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

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Abstract: This manuscript describes an innovative approach to 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. This semi-quantitative methodology is based on a sound conceptual framework grounded in the combination of social life cycle analysis and multi-criteria decision analysis methods and supports decision making based upon socio-economic impacts assessed over the full life cycle of a product. To facilitate its application by industries, the methodology was implemented as an Excel-based self-assessment tool. This easy-to-use, cost- and time-efficient tool can guide users through their SSbD decision making regarding newly developed nanomaterials and NEPs and can also be applied to re-evaluate existing materials and NEPs in order to improve their sustainability from a socio-economic perspective. The relatively low requirements of this tool regarding the level of efforts and expert knowledge needed for its application make it a good starting point for initial assessment to highlight socio-economic issues in the value chain. The results of this initial screening can be further used for more detailed analysis in the later stages of product development by performing a full social life cycle assessment (S-LCA).

Keywords: socio-economic impacts; product life cycle; engineered nanomaterials; nano-enabled products; life cycle thinking; social life cycle assessment; multi-criteria decision analysis; safe-and-sustainable-by-design

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1. Introduction

The European Green Deal [1] policy ambitions set out in the new Action Plan for a Circular Economy [2], the European Industrial Strategy and the Chemicals Strategy for Sustainability [3] aim to transform the European Union's (EU) economy for a more sustainable future. These efforts have the goal to encourage innovation in Key Enabling Technologies (KETs) (see Appendix A for the list of acronyms), while better protecting public health and the environment as part of an ambitious approach to tackle pollution from all sources and move towards a toxic-free environment [4]. These policy initiatives call for a new safe-and-sustainable-by-design (SSbD) approach to chemicals. These are aimed at addressing safety and sustainability of a material or a product at the early stage of the design process instead of adopting a retroactive approach, which relies on measures to mitigate their health and environmental impacts once the products are already on the market. In this context, SSbD is a systems approach that integrates safety, circularity and functionality of chemical substances, including new advanced (nano)materials, products and processes throughout their life cycle [5]. The application of the SSbD concept to engineered nanomaterials (ENM) and nano-enabled products (NEPs) (e.g., metal complexes used in scratch and abrasion-resistant coatings for the construction sector, core–shell silicon carbide–titania anti-stick coatings for use in consumer products, graphene oxide-based materials for electrodes and energy storage) is strongly promoted as nanotechnologies are KETs that could contribute to economic growth and a more sustainable future [5]. Despite the substantial progress the scientific community has made in nearly two decades of accumulating knowledge on the environmental, health and safety implications of ENMs and NEPs, some questions relating to their safety and sustainability remain still challenging and open. A high number of approaches, methodologies and tools exist to evaluate the safety of these materials, but there are less approaches for assessing their sustainability that are suitable to support SSbD decision making by industries, especially SMEs, in the early stages of product development. A key study summarizing these tools has been recently produced by the European Commission (EC) [6] where the authors provide an overview of the key European SSbD initiatives and present an inventory of related tools. From the reviewed tools, it is evident that a common approach to assess product sustainability should adopt life cycle thinking. Beyond the nanotechnology domain, the environmental LCA is a well-established method for assessing the potential environmental impacts of products along their life cycles [7]. Having the same foundation, economic (through life cycle costing (LCC)) and social (through social-LCA (S-LCA)) assessments have emerged to provide different perspectives and therefore a more holistic and fine-grained analysis to product sustainability. Thus, for a holistic evaluation of product sustainability, the life cycle sustainability assessment (LCSA) was established, which is an integration of the three methodologies (LCSA = S-LCA + environmental LCA + LCC) [8] to account for the three pillars of sustainability. Despite the relatively long history of application of LCA, within the nanotechnology field, LCA product assessments are currently hindered by knowledge gaps, especially regarding nanomaterials released into the environment, and are focused on only a few nanomaterial types (e.g., nano-TiO_2, nano-ZnO, nano-SiO_2, nano-FeOx, nano-AlOx, nano-CeO_2, nano-Ag, CNT, CNF, graphene, C60 (fullerene) and quantum dots, among others) [9]. In addition, LCC and S-LCA studies or integration of the three approaches (LCSA) have been virtually absent in the field with only a few exceptions, as in [10,11], where the authors developed an S-LCA framework to assess the social impacts of prospective production scenarios involving a nano-copper oxide (n-CuO)-based paint with biocidal functionality. At the moment, it is unclear how environmental LCA could properly address the complexity of existent simple nanomaterials and the emerging multi-component advanced nanomaterials. In addition, the scarcity of studies and data evaluating economic and social impacts makes it nearly impossible to obtain a meaningful result regarding the overall sustainability of ENMs and NEPs, unless more systematic, long-term studies integrating the LCA, LCC and S-LCA are conducted. However, such studies are resource-intensive and require a level of expertise that is not always available in industries, especially SMEs. Therefore, they are not applicable to support SSbD decision making in the early stages of product development, where the industries are faced with making decisions between design alternatives and need fast, easy and inexpensive screening-level approaches to generate results for comparative purposes.

The SSbD concept is based on the notion that safety, functionality and sustainability should be ensured from the early stages of product development [12]. The Safe Innovation Approach (SIA) can be seen as a framework to achieve this. SIA combines two complementary concepts: SSbD in industrial settings and Regulatory Preparedness (RP) [13,14]. The SIA aligns the SSbD concept with the Cooper's stage gate [15] innovation model, which guides the innovation process through stages with a decision point at each gate as to whether proceed, stop or adjust the innovation. To develop a safe and sustainable product, SSbD decisions need to be made at each gate based on balancing criteria related to risks (safety), benefits (functionality) and economic viability (cost vs. commercial probability of success). In addition, adopting life cycle thinking as early as possible in this process is the key to obtaining all necessary information to substantiate "go-to-next gate", "adjust" or "stop" decisions. While full risk assessment and LCAs in each stage of the innovation process will be time-consuming and cost-prohibitive for industries, especially SMEs, screening tools to assess safety and sustainability applied in the early stages of the product development are essential for the SSbD approach to function. Several tools for safety screening and for comparing safety to environmental sustainability exist (e.g., [16,17]) and are currently being further developed in ongoing research projects such as H2020 SUNSHINE (www.h2020sunshine.eu, accessed on 15 March 2022). However, there is a lack of screening-level tools to assess socio-economic impacts in the early stages of product development, which is a major gap identified at the Second high level Safe and Sustainable by Design stakeholder workshop organized by the EC on 22 March 2022, which presented the first results of a major EC project on defining SSbD criteria for chemicals (see [18] for a full technical report).

In this study, we aim to address this issue by presenting an innovative self-assessment screening tool designed to support users from industry, especially SMEs, in the assessment of the socio-economic impacts along the full life cycles of ENMs and NEPs, starting from the early stages of innovation. The tool is a scoring procedure built upon a solid conceptual basis grounded in the S-LCA and multi-criteria decision analysis (MCDA) methodologies, and it can be applied to compare different NEP and/or conventional alternatives at each gate of the stage gate innovation process to select options that would lower the negative socio-economic impacts of the products. It can also be applied to re-evaluate existing materials and products in order to improve their sustainability from a socio-economic perspective. Considering the current limitations related to data quality and availability while applying full S-LCAs or other socio-economic assessments, the tool was designed to serve as a good starting point for early-stage initial assessments by highlighting social issues in the value chain. The results from this initial screening can be further used for more detailed analysis in the later stages of the innovation process by means of full S-LCA and LCC studies.

2. Materials and Methods

2.1. Social Life Cycle Assessment (S-LCA)

LCA experts started discussions around the consideration of social aspects in the product life cycle as early as the 1900s [19]. S-LCA was developed as a methodological approach to assess the positive and negative social aspects in the life cycle, from the extraction of raw materials stage until the final disposal of a product [20]. In addition, the method can be used (i) to determine, to understand, to communicate and to demonstrate the social impacts, for the purpose of supporting the implementation of improvement strategies and (ii) to facilitate decision-making procedures, such as choice of supplier. A key document explaining the S-LCA methodology was launched in 2009 by the United Nations Environment Programme (UNEP)/SETAC life cycle initiative outlining Guidelines for conducting S-LCA of products [21]. The Guidelines pave the assessment of the social and socio-economic aspects, referred as the social level in the traditional LCA framework. This framework is in accordance with the ISO 14040 and 14044 standards [17,22] adapted for the social aspects. S-LCA takes a stakeholder approach where the potential impacts on different stakeholder groups are considered. This mirrors the fact that social sustainability is about identifying and managing both positive and negative impacts. According to the Guidelines [21], stakeholders are divided into five groups: workers, local communities, consumers, the society and all value chain actors. Six impact categories are defined featuring human rights, health, working environment, cultural heritage, socio-economic response and governance. A more recent version of the S-LCA Guidelines was produced in 2020. In the new Guidelines [23], children have been added as a new stakeholder in addition to creating new impact subcategories such as smallholders including farmers, among others, as well as two approaches for impact assessments. A more detailed S-LCA evolution and a good summary of the S-LCA methodology are available in [24].

2.2. Multi-Criteria Decision Analysis (MCDA)

MCDA involves a large family of methods applied to integrate multiple sources of information to support structured decision making. In the methodology proposed in this manuscript, the Multi-Attribute Value Theory (MAVT) method is used [25–27]. MAVT applies value functions to aggregate criteria and metrics that can be presented in native units (e.g., $, size, child labor) or in ordinal scale (e.g., high, medium, low) into numerical scores for different alternative choices in order to compare them for making a decision. Weights are applied as scaling factors that represent the relative importance of each criterion/metric from the decision maker's point of view. They are typically on a 0 to 1 scale summing to 1, with higher values indicating higher importance.

2.3. Applying the Proposed S-LCA Scoring Methodology

S-LCA must follow the typical four phases of life cycle thinking analysis [23]:

1. Goal and scope definition.
2. Life cycle inventory.
3. Life cycle impact assessment.
4. Interpretation of results.

In the S-LCA framework, the stakeholder categories are at the basis of the impact assessment (step 3) because they are the items on which the justification of inclusion or exclusion in the scope needs to be provided [23]. Grouped under impact categories (e.g., human rights, working conditions) are the impact subcategories that encompass socially significant themes or attributes (e.g., fair salary, equal opportunities/discrimination). These subcategories are assessed by the use of impact indicators which link directly with the inventory of the product life cycle (e.g., wage, discrimination levels). Indicators as well as the choice of impact subcategories may vary depending on the context of the study.

The main difference between the environmental LCA and the S-LCA is how to calculate the impacts. In S-LCA, the characterization factor is defined in a more qualitative way, and the impact categories are established based on a stakeholder approach. Thus, to measure social performance, it is important that indicators related to each stakeholder group should be considered. Likewise, it is important to note that as the S-LCA method is still in its infancy, practitioners cannot yet fully measure social impact but rather describe the social performance. To partially solve data availability issues and support the S-LCA impact assessment, several databases exist such as the Product Social Impact Life Cycle Assessment database (PSILCA) and the Social Hotspots Database (SHDB), which are constantly upgrading their inventory with social data for various sectors and countries.

To develop the S-LCA-based self-assessment tool proposed in this manuscript, an S-LCA approach was used to develop an inventory of socio-economic impacts and their respective indicators associated with the full life cycle of producing ENMs and NEPs. However, as opposed to a full S-LCA, which requires major efforts in terms of time and cost for data collection, the S-LCA-based self-assessment tool presented here provides an easy-to-use, cost- and time-efficient solution that requires relatively low level of efforts and expert knowledge. This makes it a good starting point for initial assessment to highlight socio-economic issues in the value chain. To develop the conceptual backbone of the methodology, a generalized model production and downstream use of ENM and NEP were developed (Figure 1).

Adopting the S-LCA approach, an inventory of all 40 impact subcategories (see Appendix B) from the Guidelines [23] was developed and analyzed as part of this study in terms of the life cycle stage in which they occur in the production and downstream use of ENMs and NEPs. As the aim was to create a nano-specific tool, a comparative assessment was made to select those impact subcategories that should be considered as relevant to include while evaluating the socio-economic impacts of ENMs and NEPs. To do so, specific characteristics of these materials/products along with their potential negative and positive impacts were sought and compared to those associated with alternative conventional materials/products. Justifications for these choices were found in the literature and/or based on expert judgment. For the purpose, an expert panel comprised of scientists from social, sustainability and material sciences, as well as experts in risk assessment and decision science (cf. Appendix C for details), was created, which discussed and agreed on the selection of nano-specific impact categories relevant to be assessed as part of this study. For example, in a comparative assessment approach it was argued that production of ENMs irrelevant to the product application often involves sourcing of precious metals (e.g., gold, silver) from Asia, Africa and South America where extended working hours in mining are frequent and sometimes not fully paid [28]. This generates a negative socio-economic impact related to working hours linked with the ENMs/NEPs production and thus was considered as relevant to be assessed. In a similar vein, sourcing of conflict minerals (e.g., tungsten) from Congo, where child forced labor is at very high rates, generates a negative socio-economic impact associated with the production of ENMs involving such minerals [29].

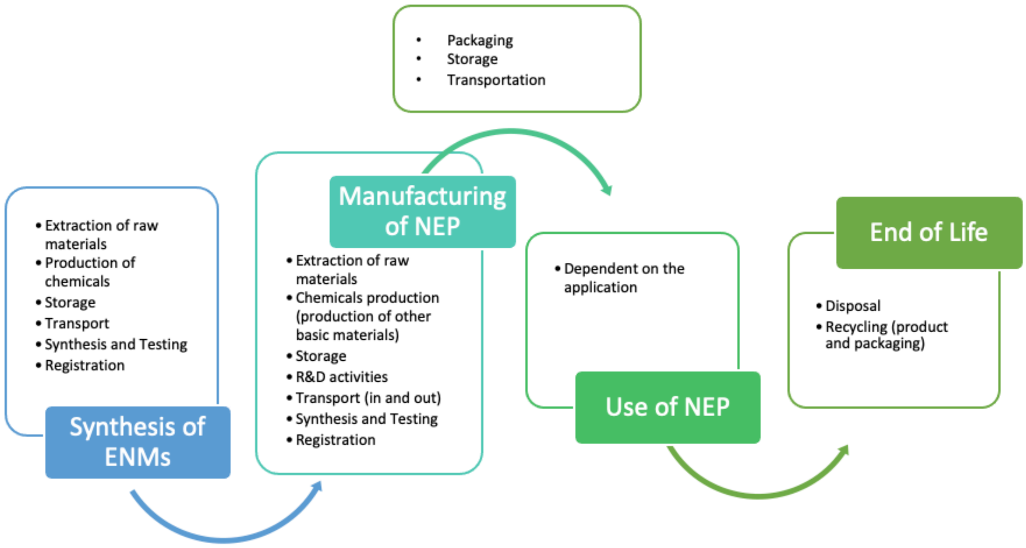

Figure 1. A generalized schematic presentation of the full life cycle of ENM and NEP production.

The analysis resulted in a list of impact subcategories that were deemed as most relevant for assessing ENMs/NEPs compared to conventional materials to serve as a foundation of the S-LCA-based self-assessment tool. Next, relevant indicators to assess the shortlisted impacts were sought from the established SHDB and/or developed by the expert panel following the S-LCA Guidelines [23].

Finally, to transform this analysis into a tool, a survey (see Appendix D) was created covering the assessment of all shortlisted impact subcategories along with introductory questions related to the producer and the product. The possible answers for each question were created by the expert panel based on available data from the SHDB or following the 2021 methodological sheets for S-LCA [30]. MAVT aggregation functions [25] were used to create a methodology to transform the survey results into scores which (i) showcase the severity of social impacts existing in the value chain and (ii) to enable comparison of alternatives in a SSbD approach.

3. Results

3.1. Social Impact Subcategories Applicable for NEPs Assessment

Nineteen impact subcategories pertaining to various stakeholder groups (workers, local community, value chain actors, consumers and society as a whole) were shortlisted by the expert panel as relevant to be assessed for nano-specific applications. In what follows, we define the aims and the scope assessment of these impacts in line with the 2021 methodological sheets for S-LCA [30].

A number of subcategories impacting workers include:

1. Child labor. The assessment aims to verify if the organization might or is employing children and to identify the nature of any child labor. The indicator should assess if the conditions are favorable for the occurrence of child labor and the existence and quality of prevention and mitigating measures taken by the organization.
2. Fair salary. This subcategory aims to assess whether practices concerning wages are compliant with established standards and if the wage provided is meeting legal requirements; whether it is above, meeting or below industry average; and whether it can be considered as a living wage.
3. Working hours. The assessment aims to verify if the number of hours effectively worked is in accordance with the International Labor Organization (ILO) standards, when overtime occurs and whether compensation in terms of money or free time is planned and provided to the workers.
4. Forced labor. Defined as any work or service that is exacted from any person under the menace of any penalty and for which that person has not offered himself or herself voluntarily [30]. This assessment aims to verify that forced or compulsory labor is not used in the organization.
5. Equal opportunities/discrimination. This subcategory aims to assess (i) equal opportunity management practices and (ii) the presence of discrimination in the opportunities offered to the workers by the organizations and in the working conditions. In this context, discrimination is defined as any distinction, exclusion or preference made on the basis of race, color, sex, religion, political opinion, national extraction or social origin, which has the effect of nullifying or impairing equality of opportunity or treatment in employment or occupation [30].
6. Workers' health and safety. The assessment aims to measure (i) the rate of incidents and (ii) the status of prevention measures and management practices. In this context, an incident is defined as a work-related event in which an injury or ill health (regardless of severity) or fatality occurred or could have occurred [30].

Impact categories pertaining to *local communities* include:

7. Access to material resources. This subcategory assesses the extent to which organizations respect, work to protect, to provide or to improve community access to local material resources such as water, land, mineral and biological resources and infrastructure such as roads, sanitation facilities and schools, among others.
8. Delocalization and migration. As economic development might lead to the large-scale migration of individuals seeking employment, involuntary resettlement may occur if organizations directly or indirectly dispossess individuals or groups of their land or resources. If operations require human relocation, organizations should engage in due diligence and procedural safeguards. Thus, this impact subcategory aims to explore whether (i) organizations contribute to delocalization, migration or involuntary resettlement within communities and (ii) populations are treated adequately.
9. Safe and healthy living conditions. Operations can impact community safety through equipment accidents or structural failures. Land-use changes can also lead to natural disasters. In addition, the generation and/or use of hazardous material and pollution emissions may lead to adverse health impacts. The aim of the assessment is to measure how operations impact community safety and health. This includes assessing the general safety conditions of operations and their impacts on public health.
10. Respect of indigenous rights. Indigenous peoples have a historical continuity with pre-invasion and pre-colonial societies that developed on their territories and consider themselves distinct from other sectors of the societies now prevailing in those territories or parts of them [31]. Respect of indigenous peoples' rights thus includes the right to lands, resources, cultural integrity, self-determination and self-government [32]. The aim of this assessment is to verify whether organizations respect the rights of indigenous peoples.
11. Local employment provides important income and training opportunities to community members. It is considered that organizations which develop relationships

with locally based suppliers will further encourage local employment and development. Organizations also may foster the development of local communities by training local employees in technical and transferable skills. Thus, the aim of this assessment is to understand whether an organization is directly or indirectly affecting local employment.

One impact subcategory pertaining to *value chain actors* has been deemed as most relevant for the social assessment of nano-enabled applications:

12. Supplier relations. Procurement practices of organizations have strong impacts on the supply chains. An organization should consider the potential impacts or unintended consequences of its procurement and purchasing decisions on other organizations and act with due diligence to avoid or minimize any negative impact (ISO 26000, [31]). The aim of the assessment should therefore try to evaluate whether an organization has a procurement process in place aimed at assessing its suppliers against social, environmental and economic criteria.

Impact subcategories pertaining to *consumers* include:

13. Consumer's health and safety. This subcategory refers to the consumers' rights to be protected against products and services that may be hazardous to health or life (ISO 26000, [31]). This assessment helps to identify whether an organization has processes and procedures in place to address consumer health and safety across the organizations involved in the life cycle of the product.
14. End-of-life responsibility. In an environmental context, end-of-life is commonly referred to as extended producer responsibility. This concept refers to product disposal, reuse or recycling. Product disposal can lead to significant environmental and social concerns, such as environmental and public health impacts that stem from the accumulation of hazardous material in waste. The aim of this assessment is to examine management efforts to address the social impacts of product end-of-life. Usually based on regulatory requirements, organizations should provide accurate, complete and clear information to consumers regarding appropriate end-of-life options. In some cases, producers could offer to collect, buy back and recycle to ensure safe waste disposal.

A number of aspects that have an impact on the society as a whole include:

15. Contribution to economic development. Businesses can foster economic development in many ways such as to generate revenue, create jobs, provide education and training, make investments or forward research. The aim of this assessment is to measure to what extent the organization/product or service contributes to the economic development of the society (e.g., annual growth rate of real GDP per employed person).
16. Prevention and mitigation of armed conflicts. This subcategory considers if and how an organization acts in conflict zones. It assesses as well if the organizations have in place strategies, measures and/or action plans to reduce and prevent conflicts when it operates in conflict zones or its supply chain operates in conflict zones.
17. Technology development is an overarching concept in which key elements such as technology needs, technology information, enabling environments, capacity-building, financial and institutional mechanisms are playing an important role. In this framework, technology transfer is defined as a process for converting research into economic development [23]. Thus, the aim of this assessment is to identify whether the organization participates in joint research and development efforts for more efficient and sound technologies. Technology transfer between more advanced economies and developing economies is seen as a key for the improvement of social conditions and to prevent further environmental damage related to old technology.
18. Corruption. This indicator assesses whether an organization (i) has implemented appropriate measures to prevent corruption and (ii) if there is evidence that it has engaged or has been engaged in corruption.

19. Ethical treatment of animals focuses on the welfare of animals that are affected by product systems and/or organizations' behavior (e.g., products that use animals for testing practices). The aim of the assessment is to (i) verify how the organization manages the life, treatment and death of animals and (ii) whether it has appropriate policies in place to address ethical treatment of animals across its supply chain.

3.2. Overview of the S-LCA Self-Assessment Screening Tool

As introduced, the S-LCA self-assessment screening tool was designed to guide users through their decision-making processes regarding new ENMs/NEPs but may also be used to re-evaluate existing nanomaterials/products in order to improve their sustainability from a socio-economic perspective. Its ultimate aim is to serve as an early time- and cost-efficient screening tool that can inform "go-to-next stage", "adjust" or "stop innovation" decisions by flagging potential socio-economic issues in the value chain. Based on consultations with nanotechnology associations and SMEs conducted to support the design and development of similar self-assessment tools for safety assessment [16], the tool design was developed following three guiding principles:

- Clarity. The tool should be easily applicable and understandable (i.e., nonexperts should be able to use it) and should yield transparent results.
- Efficiency. The tool should require a minimum of time and data (not more than a couple of hours).
- Reproducibility. It should yield reproducible results that can be used for comparative purposes.

As it was designed as an early-stage screening tool and does not require detailed information on specific ENMs/NEPs, it cannot replace a full in-depth S-LCA or LCC but should be seen as complementary to these higher-tier approaches as it covers the relevant issues that need to be considered for developing a sustainable nanoproduct. Therefore, the tool is a good starting point for an initial assessment that also prepares for further and more detailed assessment. The tool enables users to:

- Flag/identify social issues over the life cycles of ENMs/NEPs that can inform "go-to-next stage", "adjust" or "stop innovation" decisions.
- Identify and semi-quantify impacts for workers, local communities, value chain actors, consumers and society associated with the production of ENMs/NEPs.
- Estimate unique scores for the full product impact and all socio-economic impact categories and subcategories included in the assessment. These scores can be used for a comparative assessment of two or more production alternatives under consideration.
- Use an innovative approach combining the S-LCA and MCDA methodologies. The tool is flexible enough to allow assigning different weights for each impact subcategory thus allowing one to fine-grain and tailor the analysis to a specific context.
- Inform their decisions based on data coming from the established SHDB. This is particularly important as developing social data inventories can be very time-consuming and costly.

The S-LCA self-assessment screening tool is an Excel-based survey application. It covers questions related to all subcategories of impacts included in Section 3.1. The possible answers and scales were designed based on (i) social impacts data from the SHDB and (ii) common knowledge about nanomaterial properties and assessment, discussed in several iterations with the expert panel. Corresponding scales were designed to calculate how a provided answer will score in the overall assessment (e.g., wage levels below the national average will give a low score on this aspect, so the final result of the screening will show that there is a social issue in the value chain related to worker's fair salary). See Section 3.3 for the full scoring methodology.

The assessment starts with an introductory part that characterizes the nanoproduct under consideration (e.g., eliciting information about the nanomaterial used, its cost, application, production and supplier(s) country, among others).

Next, a number of questions assessing impacts on workers (in-house and suppliers), local communities, consumers and society follow. For the majority of the questions, indicators directly taken from the SHDB were used. Some questions and their related answers were developed by the expert panel following the 2021 methodological sheets for S-LCA [30]. In other cases, both questions developed from the expert panel and indicators directly taken from the SHDB were used. See Appendix D for a list of questions and possible answers to the survey.

This resulted in the following operationalization of the subcategories and indicators:

1. Child labor. To give a proxy measure for this impact, users are asked to self-evaluate the risks of child labor in their own operation and their suppliers as above, below or equal to the national average. Data for assessing this impact were directly taken from the SHDB using the authors' own scoring method as described in Section 3.3.
2. Fair salary. To measure fair salary, users are asked to evaluate the risks of wage and poverty levels in their own operation and their suppliers as below or equal to the national average. Data for assessing this impact were directly taken from the SHDB using the authors' own scoring method as described in Section 3.3.
3. Working hours are operationalized in terms of excessive working time using data from the SHBD.
4. Forced labor. To give a proxy measure for this impact, users are asked to self-evaluate the risks of forced labor in their own operation and their suppliers as above, below or equal to the national average. Data for assessing this impact were directly taken from the SHDB using the authors' own scoring method as described in Section 3.3.
5. Equal opportunities/discrimination. To measure this impact, users are asked to evaluate the levels of gender inequity and discrimination in their own operation and their suppliers as above, below or equal to the national average. Data for assessing this impact were directly taken from the SHDB using the authors' own scoring method as described in Section 3.3.
6. Workers' health and safety. To assess this impact, users are asked to evaluate the risks of occupational toxics and hazards and cases of injuries and fatalities at their own operation. Data for assessing this impact were directly taken from the SHDB using the authors' own scoring method as described in Section 3.3.
7. Access to material resources. To assess this impact, users are asked (i) if they assess the impacts their operation has on the local community (e.g., use of material resources such as water, minerals) or (ii) if they have a certified environmental management system.
8. Delocalization and migration. To measure this impact, users are asked to evaluate the risks to migrant workers in their own operation and their suppliers as above, below or equal to the national average. Data for assessing this impact were directly taken from the SHDB using the authors' own scoring method as described in Section 3.3.
9. Safe and healthy living conditions for suppliers. To assess this impact, users are asked to evaluate (i) communicable diseases, (ii) non-communicable diseases, (iii) access to drinking water and (iv) access to sanitation at their suppliers' using data from the SHBD.
10. Respect of indigenous rights. To assess this impact, users are asked to evaluate the overall risk of indigenous rights being infringed. Data for assessing this impact were directly taken from the SHDB using the authors' own scoring method as described in Section 3.3.
11. Local employment is operationalized in terms of the unemployment rate in local communities using data from the SHBD.
12. Supplier relations are assessed in a two-step approach. 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 (see indicators for 1–6; 8–11; 18–19).

13. Consumer's health and safety. To operationalize this impact, users should report whether they assess the hazard, social and ecological impacts their products might have on consumers.
14. End-of-life responsibility. To operationalize this impact, users should assess whether they (i) have incidents of non-compliance with regulatory labeling requirements, (ii) do not have incidents of non-compliance with regulatory labeling requirements or (iii) have systems in place to ensure that clear information is provided to consumers on end-of-life options.
15. Contribution to economic development. To measure this impact, users need to assess whether their innovative (nano-enabled) product is creating more value for society compared to their conventional product.
16. Prevention and mitigation of armed conflicts. To operationalize this impact, users are asked whether they are evaluating and choosing their suppliers based on sourcing from conflict-free regions.
17. Technology development. To give a proxy measure for this impact, 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.
18. Corruption. To operationalize corruption, 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.
19. Ethical treatment of animals. To develop a proxy measure for this impact, users are asked whether they have a code of conduct/follow procedures for ensuring ethical treatment of animals in their value chain (including in their own operation and their suppliers).

3.3. Scoring Methodology and Tool Results

To calculate a unique final score and intermediate scores for each impact subcategory and category, a novel scoring methodology was developed based on MAVT algorithms [29,32,33]. MAVT seeks to associate a value function to the assessed criteria and aggregate them in a hierarchical scoring function, which also takes into account the decision maker's preferences. Criteria utilized in this proposed methodology are related to the user's answers to specific questions (Appendix D) associated with the social assessment indicators introduced in the previous sections. Two types of questions are proposed: (i) generic questions related to the producer and the nanomaterial/nanoproduct under consideration as proposed by the expert panel and (ii) questions directly derived from the SHDB. A question related to the cost of the nanomaterial used in the product is asked to serve as an activity variable in the successive overall impact calculation. An activity variable is a measure of process activity that can be related to process output and is used to reflect the *share* of a given activity associated with each process [23] (e.g., working injuries can be partitioned among processes based on worker hours per process).

For each generic question, answers can be selected by the user from among a predefined list composed of two or more options. To each option, a corresponding score was associated which represents its inherent social impact (the higher the score the higher the negative impact).

SHDB-derived questions are each related to a specific SHDB indicator (e.g., wage, injuries and fatalities, etc.). All questions present the same three possible answers: "*Below national average*", "*In line with national average*" and "*Above national average*". Such questions are posed both for the producer itself and for all its suppliers and are subjected to the prior selection of the main country of operation and typology of processes operated by the company. To this end, a restricted list of nano-specific process typologies (e.g., coal, metal, minerals, etc.) was derived from a complete list included in the SHDB.

To create base scores to be associated to each country and process type selection, SHDB impacts were calculated for all countries and processed possible combinations. Next, for each of the obtained impact categories, the scores of all countries for the same process typology were assessed and divided into 10 bins with the same number of counties each, i.e., countries were associated with a score between 1 and 10 using their impact percentile for each specific process type and assessed impact. When the user selects "*In line with national average*", the default score is used. Otherwise, it is lowered or raised according to the "*Below national average*" or "*Above national average*" selection.

As scores for each question, whether generic or SHDB-derived, present different domains, they must be normalized prior to being hierarchically integrated. Such normalization was performed by linear transformation into the (0, 1) domain so that the most impacting answer scores one and the less zero. As the number of suppliers may vary from producer to producer, the scores related to each separate supplier are immediately aggregated into a single representative *suppliers'* group of answers where the mean aggregation function is used for the different scores of the same questions along the different suppliers. More than one question can be associated to the same indicator. Indicator's scores are obtained by averaging the scores for the respective questions.

Once initial indicators' scores have been obtained, hierarchical integration takes place following the structure depicted in Table 1. The first level of integration aggregates different indicators into the corresponding subcategories, then subcategories are integrated into categories and finally into a single score useful for comparison of alternatives. Such a single score represents the simplified social impact per dollar of production, following the way SHDB scores are generated. This single score figure can then be multiplied by the total cost of the annual production to reach a total impact that can be compared among different producers and that takes into account their production volumes.

Table 1. Hierarchical organization of indicators.

Indicator Type	Indicator	Impact Subcategory	Impact Category
SHDB	Indigenous rights	Respect of indigenous rights (3.2.10.)	Cultural heritage
SHDB	Legal system	Corruption (3.2.18.)	Governance
SHDB	Corruption		
Generic	Corruption-free operations		
Generic	End-of-life management	End-of-life responsibility (3.2.14.)	
Generic	Product impact on consumers	Health and safety for consumers (3.2.13.)	Health and safety
SHDB	Occupational toxics and hazards	Health and safety for workers (3.2.6.)	
SHDB	Injuries and fatalities		
SHDB	Non-Communicable diseases	Safe and healthy living conditions (for suppliers) (3.2.9.)	
SHDB	Communicable diseases		
SHDB	Access to drinking water		
SHDB	Access to sanitation		
Generic	Local community	Access to material resources (3.2.7.)	Human rights
SHDB	Migrant labor	Delocalization and migration (3.2.8.)	
SHDB	Discrimination	Equal opportunities/discrimination (3.2.5)	
SHDB	Gender equity		
SHDB	High conflict zones	Prevention and mitigation of armed conflicts (3.2.16.)	
Generic	Conflict-free operations		
Generic	Value created	Contribution to economic development (3.2.15.)	Socio-economic repercussions
Generic	Animal welfare	Ethical treatment of animals (3.2.19.)	
Generic	R&D partnerships	Technology development (3.2.17.)	
SHDB	Child labor	Child labor (3.2.1.)	Working conditions
SHDB	Wage	Fair salary (3.2.2.)	
SHDB	Poverty		
SHDB	Forced labor	Forced Labor (3.2.4.)	
SHDB	Unemployment	Local employment (3.2.11.)	
Generic	Suppliers' assessment	Supplier relationships (3.2.12.)	
SHDB	Excessive working time	Working hours (3.2.3.)	

At each level of the aggregation hierarchy a weighted average is used, default weights are always posed to the same default value of one for each element except when integrating indicators into subcategories where a lower score of 0.5 was assigned to generic indicators as opposed to SHDB ones. This was performed to reflect the lower level of confidence of generic indicators (developed by the expert panel), which may be considered less established in comparison to the SHDB-derived ones. In order to allow more flexibility, the proposed default weights can be modified by the user to better reflect their personal beliefs.

Results generated by the system relate to the social impact level of the different assessed aspects at successive levels in the aggregation hierarchy: indicators, subcategories, categories and single score. The final single score represents the relative socio-economic impacts generated along the value chain of a specific NEP (e.g., scratch and abrasion-resistant coatings for construction, core–shell SiC–titania anti-stick coatings for consumer products). This score can be used in an SSbD approach to compare different nano-enabled and/or conventional alternatives in the early stages of product development to select options that would have a lower negative socio-economic impact for the product being developed. The score can also be used to compare already-developed NEPs and/or conventional materials in order to select more societally favorable alternatives for specific applications.

Such results are classified in four categories of social impact: negligible, mild, moderate and high. Each category is also associated with a "semaphore" color system ranging from green to red for a simplified interpretation. Examples of how results are presented to the user are reported in Figures 2–5.

As depicted in Figure 2, an *indicator-level* score is generated. Thanks to the "semaphore" color system, it can be seen that the majority of the impacts in the example are negligible or mild, with only a few impacts being considered as high (e.g., issues in the legal system, occupational toxics and hazards, migrant labor, excessive working time, forced labor and poverty). It can also be seen that in some cases there are no negative impacts based on the answer given in the assessment (e.g., local community). This indicator-level analysis can be very useful in cases in which the overall assessment shows that there are only a few impacts with "high" severity in the value chain. In such cases, this analysis will allow users to identify the exact hotspots in terms of categories of stakeholders and impacts so they can search for ways to manage them (e.g., by developing action plans and/or replacing unfavorable aspects such as processes, procedures and suppliers in the value chain).

Similarly, in Figure 3, a *subcategory-level* score is generated. This visualization is useful to give a snapshot of how the product under assessment scores on the subcategories of impacts as defined in the S-LCA Guidelines (e.g., ethical treatment of animals, corruption, etc.). This analysis is useful to support decision-making discussion on whether the number and severity of the impacts are acceptable or non-acceptable for a specific context. This analysis can also support a further in-depth S-LCA assessment (moving to the next stage gates of the innovation process).

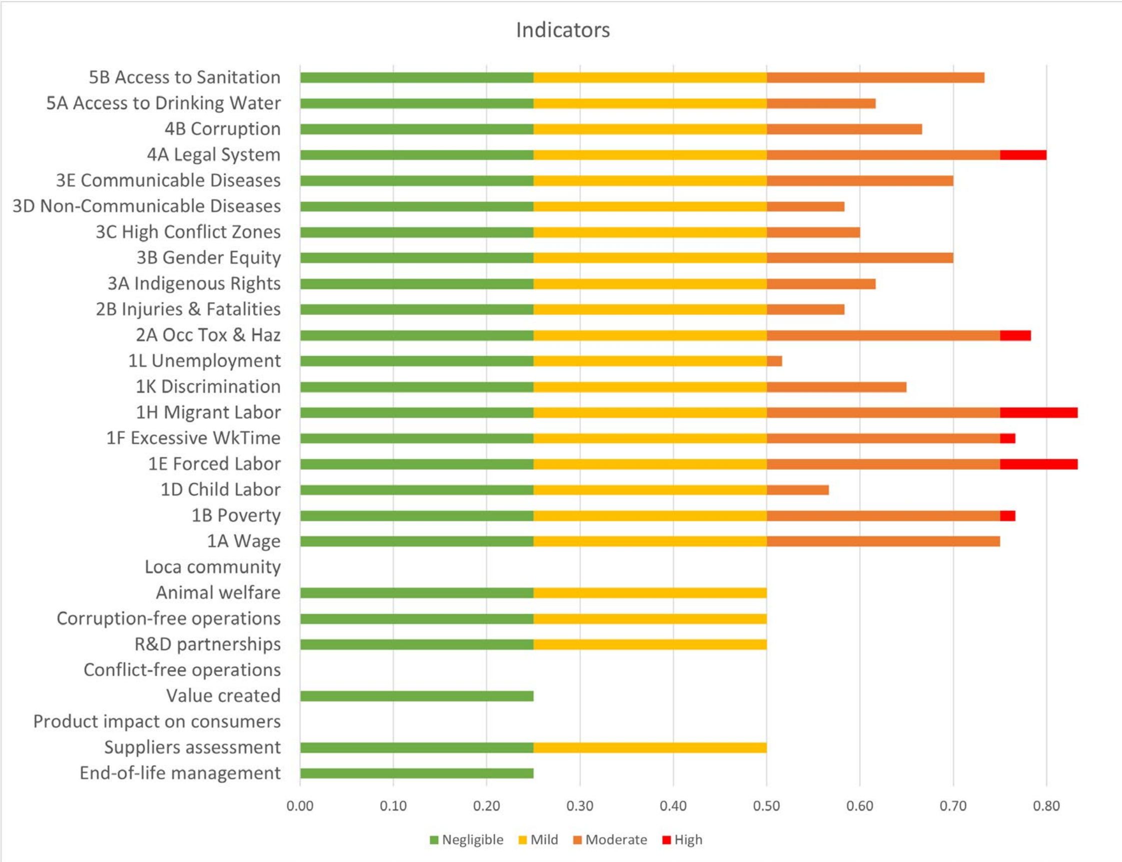

Figure 2. Indicators level results.

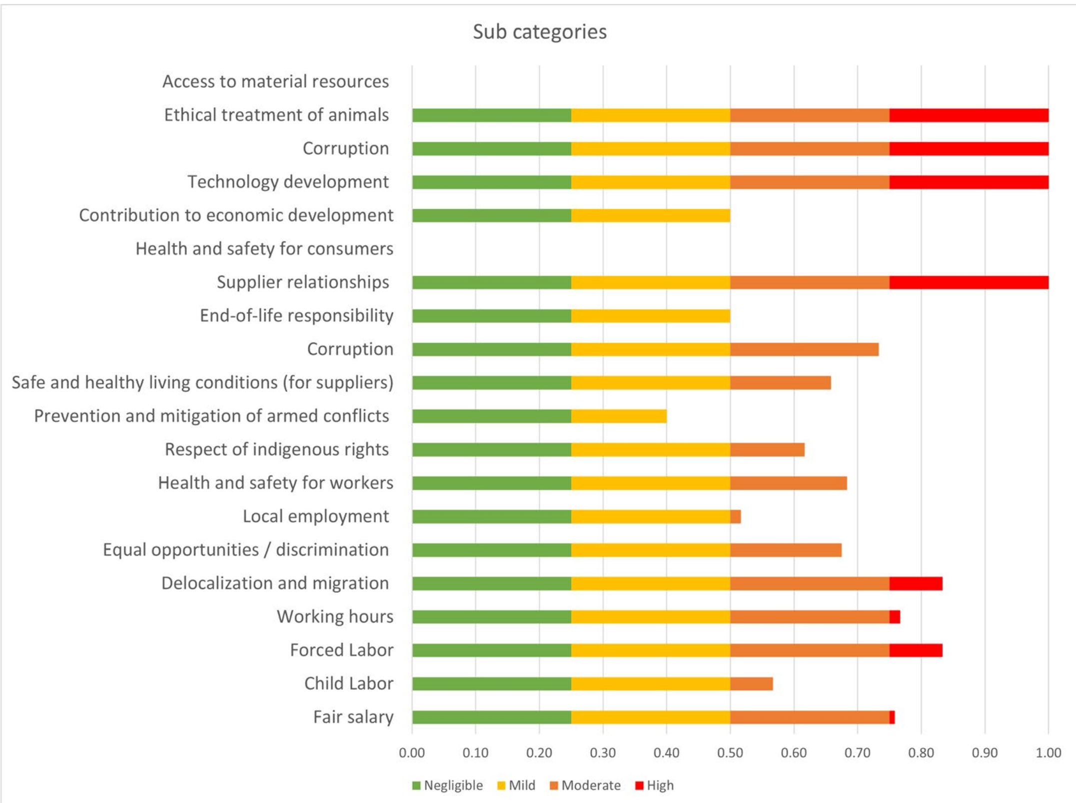

Figure 3. Subcategory level results.

Figure 4 provides a *category-level* score. This is the higher level of aggregation of results that gives a meaningful result in terms of whether and where there are socio-economic issues along the value chain. Similar to the subcategory level, the category level results can support high-level discussions and be the basis for further in-depth assessments.

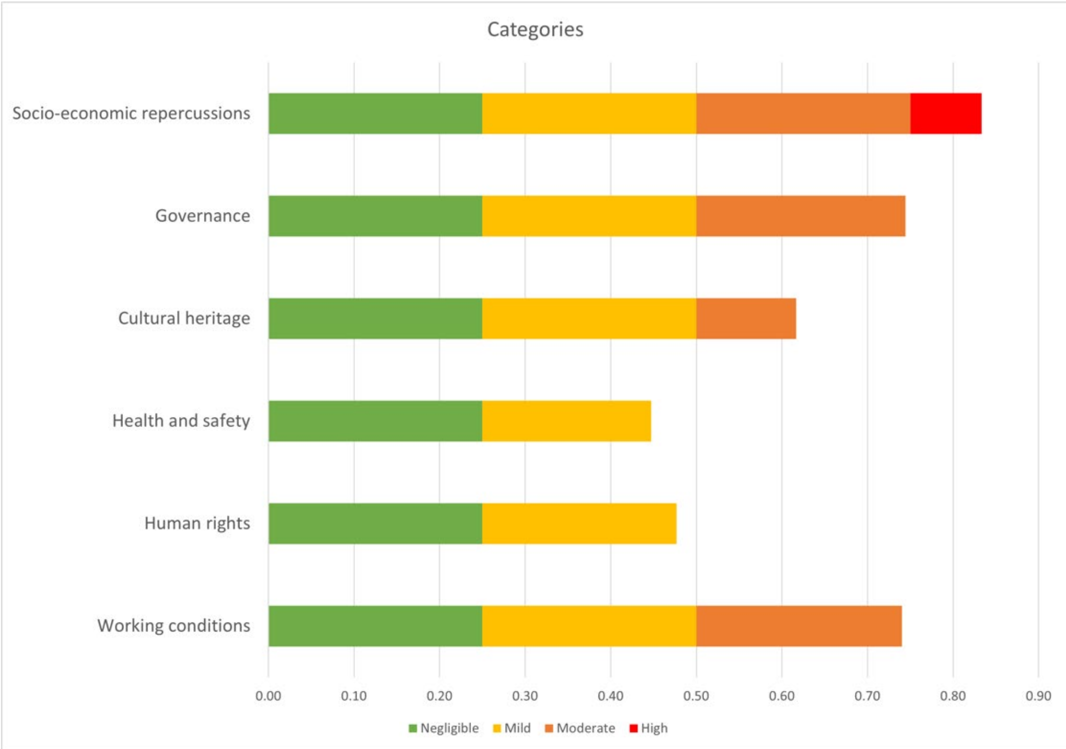

Figure 4. Category level results.

Finally, Figure 5 provides a *single score* result. This result is useful as a starting point for comparing two or more production alternatives. In addition, based on this score, the tool is capable of calculating how this result is translated into a more easily understandable unit (e.g., cost in US dollars) associated with the product impact, which can allow the user to evaluate the significance of the impact. For example, if the amount of the nanomaterial used in the product is very small (the reported cost for it is very low), the user can argue that despite visible instances of issues in the value chain, this production scenario is in fact not generating a high negative impact compared to a similar production scenario in which higher quantities are used.

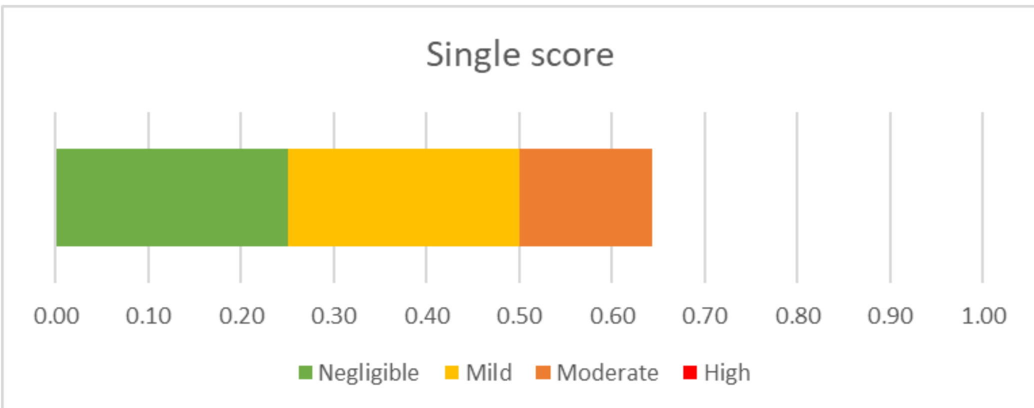

Figure 5. Single score results.

4. Discussion

The urge of the recent policy ambitions towards transforming the EU's economy for a more sustainable future calls for a holistic (life cycle) and pro-active (SSbD) approach to ensuring safer and more sustainable chemicals. Thus, SSbD decisions need to be made at each gate of the product innovation process, based on criteria pertaining to safety and sustainability. While the "safety aspects" of ENMs/NEPs have been exhaustively researched over the past two decades, the "sustainability aspects" encompassing social and economic aspects along with environmental concerns have begun to emerge only recently. While hazard assessments and environmental LCA studies have been extensively conducted, socio-economic assessments of NEPs have been very scarce. In terms of toolkits, few tools combining safety and sustainability exist (e.g., [10,16]). However, these tools also come with a few limitations partially stemming from data availability and the methodology development itself (e.g., despite being based on extensive research aimed at developing impact categories specific for ENMS/NEPs following S-LCA Guidelines [10,11], their proxy measurement is using overall company or country-level data). While these choices are understandable and practical, one can argue that this assessment approach is not capable of disentangling whether impacts are stemming from the production alternative itself or the overall operation of the company. In simple terms, the associated socio-economic impact cannot be fully assigned to the ENM/NEP and comparing production alternatives in the same operation may lead to similar socio-economic impacts.

Such limitations can be easily traced back in the application of the S-LCA methodology. First, within the S-LCA community there are controversial opinions regarding the accuracy of the results stemming from the use of site-specific (obtained by interviews or surveys) [33] vs. generic data (coming from statistical databases or company reports) [34]. In this context, according to UNEP Guidelines [23], social hotspot databases such as SHDB and PSILCA are identified as important sources for the evaluation of social impacts. Second, stemming from the S-LCA method itself, the definitions and scopes of the impact categories and indicators to be used in the assessment in fact call for obtaining more site-specific and country-level data inventories rather than product/process-specific data. At a methodological level in a full S-LCA, this issue is solved by the use an activity variable in the impact quantification process. The activity variable reflects the *share* of a given activity associated with each process [23] (e.g., working injuries can be partitioned among processes based on worker hours per process).

To overcome these limitations, the S-LCA self-assessment methodology presented here was designed based on (i) data directly taken from a social hotspot database and (ii) the calculation method included an activity variable impact assessment approach (as described Section 3.3) in order to disentangle impacts stemming from the ENM/NEP scenario itself rather than the overall operation of the company. While this framework was designed to overcome shortcomings in previous tools, testing and further refinement will be needed for its calibration. As the results from the tool provide an early-stage rough semi-quantification of the socio-economic issues associated with NEP production scenarios, a more detailed and in-depth analysis should be conducted to substantiate "go-to-next-stage" decisions. Specifically, as the framework was built as an early-stage screening level tool, it was greatly drawn from the S-LCA methodology, which encompasses both *social* and *economic* indicators. While an inclusion of indicators from the LCC methodology could give a more holistic picture of the economic impacts in the product evaluation, it calls for more case-specific data (such as initial cost, maintenance cost, rehabilitation cost and operating cost, among others), which has made it impractical for incorporation in an early-stage screening tool. Therefore, for product adjustments and "go-to-market" decisions, full S-LCA and LCC analyses need to be conducted. Provided that the user understands these limitations, the S-LCA self-assessment tool presented here provides a powerful, easy-to-use and efficient (time- and cost-saving) solution to support SSbD manufacturing.

This is a great advantage of the proposed approach as its application requires much less time, resources and technical knowledge to apply than the full S-LCA and LCC, which makes it particularly useful for SMEs. The possibility to apply this approach in the early stages of product development faster and at lower cost makes it directly relevant for supporting SSbD decision making. Nevertheless, the conceptual framework on which the methodology is based calls for a number of avenues for future research and refinement. First, the tool should be tested as much as possible with specific case studies. This has been facilitated by developing a stakeholder community of testers and users from industry in the H2020 SUNSHINE project. Second, as S-LCA and SSbD knowledge is constantly progressing, keeping pace with the latest trends and discussions around the EC-led development of SSbD criteria for chemicals and materials [18] will allow for further refinement of the tool. Furthermore, the S-LCA self-assessment tool will be integrated as a mid-level (Tier 2) sustainability assessment in the H2020 Gov4Nano project Risk Governance Portal and in the H2020 SUNSHINE project e-infrastructure. This will allow for further user testing and refinement of the tool in real case studies, including but not limited to photocatalytic ZnO/Silica complexes used in scratch and abrasion-resistant coatings for the construction sector, core–shell silicon carbide (SiC)–titania (TiO_2) anti-stick coatings for use in consumer products and graphene oxide-based materials for electrodes and energy storage (batteries). These case studies are now in their initial phase and will be published in separate articles.

5. Conclusions

The aim of this paper was to describe an innovative approach to socio-economic assessment of NEPs to support SSbD nanomanufacturing. The S-LCA self-assessment tool presented is a unique solution as it addresses socio-economic aspects specific for nanomaterial applications. It is based on a sound conceptual framework grounded in the S-LCA and MCDA methodologies to support decision making based upon socio-economic impacts assessed over the full life cycle of a product. The tool is an Excel-based easy-to-use, time and cost-saving application useful for an early-stage assessment or screening.

Currently, there are only a few quantitative socio-economic assessment tools [9,10], and more tools are being developed (e.g., H2020 SUNSHINE e-infrastructure), but they require higher levels of background data and knowledge and are intended for more detailed analysis. This makes them impractical for fast and cost-efficient application at the very early stages of product development. The proposed S-LCA self-assessment tool overcomes this limitation as the levels of effort and expert knowledge required for its application are rather low. In addition, using data from the established SHDB, the tool overcomes issues with data quality and availability and avoids the costly, complex and time-consuming data-gathering process when undertaking full assessments. Understanding the limitations of the tool as presented in the Discussion section, this solution can be considered as a valuable, practical decision-making aid for more sustainable nano-manufacturing.

The presented work makes a number of contributions. At the practical level, it provides an easy-to-use cost- and time-efficient decision-making tool to support SSbD choices in nano-manufacturing. At the methodological level, it combines S-LCA and MCDA to develop a unique nano-specific socio-economic assessment framework implemented via a scoring methodology. As such, it (i) identifies, defines and operationalizes 19 subcategories of impacts, which are relevant for the assessment of nano-enabled applications, and (ii) develops a high-quality data-reliant scoring methodology to translate socio-economic indicators into meaningful results to support decision making. At the policy level, it contributes to an ever-increasing demand for knowledge to support the transition to a more sustainable future by providing a science-based conceptual framework that incorporates life cycle and sustainable-by-design thinking for KETs.

To ensure the uptake and utilization of the proposed S-LCA self-assessment methodology by stakeholders from industry, consultancy, academia and the civil society, it will be converted into an open access web-based tool, which will be included in the Risk Governance Portal and the SSbD e-infrastructure that are currently being developed in the H2020 Gov4Nano and SUNSHINE projects, respectively. Moreover, further user testing and refinement of the tool in real industrial case studies will be pursued in these projects to demonstrate and confirm its robustness and its added value for industry, especially SMEs.

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Appendix A

Table A1. Table of acronyms.

ENMs	Engineered nanomaterials
EC	European Commission
EU	European Union
ILO	International Labor Organization
ISO	International Standardization Organization
KETs	Key Enabling Technologies
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
MCDA	Multi-criteria Decision Analysis
n-CuO	Nano-copper oxide
NEPs	Nano-enabled products
PSILCA	Product Social Impact Life Cycle Assessment database
RA	Risk Assessment
RP	Regulatory Preparedness
S-LCA	Social-Life Cycle Assessment
SbD	Safe-by-Design
SHDB	Social Hotspots Database
SIA	Safe Innovation Approach
SSbD	Safe and Sustainable-by-Design
SUNDS	Sustainable Nanotechnology Decision Support System
UNEP	United Nations Environment Programme

Appendix B

Table A2. Developing an inventory of impact subcategories relevant for consideration in nano-enabled applications.

Stakeholder Categories	Impact Subcategories	Life Cycle Stage in Which the Impact Occurs S *	M *	U *	EoL *	Relevant to Compare NEP with Conventional Product? Specify Potential Positive and Negative Impacts	Reference
Workers **	Freedom of association and collective bargaining		X		X	Not expected to be different. Major nanotechnology producers are (publicly listed) US or EU-based companies where freedom of association and collective bargaining issues are adddressed in labor contracts and sustainability disclosure. In addition, such considerations are not specific for nanomaterial production but rather a company-level characteristic.	Expert Panel
	Child labor **	X	X			Yes. The production of ENMs and NEPs involves sourcing of precious metals (e.g., gold, silver) and conflict minerals (tungsten) from Asia, Africa and South America where child labor in mining is still present and at very high rates. This generates a negative socio-economic impact stemming from the NEP production.	https://www.ilo.org/wcmsp5/groups/public/@dgreports/@dcomm/documents/publication/wcms_575541.pdf, accessed on 6 July 2021
	Fair salary **	X	X		X	Yes. The production of ENMs involves sourcing of precious metals (e.g., gold, silver) and conflict minerals (e.g., tungsten) from Asia, Africa and South America where fair salary could be an issue (minimum wages may not be able to cover basic needs). This generates a negative socio-economic impact stemming from the NEP production.	https://www.fairphone.com/wp-content/uploads/2020/05/Fairphone-report_final.pdf, accessed on 6 July 2021
	Working hours **	X	X		X	Yes. The production of EENMs involves sourcing of precious metals (e.g., gold, silver) from Asia, Africa and South America where extended working hours (overtime) in mining are frequent and sometimes not fully paid. This generates a negative socio-economic impact stemming from the NEP production.	https://www.sciencedirect.com/science/article/pii/S2093791118302956 accessed on 6 July 2021; https://aidc.org.za/overtime-scam-gold-mining/, accessed on 6 July 2021
	Forced labor **	X	X			Yes. The production of ENMs involves sourcing of conflict minerals (e.g., tungsten) from Africa where forced labor is at very high rates. This generates a negative socio-economic impact stemming from the NEP production.	https://www.dol.gov/agencies/ilab/resources/reports/child-labor/congo-democratic-republic-drc, accessed on 6 July 2021
	Equal opportunities/discrimination **	X	X			Yes. The production of ENMs involves sourcing of conflict minerals (e.g., tungsten, gold) from Africa (e.g., Congo) where discrimination issues are reported in the mining sector. These include the lack of women's participation in decision-making processes in the mining sector, the prohibition of access to artisanal mining activities, poor labor conditions, low incomes and environment pollution with harmful effects on the health of women and children). This generates a negative socio-economic impact stemming from the NEP production.	https://www.cordaid.org/en/news/advocating-for-womens-rights-in-the-mining-areas-of-drc/, accessed on 6 July 2021
	Health and safety **	X	X		X	Yes. There are uncertain risks associated with the ENM and NEP production that may lead to work-related ill health. This generates a negative socio-economic impact stemming from the NEP production.	https://osha.europa.eu/en/emerging-risks/nanomaterials, accessed on 6 July 2021
	Social benefits/social security		X		X	Not expected to be different. Major nanotechnology producers are (publicly listed) US or EU-based companies where freedom of social benefits and security issues are adddressed in labor contracts and sustainability disclosure. In addition, such considerations are not specific for nanomaterial production but rather a company-level characteristic.	Expert Panel
	Employment relationship	X	X		X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Sexual harassment	X	X			Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Smallholders including farmers					Not applicable to ENM anf NEP production.	Expert Panel
Local community **	**Access to material resources** **	X	X			Yes. Mining might have negative effects on local communities in terms of excessive use of material resources (water, minerals) due to extraction works but also positive effects in terms of contributing to developing better infrastructure.	https://www.sciencedirect.com/science/article/pii/S0301420717301484#t0010, accessed on 6 July 2021

Table A2. *Cont.*

Stakeholder Categories	Impact Subcategories	Life Cycle Stage in Which the Impact Occurs S *	M *	U *	EoL *	Relevant to Compare NEP with Conventional Product? Specify Potential Positive and Negative Impacts	Reference
	Access to immaterial resources	X	X			Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Delocalization and migration **	X				Yes. Developing new mining sites might involve delocalization of local communities. This generates a negative socio-economic impact stemming from the NEP production.	https://www.sciencedirect.com/science/article/pii/S0301420717301484#t0010, accessed on 6 July 2021
	Cultural heritage	X	X	X	X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Safe and healthy living conditions **	X	X	X	X	Yes. Risks from exposure to NEPs are still being researched and are not known in the longer term. This can generate a negative socio-economic impact stemming from the NEP production.	https://www.sciencedirect.com/science/article/pii/S2452074817300873, accessed on 6 July 2021
	Respect of indigenous rights **	X	X			Yes. Developing new mining sites might involve engagement/public consultations with indigenous communities where risks of disrespecting indigenous rights might be high. This can generate a negative socio-economic impact stemming from the NEP production.	https://www.sciencedirect.com/science/article/pii/S0301420717301484#t0010, accessed on 6 July 2021
	Community engagement	X	X	X	X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Local employment **		X			Yes. Producing NEPs requires specific skills, training and knowledge. This might effect positively or negatively the local employement rates.	https://www.cedefop.europa.eu/files/5170_en.pdf, accessed on 6 July 2021
	Secure living conditions	X	X		X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
Value chain actors (not including consumers) **	Fair competition	X	X		X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Promoting social responsibility	X	X	X	X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Supplier relationships **		X		X	Yes. Producing NEPs requires specific skills, specific technical background and equipment and is considered an innovation process. This might require moving from simple transaction to a deeper engagement which has potential to contribute significantly to improvement of social conditions in supply chains.	https://hal-audencia.archives-ouvertes.fr/hal-01289738/document, accessed on 6 July 2021
	Respect of intellectual property rights Wealth distribution		X			Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Wealth distribution	X	X		X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
Consumer **	**Health and safety** **			X		Yes. Long-term health and safety risks from NEPs are still not known, so specific measures should be taken in place to ensure the monitoring and assessment of consumer health and safety. This might generate a negative socio-economic impact stemming from the NEP production.	https://www.sciencedirect.com/science/article/pii/S2452074817300873, accessed on 6 July 2021
	Feedback mechanism			X		Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Consumer privacy			X		Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Transparency			X		Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel

Table A2. *Cont.*

Stakeholder Categories	Impact Subcategories	Life Cycle Stage in Which the Impact Occurs S *	M *	U *	EoL *	Relevant to Compare NEP with Conventional Product? Specify Potential Positive and Negative Impacts	Reference
	End-of-life responsibility **			X	X	Yes. Long-term health and safety risks from NEPs are still not known, so specific measures should be taken in place to ensure that accurate, complete and clear information is provided to consumers regarding appropriate end-of-life options and/or develop recycling and safe waste disposal initiatives. Failure to do so might generate a negative socio-economic impact stemming from the NEP production.	https://www.nature.com/articles/s41598-018-19275-4, accessed on 6 July 2021
Society **	Public commitments to sustainability issues	X	X		X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company activitiy.	Expert Panel
	Contribution to economic development **	X	X			Yes. Producing NEPs requires specific skills, training and knowledge. This can possitvely affect the contribution to economic development in terms of job creation and education.	https://www.oecd.org/sti/emerging-tech/Washington%20Symposium%20Report_final.pdf, accessed on 6 July 2021
	Prevention and mitigation of armed conflicts **	X	X			Yes. The production of ENMs involves sourcing of conflict minerals (e.g., tungsten) from Africa. Thus, sourcing from such countries will have a negative impact on the prevention of armed conflicts.	https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/regulation-explained/, accessed on 6 July 2021
	Technology development **	X	X			Yes. Producing ENMs and NEPs often involves partcipation to join research and development activities where collaboration with underdeveloped countries is encouraged.	Expert Panel
	Corruption **	X	X			Yes. The production of ENMs and NEPs involves sourcing of precious metals (e.g., gold, silver) and conflict minerals (tungsten) from Asia, Africa and South America where corruption rates in mining areas are high.	https://www.jstor.org/stable/26384734; https://www.sciencedirect.com/science/article/pii/S0301420717301484#t0010, accessed on 6 July 2021
	Ethical treatment of animals **	X	X			Yes. Nanotechnology involves more animal testing as there are so many different types of nanomaterials. In addition, monitoring of the impementation of appropriate measures for ethical treatment of animals must be established. Failure to monitor this may generate negative impact stemming from the NEP production.	https://www.peta.org.uk/blog/nanotechnology-can-lead-tests-animals-peta-scientists/, accessed on 6 July 2021
	Poverty alleviation	X	X		X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company!activitiy.	Expert Panel
Children	Education provided in the local community	X	X			Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company!activitiy.	Expert Panel
	Health issues for children as consumers			X	X	Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company!activitiy.	Expert Panel
	Children concerns regarding marketing practices			X		Not expected to be different as those potential impacts are not stemming from the nanomaterial production activity but are attributed to the general company!activitiy.	Expert Panel

* S—synthesis; M—manufacturing; U—use; EoL—end of life. ** Stakeholder categories and impact subcategories which are deemed to be relevant for inclusion in a nano-enabled product evaluation.

Appendix C

Table A3. Panel of experts participating to identify nano-relevant impact indicators.

Expert	Institution	Expertise
Dr. Alex Zabeo	Greendecision Srl., Venice, Italy	Sustainability Assessment (LCA), Decision Science
Dr. Lisa Pizzol	University Ca' Foscari of Venice, Venice, Italy	Sustainability assessment (LCA, Water/Carbon Footprint), Risk Assessment

Table A3. *Cont.*

Expert	Institution	Expertise
Dr. Danail Hristozov	EMERGE Ltd., Sofia, Bulgaria	Risk Assessment, Decision Science
Dr. Stella Stoycheva	Yordas Ltd., Forcheim, Germnay	Social sciences, Sustainability Assessment (s-LCA, LCC)
Dr. Bernd Nowack	EMPA, St. Gallen, Switzerland	Life Cycle Thinking, Risk Assessment, Materials Science
Dr. Claudia Som	EMPA, St. Gallen, Switzerland	Technology Analysis (Life Cycle Thinking, Foresight), Risk Assessment
Dr. Hyunjoo Hong	EMPA, St. Gallen, Switzerland	Life Cycle Thinking, Risk Assessment, Materials Science

Appendix D

Table A4. Questions and possible answers developed to create the S-LCA self-assessment tool.

Question	Answer
Nanomaterial used in the product	Aluminum, Aluminum oxide, Aluminum hydroxide, Antimony oxide, Antimony pentoxide, Barium carbonate . . .
Cost of the nanomaterial used in the product	. . . USD
Specify your product or application	. . .
Which is your main production country?	Albania, United Arab Emirates, Argentina, Armenia . . .
Producer type	Chemical, rubber, plastic products, ferrous metals, metal products . . .
Supplier name	. . .
Supplier country	Albania, United Arab Emirates, Argentina, Armenia . . .
Supplier type	Chemical, rubber, plastic products, ferrous metals, metal products . . .
How do you ensure you manage properly the end of life of your product?	We have incidents of non-compliance with regulatory labeling requirements We don't have incidents of non-compliance with regulatory labeling requirements We have systems in place to ensure that clear information is provided to consumers on end-of- life options
Do you assess the hazard, social and ecological impacts your products might have on consumers?	Yes No
How are your innovative (nano-enabled) products creating value to society compared to your conventional products?	My innovative product creates more value than the conventional one as it requires more special skill and training My innovative product creates as similar value to society as my conventional one I am not sure if my innovative product creates value than the conventional one
Are your evaluating and choosing your suppliers based on sourcing from conflict-free regions?	Yes No
Are your product R&D activities based on	Global collaboration Local collaboration My own know-how
Are you evaluating and choosing your suppliers based on sourcing from corruption-free areas?	Yes No

Table A4. *Cont.*

Question	Answer
Do you have a code of conduct/follow procedures for ensuring ethical treatment of animals in your value chain?	At both my own operation and at my suppliers' operations At my own operation I don't have such procedures neither I have such expectations from my suppliers
Do you assess/keep records of the impacts your operation has on the local community (e.g., use of material resources such as waters, minerals) or have a Certified environmental management system?	Yes No
How would you rate yourself against the following social impact categories (where Above national average means less social negative impacts)? Wage, Poverty, Child Labor, Forced Labor, Excessive Working Time, Migrant Labor, Discrimination, Unemployment, Occ Tox & Haz, Injuries & Fatalities, Indigenous Rights, Gender Equity, High Conflict Zones, Non-Communicable Diseases, Communicable Diseases, Legal System, Corruption, Access to Drinking Water, Access to Sanitation	Below national average In line with national average Above national average
How would you rate your supplier 1, 2, 3 . . . against the following social impact categories (where Above national average means less social negative impacts)? Wage, Poverty, Child Labor, Forced Labor, Excessive Working Time, Migrant Labor, Discrimination, Unemployment, Occ Tox & Haz, Injuries & Fatalities, Indigenous Rights, Gender Equity, High Conflict Zones, Non-Communicable Diseases, Communicable Diseases, Legal System, Corruption, Access to Drinking Water, Access to Sanitation	Below national average In line with national average Above national average

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