evaluating and choosing their suppliers based on sourcing from conflict-free regions (Generic)	Organization's role in the development of conflicts
		Disputed products
17. Technology development		
Tier1	Tier2	Methodological sheet indicator (Tier3)
Did you consider if the manufacturing process results in technological development, additional education opportunities?	Users are asked to choose whether their product R&D activities are based on (i) their own know how, (ii) local collaboration or (iii) global collaboration (Generic)	Involvement in technology transfer program or projects
		Partnership in research and development
		Investments in technology development/technology transfer

18. Corruption		
Tier1	Tier2	Methodological sheet indicator (Tier3)
	Users are (i) asked whether they are evaluating and choosing their suppliers based on sourcing from corruption-free areas in addition to (ii) corruption rates data directly taken from the SHDB	Formalized commitment of the organization to prevent corruption, referring to recognized standards
		The organization carries out an anti-corruption program
		The organization installs or co-operates with internal and external controls to prevent corruption
		Written documents on active involvement of the organization in corruption and bribery; convictions related to corruption and bribery

19. Ethical treatment of animals		
Tier1	Tier2	Methodological sheet indicator (Tier3)
	Users are asked whether they have a code of conduct/follow procedures for ensuring ethical treatment of animals in their value chain (Generic)	Presence/number of serious injuries, illnesses, and unforeseen fatal casualties reported by workers and animal specialists
		Presence/number of behavioural disorders or occupational diseases reported by workers, animal specialists, and/or civil society members
		Quality, dimension and hygiene of livestock farming conditions; livestock density
		Presence of regular check-ups and frequency of animal welfare conducted by specialists (vets, animal biologists, or others)
		Complaints from consumers or civil society organizations representing animal welfare issues
		Actions in response to complaints or serious unforeseen cases putting the lives or welfare of the animal at risk
		Presence of any label certifying the fair treatment of animals
		Improvements over time concerning the prevention of injuries, illnesses, and unforeseen fatal casualties
		Improvements over time concerning the prevention of behavioural disorders and occupational diseases

Once the first version of Tier1 had been compared with Tier2, new questions had to be developed to fill the gaps revealed by the comparison. It was considered appropriate to implement a question for each of the stakeholder category included in Tier2. Questions to cover Local community, Value chain actors, Workers and Society were added since they were missing for all the life cycle phases, Use phase excluded. In this phase only Local community and Consumer was assessed. This was because the Use phase is usually less related to processes and dynamics covered by the subcategories developed for Value chain actors and Society. Following, the new questions developed are listed, organized by stakeholder and life cycles stage, in line with Table 4-3. Questions in blue are the one added during the tuning. Questions stricken through are the one that were removed from the original version.

The description of the development of the new questions is reported in

Appendix 1. Reasoning behind the development of the new questions for Tier1

Table 4-3 Tier1 questionnaire, after the tuning with Tier2

Aspects	Ambition	Stakeholder	Subcategory	Objectives/ criteria	Indicators	Questions Tier1
Social sustainability	**Improvement of the social aspects**	Local community	Access to material resources	Access to material resources	Material resources access	Do your suppliers respect and protect community access to local material resources (i.e. water, land, mineral, and biological resources) and infrastructure (i.e. roads, sanitation facilities, schools, etc.)?
			Safe and healthy living conditions	Safe and healthy living conditions	Health and safety improvement	Does the activity contribute to improve (e.g., through sharing health services) or damage (e.g. use of hazardous materials, pollution) safety and health of the local community?
		Value chain actors	Supplier relationships	**Traceability**	Traceability of raw materials	Are there policies in place to allow traceability of your raw materials?
		Workers	Child labour, health and safety, equal opportunities/discrimination,	Child labour, health and safety, equal opportunities/discrimination,	Raw materials coming from underdeveloped, developing or third world countries	Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?
		Society	Prevention and mitigation of armed conflicts	Prevention and mitigation of armed conflicts	Absence of armed conflicts	Is the origin country of raw materials free from armed conflicts?
		Local community	~~Cultural heritage~~	~~**Traceability**~~	~~Promotion of regional products~~	~~Are supplies used during the production process promoting regional products?~~
			Safe and healthy living conditions	Safe and healthy living conditions	Health and safety improvement	Does the activity contributes to improve (e.g. through sharing health services) or damage (e.g. use of hazardous materials, pollution) safety and health of the local community?
			Local employment	Local employment	Local employment	Does the organization affect the local employment rates?
		Value chain actor	Supplier relationships	Supplier relationships	Assessment of suppliers	Are suppliers socially responsible (e.g., if they implement CSR principles)?
		Workers	Child labor, health and safety, equal opportunities/discrimination,	Child labor, health and safety, equal opportunities/discrimination,	Raw materials coming from underdeveloped, developing or third world countries	Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?
		Society	Technology development	**Increase in value**	Technological development, economic impact, education opportunities	Did you consider if the production process results in technological development, additional education opportunities?
		Local community	~~Cultural heritage~~	~~**Traceability**~~	~~Promotion of regional products~~	~~Are supplies used during the manufacturing promoting regional products?~~
			Local employment	Local employment	Local employment	Does the organization affect the local employment rates?
		Value chain actor	Supplier relationship	Supplier relationship	Assessment of suppliers	Are suppliers socially responsible (e.g., if they implement CSR principles)?
		Workers	Child labor, health and safety, equal opportunities/discrimination,	Child labor, health and safety, equal opportunities/discrimination,	Raw materials coming from underdeveloped, developing or third world countries	Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?
		Society	Technology development	**Increase in value**	Technological development, economic impact, education opportunities	Did you consider if the manufacturing process results in technological development, additional education opportunities?
		Local community	Cultural heritage	**Traceability**	Promotion of regional products	Is the product promoted regionally?
		Consumer	End-of-life responsibility	End-of-life responsibility	End-of-life information	Is clear information on end-life-options provided through labelling?

4.2 Social Life Cycle Assessment

As reported in paragraph 2.2.2, the Social Life Cycle Assessment is organized according to four phases, goal and scope definition, life cycle inventory, life cycle impact assessment and life cycle interpretation. In the next paragraphs the four phases applied to the case study are shown.

Goal and scope definition

The main goal of this S-LCA was to evaluate through the UNEP/SETAC Guidelines, the social risks from cradle to grave of a nano-enabled paint used in the baking industry for the whole life cycle except the end-of-life phase. Indeed, the Social Hotspot Database (SHDB) available for SimaPro does not include data on end-of-life and consumer impacts, therefore it was not possible to include the impacts related to this phase in this study (Raneses, 2018). The assessment results aim at producing new knowledge for the Research and Development unit of the company producing the MCNM, for the continuous improvement of the product before its market release.

As it is described in the introduction of this chapter, the paint contains an engineered nanomaterial that is responsible for the anti-sticking function. The positive outcome envisioned through the development of this product is to obtain a material that present minimum risks for human health, the environment, and social matters.

The S-LCA study covers aspects related to the extraction and transport of the main materials (upstream process), the production of the paint containing the MCNMs (core process), and the application of the paint on industrial baking trays by a third company (downstream process). The MCNM production process is based in the company factory in Spain, while the application of the paint on baking trays is competence of another company. The presented S-LCA considers all the main materials used and the quantification of energy and water consumption.

Simplified flowcharts illustrating the upstream, core, and the downstream processes are reported in Figure 4-2, Figure 4-3, and Figure 4-4.

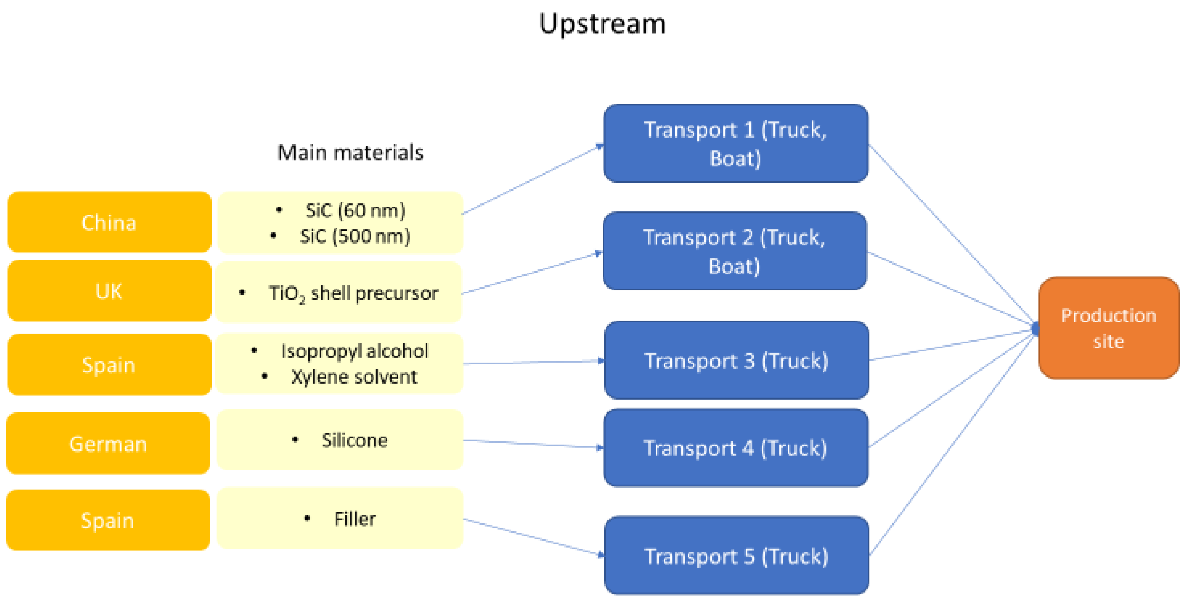

Figure 4-2 Upstream process comprising raw materials and their transport to reach the company producing the nano-enabled paint

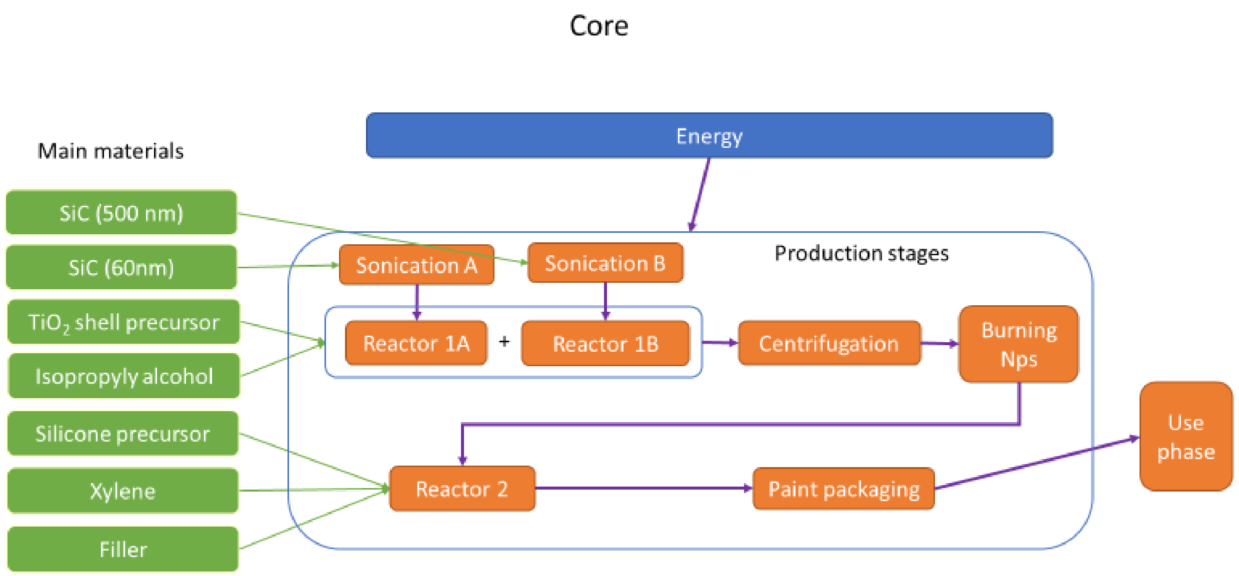

Figure 4-3 Core process comprising the production stages of the nano-enabled paint

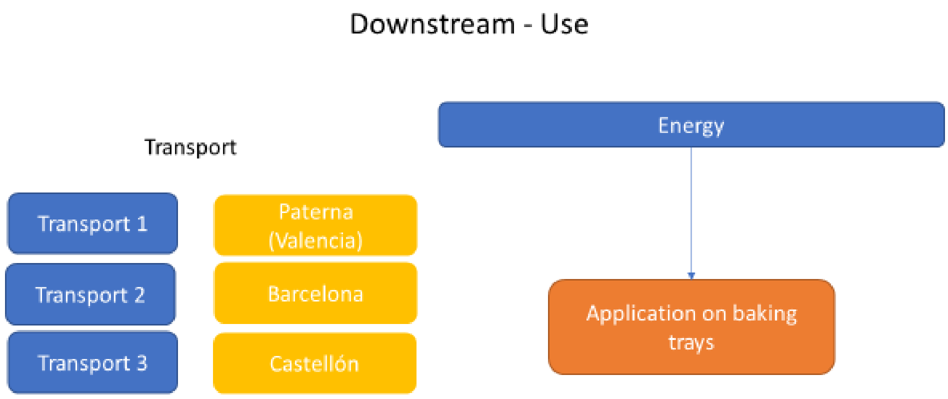

Figure 4-4 Downstream process comprising the transport and use of the nano-enabled paint by its application on baking trays by an external company

The functional unit (FU) chosen for this case study is 0,1 kg of paint, needed to cover 1 m^2 of baking tray that can be used for 6 months, a period of time after which it requires maintenance. It corresponds to three industrial baking tray, which average size was retrieved from literature. The system boundaries also include the process of application of the paint on a baking tray, by an external company.

The stakeholder selection was subordinated to the subcategories assessed by the SHDB implemented within the SimaPro software. The version used is SHDB 2016, that includes subcategory indicators for four stakeholders' categories: workers, local community, value chain actors, and society. As already introduced, consumer and children are not included in the SHDB 2016 version, but they have been included in the last version released (SHDB 2019) which was not available as database to be integrated within SimaPro at the time of the thesis development. Nonetheless some subcategories cover children related social issues (i.e.; Child Labour, Children out of School).

Life cycle inventory

Life cycle inventory was carried out in order to obtain data for an Impact Pathway social life cycle assessment (IP S-LCA) through the software SimaPro, and therefore modelled on a (Environmental) LCA data collection. Indeed, as described in paragraph 2.2.2 a S-LCA study can be performed according to two different approaches: Reference Scale Assessment (RS S-LCA) and Impact Pathway Assessment (IP S-LCA), and for this study the latter was chosen. For the collection of data from the involved company, an Excel file was prepared, organized into tables already pre-disposed for data elaboration. Primary data were collected through the submission of these documents to the production company, which was provided with a detailed step-by-step explanation on how to perform the information collection. The tables included specific column indicating the origin of the main materials used and the costs of the materials. These data specifically concern the S-LCA assessment, that specifically requires information on countries of origin. Indeed, impacts are heavily dependent from location, and the cost used to infer the working hours is based on data on country average salary in the specific sector.

Once obtained the data, the values were elaborated according to the selected FU. Data were provided divided by each step of the nanomaterial processing. As reported in Figure 4-3, the production stages are the following:

- Sonication of SiC 60nm (Sonication A);
- Sonication of SiC 500nm (Sonication B);
- Reactor A, where the 60 nm SiC is binded with TiO_2;
- Reactor B, where the 500nm SiC is binded with TiO_2;
- Centrifugation;
- Burning Nps;
- Reactor 2;
- Paint packaging.

To insert the data in the SimaPro software, each main material, from now "main process", was associated with a SHDB process. SHDB processes are organized by Global Analysis Project (GTAP) sector and by country, whose code can be found after the sector indication (CHN – China; GBR – United Kingdom; ESP – Spain; DEU – Germany). The associations can be found in Table 4-4.

Table 4-4 Model of nano-enabled anti-sticking coating

Life cycle inventory modelling
Assumptions: the SHDB list of GTAP sectors does not include all of the available ones. Isopropyl alcohol and Xylene solvent pertains to the GTAP sector "chm - Manufacture of chemicals and chemical products". However, being it not included in the SHDB, the two materials were associated to "Chemical, rubber, plastic products", losing in accuracy. For the model by process, transports were allocated to processes based on the amount of material entering the specific process. Transportation, even if specified by type "truck" or "boat", could not be associated with database processes specific for means of transport, since the SHDB only provides the general process "transport", by country.

Difference in impacts of different types of transports are therefore not included in the assessment.		
Nature	**Main processes**	**SHDB processes**
Material	SiC 60 nm	Mineral products nec/CHN S
Material	SiC 500 nm	Mineral products nec/CHN S
Material	TiO2 shell precursor	Metal products/GBR S
Material	Isopropyl alcohol	Chemical, rubber, plastic products/ESP S
Material	Xylene solvent	Chemical, rubber, plastic products/ESP S
Material	Silicone	Mineral products nec/DEU S
Material	Filler	Mineral products nec/ESP S
Energy	Electricity for production	Electricity/ESP S
Energy	Electricity for use	Electricity/ESP S
Transport	Transport SiC 60 nm	Transport nec/CHN S
Transport	Transport SiC 500 nm	Transport nec/CHN S
Transport	Transport TiO2 shell precursor	Transport nec/GBR S
Transport	Transport Isopropyl alcohol	Transport nec/ESP S
Transport	Transport Xylene solvent	Transport nec/ESP S
Transport	Transport Silicone	Transport nec/DEU S
Transport	Transport Filler	Transport nec/ESP S

Life Cycle Impact Assessment

In this study, the software SimaPro was used to model the product system of the innovative enabled nanomaterial for non-stick paint. The tool provides a professional way to collect analyse and monitor sustainability performances through company data on products and services. This assessment was conducted in the one step of social risk hotspot assessment, using the Social Hotspot Database available for SimaPro. Due to the recent release of the last updated version of the SHDB (2019), the study was carried out with the SHDB 2016.

For the purposes of the Social Life Cycle Assessment, the product system was modelled by production stages, each including the corresponding *material, energy,* and *transport* main processes, as follow:

1. **Sonication A** (SiC 60nm; isopropyl alcohol; electricity; water; transport SiC 60 nm; transport Isopropyl alcohol);

2. **Sonication B** (SiC 500nm; isopropyl alcohol; electricity; water; transport SiC 500 nm; transport Isopropyl alcohol);
3. **Reactor A** (Sonication A product; TiO2 shell precursor; isopropyl alcohol; electricity; water; transport TiO2 shell precursor; transport isopropyl alcohol);
4. **Reactor B** (Sonication B product; TiO2 shell precursor; isopropyl alcohol; electricity; water; transport TiO2 shell precursor; transport isopropyl alcohol);
5. **Centrifugation** (Reactor A product; Reactor B product; isopropyl alcohol; electricity, transport isopropyl alcohol);
6. **Burning Nps** (Centrifugation product; electricity);
7. **Reactor 2** (Burning Nps product; xylene solvent; silicone; filler; electricity; transport xylene solvent; transport silicone; transport filler);
8. **Paint packaging** (Reactor 2 product; electricity).

The final product, after the last production stage "paint packaging", is a drum of paint that will be used by the external company for the application on baking trays for the use life cycle stage.

However, once obtained the result for the model, it was deemed necessary to also create a model by main process, to better understand the contribution of each to the final social footprint of the product. Indeed, the results obtained from the model by process were too aggregated to be useful to the drawing of final conclusions. Therefore, the life cycle was modelled accordingly to what was considered the more appropriate way to present results in a clear and comprehensible way. It was decided to associate each *material* main process to its corresponding *transport* main process, creating assemblies named after the *material* main process (e.g., the *material main process* "SiC 60nm" was combined with the *transport* main process "transport for SiC 60 nm"). Electricity for production, electricity for use, and water were considered as original main processes. Figure 4-5 and Figure 4-6 shows the network diagram of the life cycle of the product, respectively by production stage and by main process. The thickness of the lines represents the relative contribution to the impacts of the different inputs.

From the first diagram is evident how the impacts sum up by the processing of the main materials, mainly due to the mineral products entering in the Sonications production stage and their transports, later summed with the other mineral products entering the Reactor2 production stage. The second diagram shows more clearly the mineral products contributions, having all the impacts related the specific main material not hided in the related production stages.

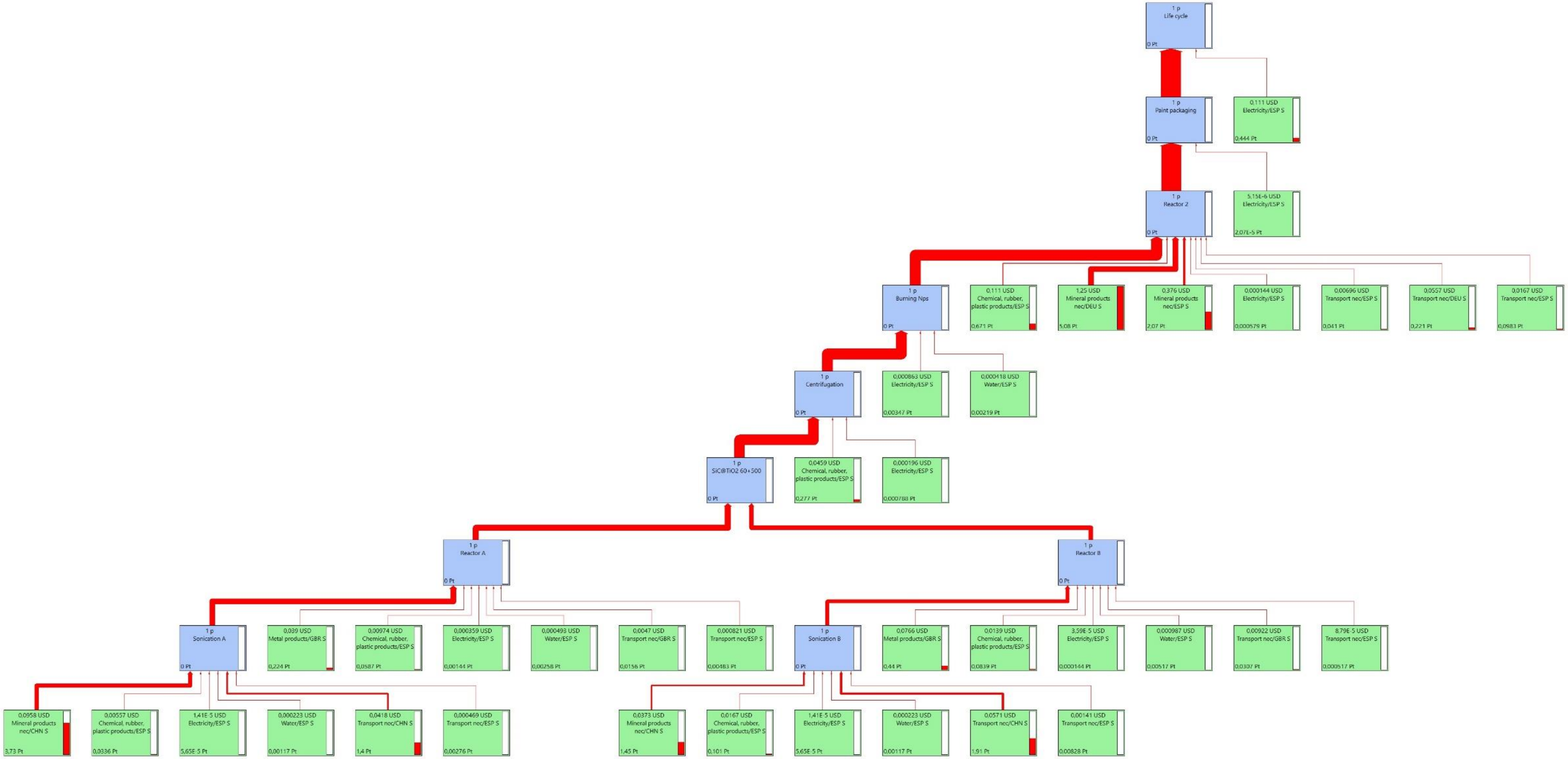

Figure 4-5 Network diagram related to the life cycle of nano-enabled paint by production stages

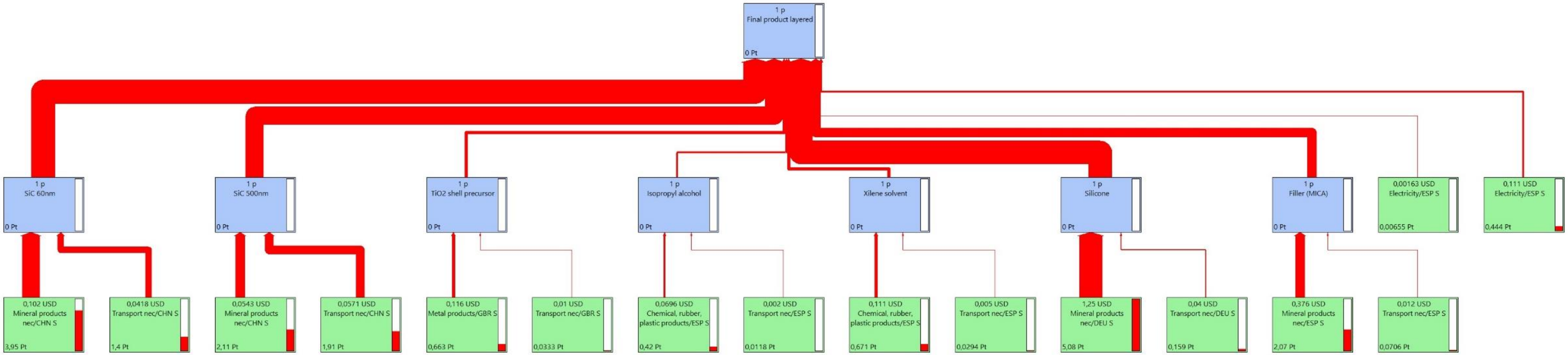

Figure 4-6 Network diagram related to the life cycle of nano-enabled paint by main processes

As reported in paragraph 2.2.2, the results of a Social Life Cycle Assessment are represented at subcategories and categories level, according to the level of detail. Indeed, the first focus on single social problems and the latter show the social impact on five aggregation levels. In the next paragraphs, the results by subcategories and categories of the S-LCA are showed.

Subcategories results

Results by subcategories are obtained using the Social Hotspot 2016 Subcategory Method w Weights available in SHDB for SimaPro. Figure 4-7 Subcategory single score results by core process (Sonication A and B, Reactor A and B, Centrifugation, Burning Nps, Reactor 2 and Paint packaging) and downstream process (use) Figure 4-8 show the social impacts estimated for the LCIA phase, on the total potential social impacts that correspond to 100%. The results indicate which subcategories should be further investigated, as to say which social hotspots are related to the life cycle of the product. The subcategories with major impacts results to be the following: child labour, freedom of association, migrant labour, occupational toxicity and hazard, high conflict zones, and corruption. They can be related to the workers and society stakeholders' categories, pointing out which are the stakeholders that should be directly consulted for a more detail S-LCA, or social handprint results. The impact contributions are mainly due to the Sonications stages and the Reactor2 stage. From Figure 4-8 it becomes clear how this is due to the main processes required for these production stages. SiC 60nm and SiC 500nm are the most impacting main processes due to their country of origin, indicated as China. It follows the Silicone, coming from Germany, and representing the third main process for impact share.

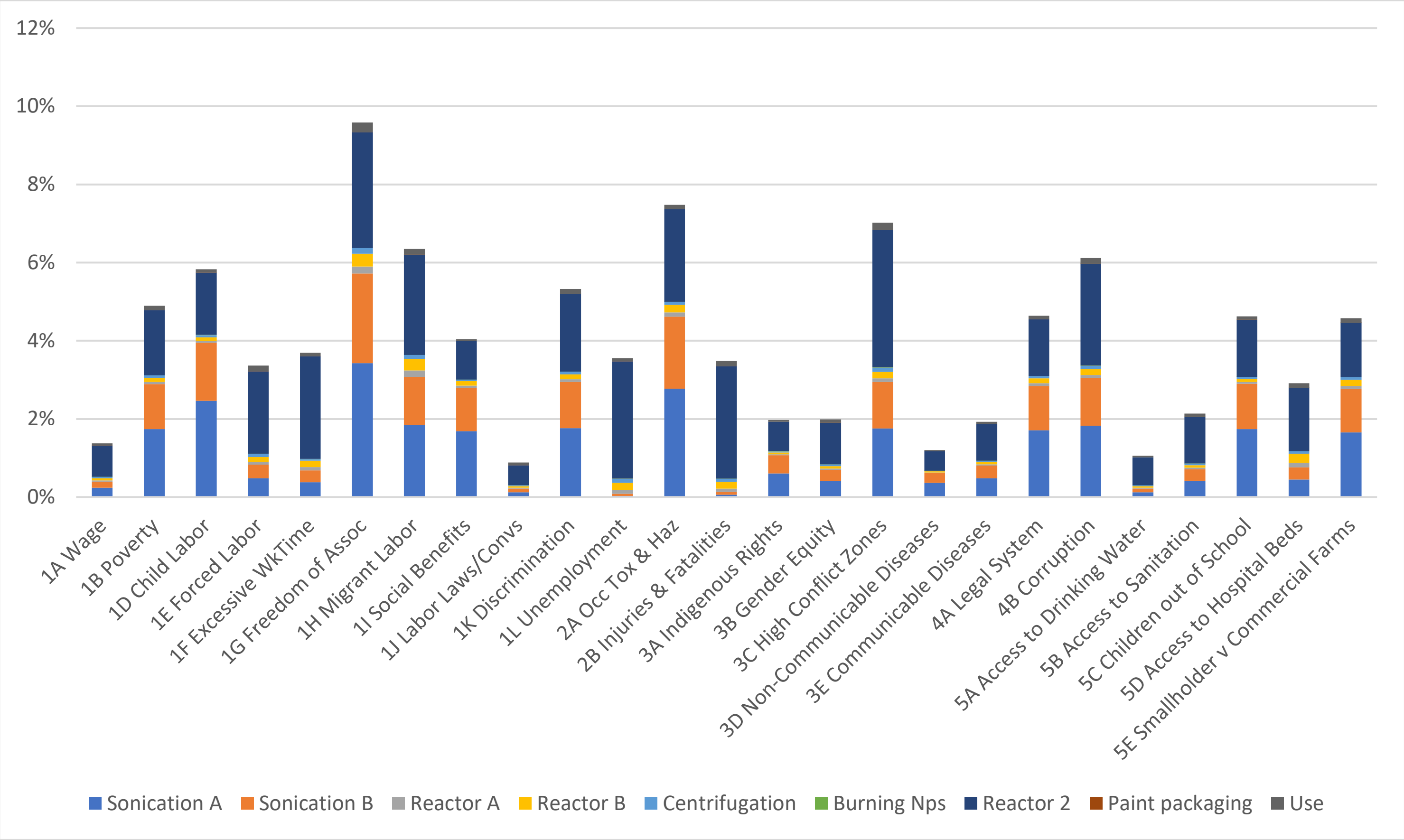

Figure 4-7 Subcategory single score results by core process (Sonication A and B, Reactor A and B, Centrifugation, Burning Nps, Reactor 2 and Paint packaging) and downstream process (use)

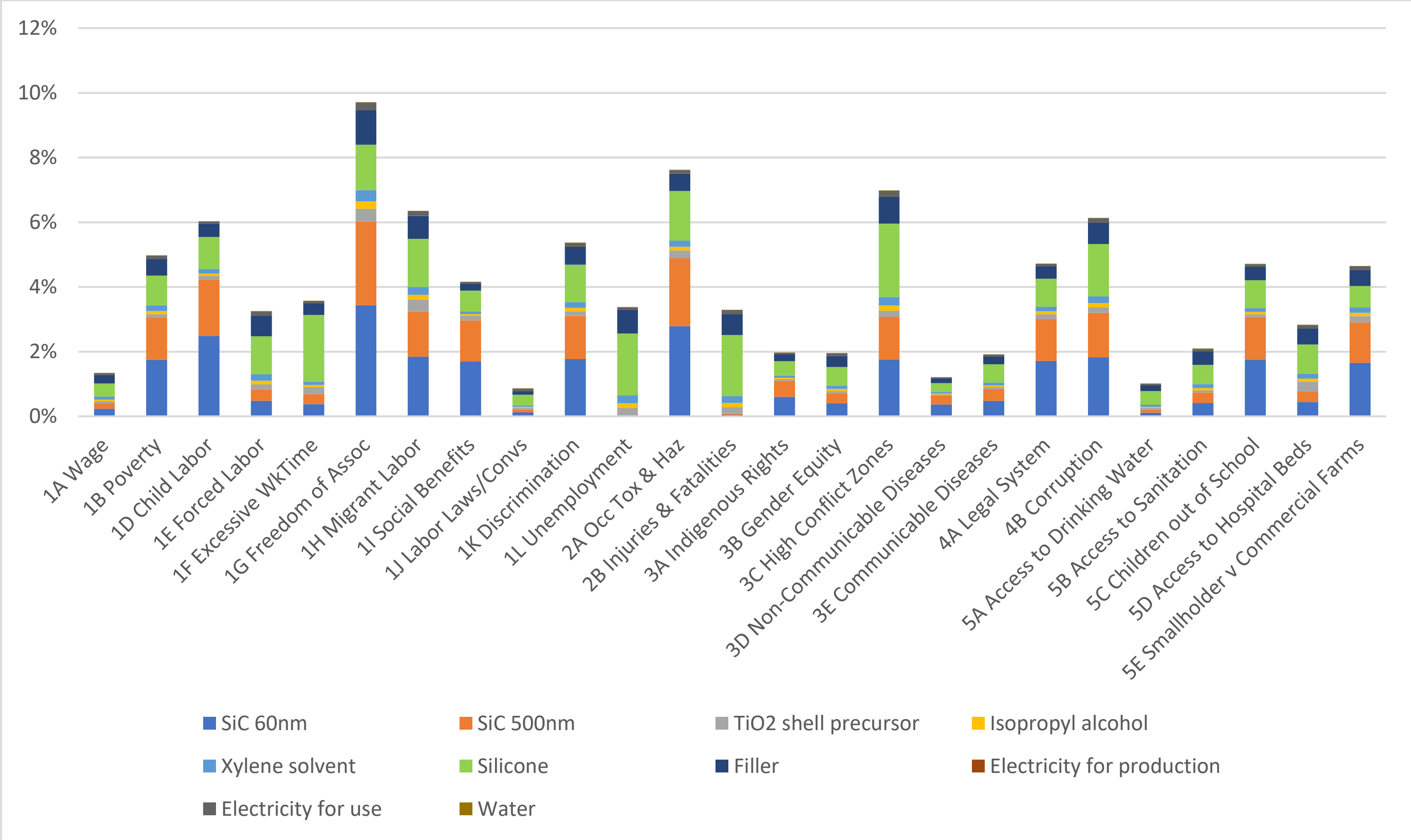

Figure 4-8 Subcategory single score results, by main processes (SiC 60nm, SiC 500nm, TiO2 shell precursor, Isopropyl alcohol, Xylene solvent, Silicone, Filler – all including transport, Electricity for production, Electricity for use, Water)

Categories results

Results by categories are obtained using the Social Hotspot 2016 Category Method w Weights available in SHDB for SimaPro. Since it can be compared to endpoint level, results are less robust as conversion to impact categories involves bigger approximation. Table 4-5 and Table 4-6 show percentages of impacts of the production stages and main process, on the total potential social impacts that correspond to 100%. The most affected category is the Health and Safety, with a share of impacts comparable to the Governance category.

Table 4-5 Category single score results. Percentages are reported for every core process (Sonication A and B, Reactor A and B, Centrifugation, Burning Nps, Reactor 2 and paint packaging) and downstream process. (use)

Category	Total	Son A	Son B	Reac A	Reac B	Centr	Burn Nps	Reac2	Paint pack	Use
Total	100%	28,04%	18,85%	1,67%	3,04%	1,51%	0,03%	44,45%	0,00%	2,41%
Labour rights and decent work	18,38%	5,02%	3,33%	0,33%	0,61%	0,29%	0,01%	8,36%	0,00%	0,44%
Health and Safety	28,18%	7,30%	4,90%	0,51%	0,93%	0,42%	0,01%	13,49%	0,00%	0,61%
Human rights	14,52%	3,73%	2,58%	0,21%	0,37%	0,24%	0,01%	6,97%	0,00%	0,42%
Governance	27,66%	9,08%	6,07%	0,39%	0,70%	0,37%	0,01%	10,45%	0,00%	0,60%
Community	11,26%	2,91%	1,98%	0,23%	0,43%	0,19%	0,00%	5,18%	0,00%	0,34%

Table 4-6 Category single score results. Percentages are reported for every main process (SiC 60nm, SiC 500nm, TiO2 shell precursor, Isopropyl alcohol, Xylene solvent, Silicone, Filler – all including transport, Electricity for production, Electricity for use, Water)

Category	Total	SiC 60nm	SiC 500nm	TiO2	Isopropyl alcohol	Xylene solvent	Silicone	Filler	EE for prod	EE for paint	Water
Total	100%	28,10%	21,12%	3,66%	2,27%	3,68%	27,50%	11,26%	0,03%	2,33%	0,04%
Labour rights and decent work	18,37%	5,03%	3,74%	0,74%	0,43%	0,70%	5,19%	2,10%	0,01%	0,43%	0,01%
Health and Safety	28,09%	7,32%	5,49%	1,14%	0,63%	1,02%	8,82%	3,07%	0,01%	0,59%	0,02%
Human rights	14,42%	3,73%	2,85%	0,42%	0,36%	0,58%	4,24%	1,83%	0,01%	0,41%	0,01%
Governance	27,93%	9,12%	6,85%	0,84%	0,56%	0,91%	6,38%	2,69%	0,01%	0,58%	0,01%
Community	11,19%	2,91%	2,19%	0,52%	0,29%	0,48%	2,88%	1,58%	0,00%	0,33%	0,00%

As shown in Figure 4-9, the impacts are caused mainly by the stages of Sonications and the Reactor 2, broken down into main processes and main processes assembly in Figure 4-10, where it results clear that SiC 60nm, Sic 500nm, and Silicone are the major contributors to the total impacts.

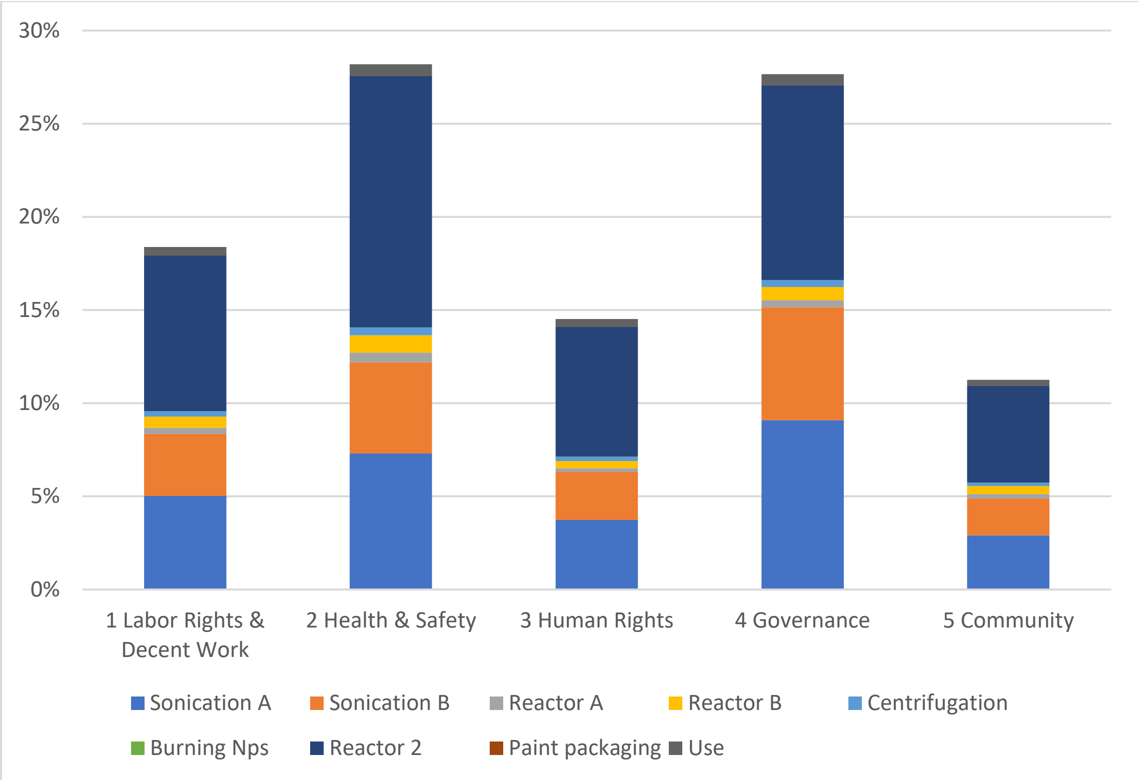

Figure 4-9 Category single score results by core process (Sonication A and B, Reactor A and B, Centrifugation, Burning Nps, Reactor 2 and Paint packaging) and downstream process (use)

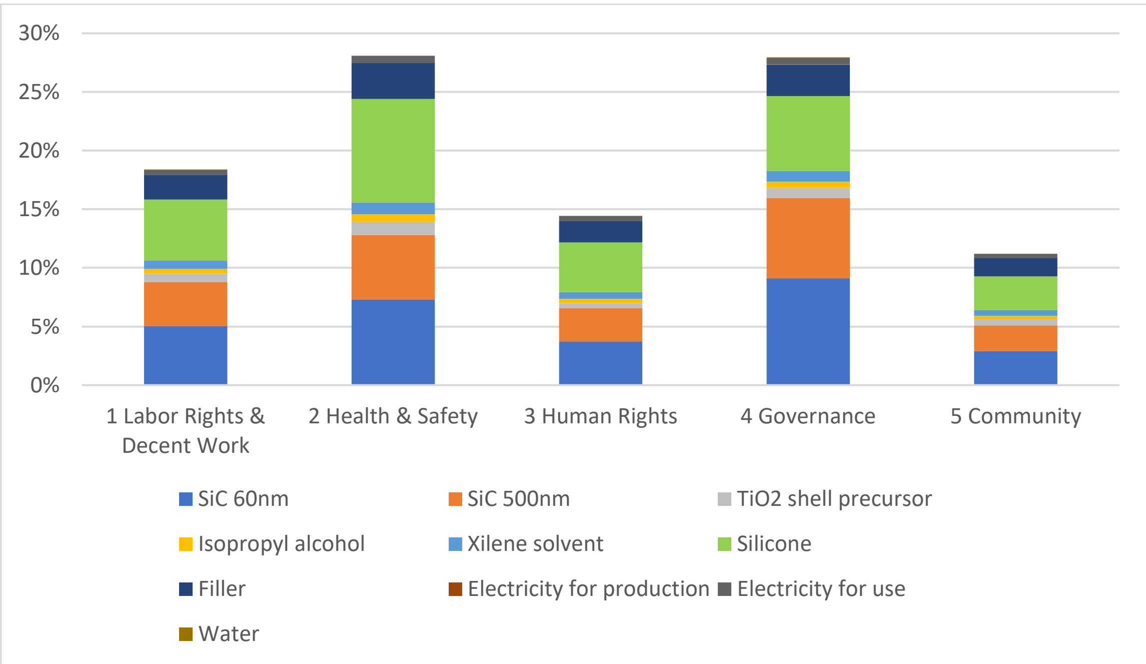

Figure 4-10 Category single score results, by main processes (SiC 60nm, SiC 500nm, TiO2 shell precursor, Isopropyl alcohol, Xylene solvent, Silicone, Filler – all including transport, Electricity for production, Electricity for use, Water)

Life cycle interpretation

Figure 4-11 shows each main process contribution in the overall impacts. In this case, the results are not presented by production stages and by main processes because the contribution to the final social impact is aggregated by main process, resulting identical in the two cases. As highlighted in the category and subcategory results, the major contribution is due to the mineral-based main processes (SiC 60nm and SiC 500nm), purchased from China. Following, the mineral-base main process (Silicone), from Germany. Process contribution column chart and pie chart are the most effective way to understand impacts share, even if uncoupled from categories or subcategory. Indeed, they allow to identify which are the specific supply chains to further investigate thus to assess and improve real social impacts.

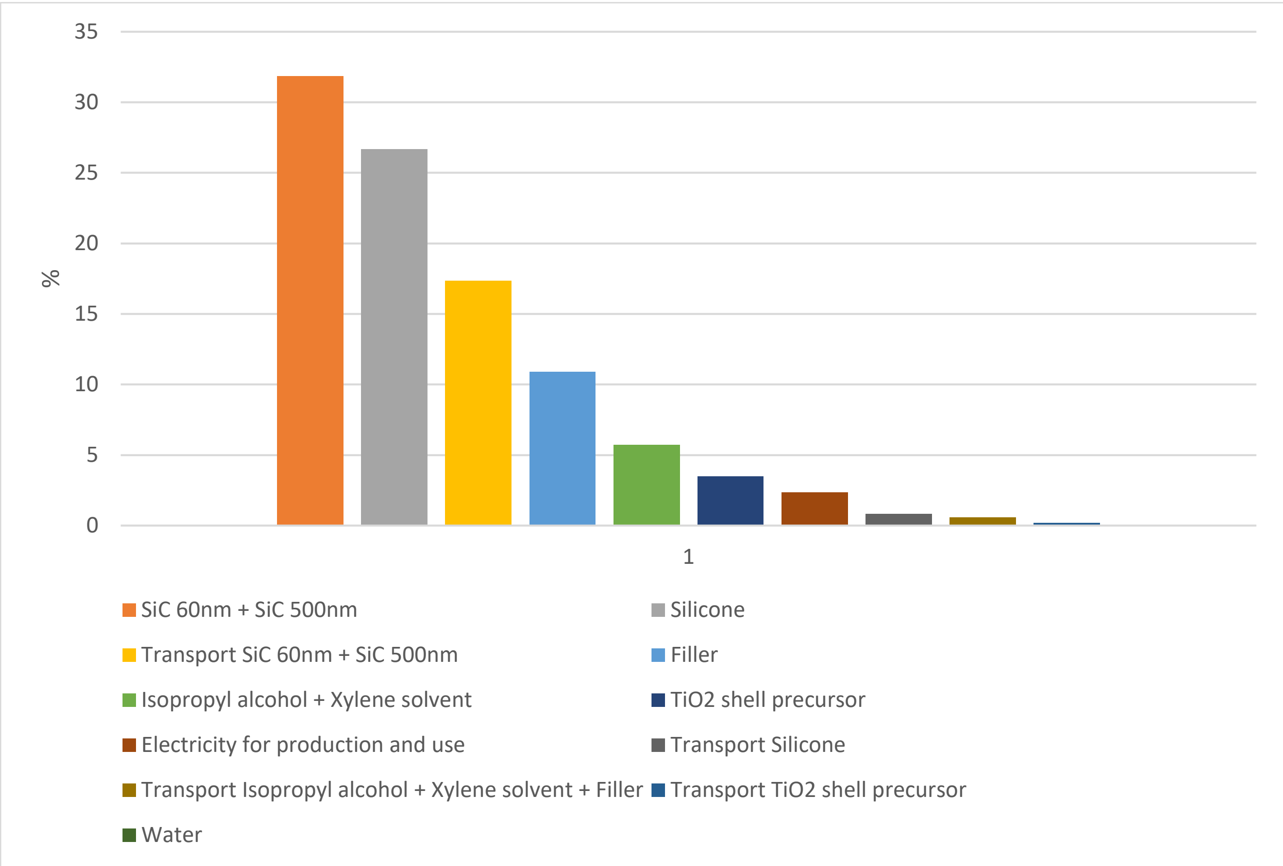

Figure 4-11 Process contribution column chart

According to the S-LCA study, the most significant results obtained are (i) the main processes contributing more to the social hotspots, (ii) the country of origin that relates to the most pressing social issues, (iii) the social aspects on which to collect more information.

As reported in Figure 4-11, the main processes “SiC 60nm + SiC 500nm” are the one contributing the most on the total share of social potential impacts. This is due to the extraction phase, which happens in China for the two main processes entering the Sonication’s stages and in Germany for the Silicone involved in the Reactor2 life cycle stage. As reported in Figure 4-7 and Figure 4-8, the subcategories with higher values were child labour, freedom of association, migrant labour, occupational toxicity and hazard, high conflict zones, and corruption. The first four are ascribable to Health and Safety, while the last two to the Governance category. Indeed, as reported in Figure 4-9 and Figure 4-10, the most impacted categories are Health and Safety and Governance, reasoning with the results at the subcategory level. As already said, the significant impacts are inherent to three main processes, coming from both China and Germany.

The Chinese mining industries is reported to deeply affect the structure and conditions of surrounding communities, on various levels. While allowing wealthy groups to thrive in the resource extraction collateral markets (transportation, maintenance, etc.), the industrial sector negatively impacts on more vulnerable social groups. Endangered health conditions, increased poverty due to the lack of good institutions, exacerbated inequalities are some of the issues faced by communities surrounding extraction sites. On a positive note, it seems that improved infrastructures related the industrial development, like clean water and improve transport connection can be identified as positive impacts of mining activities (Dou Shiquan et al., *2022*). These findings reason with the results of the S-LCA, supporting the social hotspots identified and the low-risk areas resulting from the assessment (e.g. access to clean water). Concerning the social issues inherent to the mineral products coming from Germany, further questions to the supplier are essential to verify the obtained results. Indeed, Germany appears to have a comprehensive mining legislation, in line with the European legislation requirements. Its approach is aimed at preventing risks and improving the sustainability performances, with strict requirements on many parameters, among which appears health and safety (*Sustainable Development Knowledge Platform*, Mining). The results cannot be explained on a general level and might be understand only in the specific case study context.

5 Discussion

From the interpretation of the results, the following deductions can be drawn. Tier3 S-LCA produced results that pointed out the main social hotspots of the nano-based product assessed, and the stages of the life cycle contributing the most. Tier1 questionnaire, already fulfilled in a previous step by the MCNM production company, was used as an ex-post tool to validate the results of the social life cycle assessment, comparing the hotspots identified with the qualitative answers. Indeed, since it was not possible to validate the *potential* social impacts by means of qualitative data derived from interviews and questionnaires developed on the basis of the Tier3 S-LCA, the answers collected from Tier1 were used to implement this further step of assessment and obtain information on *actual* social impacts. A detailed comparison of the S-LCA results with the results of Tier1 is reported in the next subparagraphs.

The novelty of the S-LCA approach leaves space for further improvements. On one hand, Tier1 questionnaire was aligned with Tier2 subcategories' selection to obtain information on the topics considered, by a panel of experts, the most relevant for the MCNM context. However, Tier3 covers a wider spectrum of subcategories, that made the interpretation of data more complex. A further alignment of the three tiers would be beneficial and should be performed according to the subcategories available for the assessment in the SHDB extension for SimaPro software, when it is the tool selected for the S-LCA. The reason why this was not considered before is twofold (i) it was missing a practical expertise, since in literature can be retrieved only a handful of Type II, or Impact Pathway, S-LCA case studies. Indeed, the majority of case studies already implemented adopted a Type I assessment, or Reference Scale approach, making the application of Type II S-LCA still to be explored (ii) the SHDB version used for the study was the former to last one (i.e., SHDB 2016), therefore it was considered appropriate to wait for the upload of the updated one before considering a further tuning. Moreover, the objectives of Tier1 and Tier2 are to develop screening and semi-quantitative methods to be used in the preliminary products' development phases, while Tier3 is a full S-LCA which should be comprehensive of all the identified subcategories. However, the subcategory appearing as the biggest hotspot in the present S-LCA assessment, namely freedom of association, was not considered in the other tiers. This subcategory could be further assessed to understand if it needs to be included in the previous assessment tiers. Moreover, a further improvement of the results assessment could derive from an additional questionnaire to be completed following the S-LCA, tackling the most pressing social issues highlighted, as recommended by the UNEP/SETAC Guidelines. Indeed, obtaining more qualitative data would allow to verify the presence of *actual* social impacts where *potential* social impacts have been identified, by comparing the social hotspots with the questionnaire answers. This however, even if resulting in a better level of details, would burden the production company with further cost and time efforts that could reduce the commitment toward assessing sustainability.

Moreover, it was noticed how the SHDB available for SimaPro only allows the assessment of impacts with a negative connotation, in an (Environmental) LCA fashion. Only the updated version includes the first subcategory assessing positive impacts, “socioeconomic contribution” (Norris et al., 2019). Positive impacts are more easily retrievable from the qualitative Tier1 data, that highlighted a Type B positive impact, positively affected employment rates, in both the MCNM production stage and in the production of the product incorporating the nanomaterial stage. Type B positive social impact are the impacts caused by the presence of the product or the company in the territory. Type C positive impacts, due to product utility, were spotted in the production of the product incorporating the nanomaterial stage, where it was pointed out a technological development due to the intrinsic product properties.

The MCNM production company was the one providing the data and therefore the one in charge for further improvements. The most evident issue to tackle concerns the choice of the supply chain. While many social hotspots could not correspond to actual social impact, a better knowledge of the main material suppliers would drastically reduce the uncertainty on the existence of social hotspots. Further information should be collected concerning the positive impacts identified, since it would highlight the positive outcomes of the innovative MCNM product.

It must be noted that few challenges were addressed in developing the S-LCA. To start with, limited availability of GTAP sectors and specifically for the ones covering nanomaterial related products for the Tier3 made the association of real main materials to SHDB processes less accurate, due to the assumptions required. Moreover, being qualitative interviews costly and extremely time consuming, it was possible to include in the Tier1 questionnaire only a limited number of social issues relevant questions, to encourage the company to fulfil it. On the same topic, it was possible to involve in Tier1 only the MCNM production company, while ideally more stakeholders should be involved both in the process of question selection and answering. On a final note, it is clear how the lack of practical expertise in the S-LCA is one of the main obstacles for practitioners to improve the quality of results, and therefore its implementation in the following years, fostered by the recent release of the updated guidelines and SHDB and the upcoming ISO standard, would help to create a stronger bases for future studies.

Comparison of the S-LCA with Tier1

As mentioned above, Tier1 questionnaire was already submitted and filled in by the production company, outside of the work carried out for this thesis. However, having aligned the questionnaire questions concerning social sustainability to Tier2 and partially to Tier3, it was considered as an opportunity to use the qualitative data collected in Tier1 to validate and discuss the results of the Tier3 S-LCA divided according to life cycle stages. This further step of assessment is highly encouraged by the UNEP/SETAC guidelines, since it allows to verify the *actual* presence of impacts from the *potential* impacts highlighted by the social hotspots identification in Tier3 S-LCA (UNEP, 2020).

Even though the results of Tier1 were promising for the nanomaterial based product considering its comprehensive sustainability performances, when these results were broken down to the questions relevant for the social sustainability assessment, the information collected in Tier1 is poor (*in preparation* - Pizzol et al., 2022). Table 5-1 provides the social relevant questions retrieved from the Tier1 questionnaire. The answers for the **raw material and resources production life cycle stage** are “I don’t know” for most questions. “Yes” appears in one of the health and safety improvement questions, supporting the findings of the S-LCA concerning the impacts contributions on the Health and Safety category and the Occupational toxicity and hazard subcategory, both resulted with high impact shares. It also reasons with the main processes identified as the major contributors to the impacts by the Tier3 application, that, Silicone excluded, are the components imported as main material from China (SiC 60nm and SiC 500nm).

Regarding the **production of the MCNM life cycle stage**, all questions were answered, since it is the stage under the control of the production company from which data were collected. Although it results that Health and Safety of the community is not improved, it is neither damaged. This result shows how the *potential* social impacts identified by the S-LCA analysis should be updated according to the answer of the Tier1 questionnaire. According to the answers provided in the questionnaire, the local employment results to be improved by the production company, highlighting the presence of a positive social impact, not visible from the Tier3 S-LCA results. Moreover, in the questionnaire, suppliers are marked as not socially responsible, as well as the conditions guaranteed by the main material suppliers, as verified in the previous life cycle stage. The results of Tier3 S-LCA are therefore confirmed, when they point out how the majority of impacts is to be attributed to the *material* main processes supply chain. Also, a question concerning technological development improvement was answered negatively.

The **production of the product incorporating the MCNM** is the life cycle stage with the more positive results, since their supplier coincide with the company involved in the assessment and fulfilling the questionnaire (i.e. the company producing the MCNM incorporated in the assessed product). Besides affecting positively the local employment rates, suppliers are socially responsible and concerned about minimize social issues. The technological development fosters new education opportunities, therefore improving impacts regarding the society, or the community category. Indeed, results of the S-LCA at the category level by main process show how the major share of impact is due to the *material* main processes, while the share of impacts *energy* main process corresponding to the production of the product incorporating the MCNM is rather low (Figure 4-10). This is a precious information when the *actual* social impacts are assessed. Therefore, the questionnaire answer provides an additional level of detail that allows to confirm the attribution of the major share of impact to the previous life cycle stages.

The **use phase** is not included in the Tier3 assessment and consequently will not be commented.

The comparison with Tier1 shows how the two levels of assessment, for the questions that were provided with an answer, complement each other. This is obtained by a prior identification of potential social hotspots in the bigger picture, with Tier3 (S-LCA), followed by the confirmation of the results for the real case study, with Tier1. Although Tier1 should precede Tier3 both conceptually and temporary, the case study shows how it provides an opportunity of assessing *actual* social impacts when a further step of qualitative assessment is not possible. On the other hand, the associated limitation was mainly due to the high number of “I don’t know” answers.

Table 5-1 Tier1 questionnaire fulfilled by the MCNM production company (in preparation - Pizzol et al., 2022).

Subcategory	Indicator	Question	Answer
Life Cycle Stage: Raw materials and resources-Production			
Access to material resources	Material resources access	Do your suppliers respect and protect community access to local material resources (i.e., water, land, mineral, and biological resources) and infrastructure (i.e. roads, sanitation facilities, schools, etc.)?	I don't know
Safe and healthy living conditions	Health and safety improvement	Does the activity contribute to improve (e.g. through sharing health services) safety and health of the local community?	I don't know
Safe and healthy living conditions	Health and safety improvement	Does the activity contribute to damage (e.g., use of hazardous materials, pollution) safety and health of the local community?	YES
Supplier relationship	Traceability of raw materials	Are there policies in place to allow traceability of your raw materials?	NO
Prevention and mitigation of armed conflicts	Absence of armed conflicts	Is the origin country of raw materials free from armed conflicts?	I don't know
Child labor, health and safety, equal opportunities/discrimination,	Raw materials coming from underdeveloped, developing or third world countries	Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, forced labor, unfair salary, inequality. etc)?	I don't know
Life Cycle stage: Production of MCNM			
Safe and healthy living conditions	Health and safety improvement	Does the activity contribute to improve (e.g., through sharing health services) safety and health of the local community?	NO
Safe and healthy living conditions	Health and safety improvement	Does the activity contribute to damage (e.g., use of hazardous materials, pollution) safety and health of the local community?	NO
Local employment	Local employment	Does the organization positively affect the local employment rates?	YES
Supplier relationships	Assessment of suppliers	Are suppliers socially responsible (e.g., if they implement CSR principles)?	NO
Child labor, health and safety, equal opportunities/discrimination,	Raw materials coming from underdeveloped, developing or third world countries	Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?	NO
Technology development	Technological development, economic impact, education opportunities	Did you consider if the production process results in technological development, additional education opportunities?	NO
Life Cycle Stage: Production of the product incorporating the MCNM			
Local employment	Local employment	Does the organization positively affect the local employment rates?	YES
Supplier relationship	Assessment of suppliers	Are suppliers socially responsible (e.g., if they implement CSR principles)?	YES
Child labor, health and safety, equal opportunities/discrimination,	Raw materials coming from underdeveloped, developing or third world countries	Are there restrictive procedures to minimise social issues (e.g., child labor, political or demographic problems, forced labor, unfair salary, poor working conditions, inequality. etc)?	yes
Technology development	Technological development, economic impact, education opportunities	Did you consider if the manufacturing process results in technological development, additional education opportunities?	yes
Life Cycle Stage: Use			
End-of-life responsiibility	End-of-life information	Is there clear information on the end of life-options provided through labelling?	NO

Conclusions

The aim of this thesis work was to investigate the potential of the life cycle approach, and more specifically S-LCA, for engineered nanomaterials and nano-enabled products. The research question was twofold (i) understanding the potential of the Social Life Cycle Assessment in a Life Cycle Sustainability Assessment (LCSA) context, (ii) verify its applicability, strengths, and weaknesses within a three Tiers sustainability approach specifically developed for the MCNMs sector. Both the theoretical and the applicative part have been carried out during a collaboration and with the support of GreenDecision Srl, a Ca' Foscari *spin off.* The case study was selected among those made available by the partners of the European Horizon2020 SUNSHINE project, which has the goal to develop an overarching Safe and Sustainable by Design approach for advanced nanomaterials. The theoretical part of the thesis focused on the three methodologies available for life cycle assessment and part of the LCSA methodology. (Environmental) LCA, Social LCA, and LCC were described in their frameworks and structures to understand their similarities and differences, to better understand the role of the S-LCA performed in the applicative part of the thesis. It emerged how the S-LCA, although it shares the ISO 14040 series structure, differs from (Environmental) LCA and (Environmental) LCC for (i) the option to assess *potential* or *actual* social impacts, (ii) the minimum data required to carry out the assessment, including location and costs, since it is a country-based assessment, (iii) the importance of using qualitative data, (iv) the methodological development. On one hand, an S-LCA study has more opportunities for improving the assessment results through further qualitative data collection, while, on the other hand, it still lacks exhaustive database to support detailed assessments. Its low level of development is mainly due to the lack of standardization and the little implementation on real case studies. However, it was pointed out how the trend of S-LCA studies is rising year by year (Figure 2-10).

In the applicative part of the thesis, the use of the S-LCA allowed to achieve a better understanding of the practical use of the methodology and its contribution to the life cycle based SSbD approach, a tiered approach including screening-level qualitative (Tier1), semi-quantitative (Tier2) methodologies to be applied in the early stages of innovation and a quantitative (Tier3) assessment method for the later stages of product development. The S-LCA was contextualised as the last level (Tier3) of the tiered approach. One relevant result of the thesis is the alignment of the social aspects assessed in Tier1, Tier2 and partially Tier3 of the SSbD approach which was carried out with the support of the UNEP/SETAC methodological sheets, through which the questions from the questionnaire developed for

Tier1 were associated with the relevant stakeholder categories and subcategories indicated in the UNEP/SETAC Guidelines for Social Life Assessment. Following, they were compared with the relevant subcategory for MCNMs selected for Tier2. The new questions incorporated have the goal of tackling the most relevant social issues for nanomaterials and provide specific information for the further assessment levels. The application of S-LCA disclosed the potential it can have to provide indications and suggestions for the improvement of a company, mainly based on the origin country of the main material, if no further information is available from the supply chain companies. Once completed the analysis with the SHDB available for SimaPro, it was decided to try to validate the assessment results through the comparison with the information collected in the Tier1 improved questionnaire. The comparison with Tier1 showed how the two levels of assessment, for the questions that were provided with an answer, complement each other. This is obtained by a prior identification of potential social hotspots in the bigger picture, with Tier3 (S-LCA), followed by the confirmation of the results for the real case study, with Tier1. The limitation was mainly due to the high number of “I don’t know” answers. Additionally, this comparison allowed to develop further ideas concerning the tuning and understanding the life cycle stages that concentrate the most social hotspots. It was highlighted how it is crucial to better investigate the main materials supply chain, since it is both the stage which contributes the most in the total social impacts and the one on which companies have less information, as it was evident from Tier1 answers.

The result of this thesis contributes to the development of the SSbD integrated approach for the European Horizon2020 SUNSHINE, by structuring the part inherent to the social sustainability assessment. Given the rising interest in the social dimension of sustainability, the work carried out for this thesis can become a starting point for further development of the methodology among practitioners by its contribution with practical expertise.

Acknowledgments

I would like to express my gratitude to my supervisor Professor Daniele Brombal and my assistant supervisor Professor Elena Semenzin, that made this project possible. Additionally, this journey would not have been possible without my GreenDecision tutors Lisa Pizzol and Arianna Livieri, that guided me step by step with a not common dedication. Thank you for all the time and effort you have dedicated to me in the last months. Lastly, I'd like to mention my family and friends, who have been always there in different ways and affected my path in becoming the person that I am today.

References

A European Green Deal. Available at https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en Accessed on 3 February 2023.

Associazione Rete Italiana LCA. Available at https://www.reteitalianalca.it/. Accessed on 19 February 2023.

De Menna, F., Loubiere, M., Dietershagen, J., Vittuari, M., & Unger, N. (2016). Methodology for evaluating LCC. *Horizon2020 REFRESH*

Bouillass, G., Blanc, I., & Perez-Lopez, P. (2021). Step-by-step social life cycle assessment framework: A participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios. *The International Journal of Life Cycle Assessment*, *26*(12), 2408–2435. https://doi.org/10.1007/s11367-021-01988-w

Buyle, Audenaert, Billen, Boonen, & Van Passel. (2019). The Future of Ex-Ante LCA? Lessons Learned and Practical Recommendations. *Sustainability*, *11*(19), 5456. https://doi.org/10.3390/su11195456

Cucurachi, S., van der Giesen, C., & Guinée, J. (2018). Ex-ante LCA of Emerging Technologies. *Procedia CIRP*, *69*, 463–468. https://doi.org/10.1016/j.procir.2017.11.005

D’Eusanio, M., Serreli, M., Zamagni, A., & Petti, L. (2018). Assessment of social dimension of a jar of honey: A methodological outline. *Journal of Cleaner Production*, *199*, 503–517. https://doi.org/10.1016/j.jclepro.2018.07.157

D’Eusanio, M., Tragnone, B. M., & Petti, L. (2022). Social Organisational Life Cycle Assessment and Social Life Cycle Assessment: Different twins? Correlations from a case study. *The International Journal of Life Cycle Assessment*, *27*(1), 173–187. https://doi.org/10.1007/s11367-021-01996-w

European Commission. (2020). *Chemicals Strategy for Sustainability Towards a Toxic-Free Environment*.

Grant, T. (2019, March 4). *Social Hotspots Database Update*. Lifecycles. Available at https://www.lifecycles.com.au/single-post/2019/05/20/social-hotspots-database-update

Growth without economic growth—European Environment Agency. Available at https://www.eea.europa.eu/publications/growth-without-economic-growth Accessed on 11 February 2023.

Herrera Almanza, A. M., & Corona, B. (2020). Using Social Life Cycle Assessment to analyze the contribution of products to the Sustainable Development Goals: A case study in the textile sector. *The International Journal of Life Cycle Assessment*, *25*(9), 1833–1845. https://doi.org/10.1007/s11367-020-01789-7

Home Sustainable Development Knowledge Platform. Available at https://sustainabledevelopment.un.org/ Accessed on 6 February 2023.

ISO/CD 14075. ISO. Available at https://www.iso.org/standard/61118. Accessed on 22 November 2022.

Life Cycle Initiative. Available at https://www.lifecycleinitiative.org/ Accessed on 3 February 2023.

Jiménez et al. (2022). Safe(r) by design guidelines for the nanotechnology industry | *Elsevier Enhanced Reader*. https://doi.org/10.1016/j.impact.2022.100385

Kühnen, M., & Hahn, R. (2017). Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience: Indicators in Social Life Cycle Assessment. *Journal of Industrial Ecology*, *21*(6), 1547–1565. https://doi.org/10.1111/jiec.12663

Norris, C. B., Bennema, M., & Norris, G. (2019). Supporting documentation Update 2019.

Norris, C., Norris, G., & Aulisio, D. (2014). Efficient Assessment of Social Hotspots in the Supply Chains of 100 Product Categories Using the Social Hotspots Database. *Sustainability*, *6*(10), 6973–6984. https://doi.org/10.3390/su6106973

OECD. (2022). Sustainability and Safe and Sustainable by Design: Working Descriptions for the Safer Innovation Approach. https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV-CBC-MONO(2022)30%20&doclanguage=en

Perman, R. (Ed.). (20). Natural resource and environmental economics (3. ed., [Nachdr.]). Pearson Addison Wesley.

Petti, L., Sanchez Ramirez, P. K., Traverso, M., & Ugaya, C. M. L. (2018). An Italian tomato “Cuore di Bue” case study: Challenges and benefits using subcategory assessment method for social life cycle assessment. *The International Journal of Life Cycle Assessment*, *23*(3), 569–580. https://doi.org/10.1007/s11367-016-1175-9

In preparation - Pizzol, L., Livieri, A., Salieri, B., Farcal, L., Soeteman-Hernández, L.G., Zabeo, A., Blosi, M., Costa, A. L., Peijnenburg, W., Stoycheva, S., Hunt, N., López-Tendero, M., & Hristozov, D. (2022). Practical guidance to a holistic Safe and Sustainable by Design (SSbD).

Pollok, L., Spierling, S., Endres, H.-J., & Grote, U. (2021). Social Life Cycle Assessments: A Review on Past Development, Advances and Methodological Challenges. *Sustainability*, *13*(18), 10286. https://doi.org/10.3390/su131810286

Psilca.net | Psilca. Available at https://psilca.net/

Accessed on 5 January 2023.

Ramirez, P. K. S., Petti, L., Haberland, N. T., & Ugaya, C. M. L. (2014). Subcategory assessment method for social life cycle assessment. Part 1: Methodological framework. *The International Journal of Life Cycle Assessment*, *19*(8), 1515–1523. https://doi.org/10.1007/s11367-014-0761-y

Raneses, A. (2018). Social Responsibility in Biodiesel Supply Chains

SHDB. Available at http://www.socialhotspot.org/
Accessed on 7 February 2023.

SimaPro (Director). (2019, May 27). Webinar | Updated Social Hotspots Database in SimaPro. Available at https://www.youtube.com/watch?v=TL90pspN5dI

Social Sustainability | UN Global Compact. Available at https://www.unglobalcompact.org/what-is-gc/our-work/social. Accessed on 19 February 2023.

Stoycheva, S., Zabeo, A., Pizzol, L., & Hristozov, D. (2022). Socio-Economic Life Cycle-Based Framework for Safe and Sustainable Design of Engineered Nanomaterials and Nano-Enabled Products *Sustainability*, *14*(9), 5734. https://doi.org/10.3390/su14095734

Shiquan, D., Amuakwa-Mensah, F., Deyi, X., Yue, C., Yue, C. (2022) The impact of mineral resource extraction on communities: How the vulnerable are harmed | *Elsevier Enhanced Reader*. https://doi.org/10.1016/j.exis.2022.101090

Club of Rome. The Limits to Growth. Available at https://www.clubofrome.org/publication/the-limits-to-growth/
Accessed on 19 February 2023.

Tokede, O., & Traverso, M. (2020). Implementing the guidelines for social life cycle assessment: Past, present, and future. *The International Journal of Life Cycle Assessment*, *25*(10), 1910–1929. https://doi.org/10.1007/s11367-020-01814-9

Tsalidis, G. A., & Korevaar, G. (2022). Environmental assessments of scales: The effect of ex-ante and ex-post data on life cycle assessment of wood torrefaction. *Resources, Conservation and Recycling*, *176*, 105906. https://doi.org/10.1016/j.resconrec.2021.105906

UNEP, 2011*.* Global Guidance Principles.

UNEP, 2020. Guidelines for Social Life Cycle Assessment of Products and Organizations 2020. Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese, G. (eds.). United Nations Environment Programme (UNEP).

UNEP, 2021. Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021. Traverso, M., Valdivia, S., Luthin, A., Roche, L., Arcese, G., Neugebauer, S., Petti, L., D'Eusanio, M., Tragnone, B.M., Mankaa, R., Hanafi, J., Benoît Norris, C., Zamagni, A. (eds.). United Nations Environment Programme (UNEP).

Valdivia, S., & Lie, C. M. (2011). Toward LCSA. *Sustainability Assessment*.

Zamagni, A., Amerighi, O., & Buttol, P. (2011). Strengths or bias in social LCA? *The International Journal of Life Cycle Assessment*, *16*(7), 596–598. https://doi.org/10.1007/s11367-011-0309-3

Zanchi, L., Delogu, M., Zamagni, A., & Pierini, M. (2018). Analysis of the main elements affecting social LCA applications: Challenges for the automotive sector. *The International Journal of Life Cycle Assessment*, *23*(3), 519–535. https://doi.org/10.1007/s11367-016-1176-8

Appendix 1. Reasoning behind the development of the new questions for Tier1

The reasoning behind the development of the new question is presented below, organized by stakeholder categories.

STAKEHOLDER CATEGORY: WORKERS

Life Cycle Stage: Raw materials and resources-Production

Subcategories covered: child labour, health and safety, equal opportunities/discrimination.

Question: Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?

Comment: the question was already present in the original version of Tier1 and aligned with Tier2 subcategories selection. It was suggested the inclusion in the brackets of “fair salary” and “forced labour” to better align with the subcategory indicator provided by UNEP/SETAC Guidelines.

Life Cycle Stage: Production of the MCNM, Production of the product

Subcategories covered: child labour, health and safety, equal opportunities/discrimination.

Question: Are there restrictive procedures to minimise social issues (e.g., child labour, political or demographic problems, poor working conditions, inequality. etc)?

Comment: originally not present in these sections, this question was taken from the raw material and resource production stage and included in both of these stages. Even if different activity, it was considered that the productions site has also to be evaluate for these subcategories related to workers wellbeing.

STAKEHOLDER CATEGORY: LOCAL COMMUNITY

Life Cycle Stage: Raw materials and resources-Production

Subcategories covered: access to material resources, health and safety living conditions.

Question: Do your suppliers respect and protect community access to local material resources (i.e., water, land, mineral, and biological resources) and infrastructure (i.e. roads, sanitation facilities, schools, etc.)? Does the activity contribute to improvements to the (e.g., through sharing health services) safety and health of the local community? Does the activity contribute to damage (e.g., use of hazardous materials, pollution) safety and health of the local community?

Comment: the impact that an extraction site has on the local community was considered a relevant aspect for the social impact assessment. Therefore, the relevant subcategory was included, and the question aims at obtaining information about the physical impact caused by the life cycle stage.

Life Cycle Stage: Production of the MCNM

Subcategories covered: safe and healthy living conditions, local employment.

Questions: Does the activity contribute to improvements to the (e.g., through sharing health services) safety and health of the local community? Does the activity contribute to damage (e.g., use of hazardous materials, pollution) safety and health of the local community? Does the organization affect the local employment rates?

Comment: the original version of the questionnaire included a question regarding the cultural heritage subcategory. However, being it not a subcategory selected in Tier2, it was considered appropriate to substitute its evaluation with questions concerning included subcategories. The choice regarded the subcategories of safe and healthy living conditions and local employments, driven by the consideration of the specific condition threatened by an extraction site and the consequent need for the extraction company to address the potential threats. The question concerning the safe and healthy living condition was divided in two parts in the final questionnaire due to its “yes or no” model.

Life Cycle Stage: Production of the product

Subcategory covered: local employment.

Question: does the organization affect the local employment rates?

Comment: the question was taken from the previous life cycle stage, to assess the potential positive impacts on the employment rates caused by the productions site.

STAKEHOLDER CATEGORY: VALUE CHAIN ACTORS

For this stakeholder category all question were already present and aligned with Tier2. No modification was included.

STAKEHOLDER CATEGORY: SOCIETY

Life Cycle Stage: Raw materials and resources - Production

Subcategories covered: Prevention and mitigation of armed conflicts.

Question: Is the origin country of the raw materials free from armed conflicts?

Comment: the related question from Tier2 specifically addressed the sourcing phase.

STAKEHOLDE CATEGORY: CONSUMERS

Life cycle stage: Use

Subcategory covered: End-of-life responsibility.

Question: Is clear information on end-life-options provided through labelling?

Comment: according to the subcategories selected for Tier2, it was considered relevant to include the evaluation on end-of-life destination of the product, according to the company responsibility. Even if Tier2 included two subcategories related to the Consumers stakeholder, for the Tier1 questionnaire resulted more convenient to include the mentioned one, since the other presumed a more complex reasoning and answering effort.