# The international ecosystem for accelerating the transition to Safe-and-Sustainable-by-design materials, products and processes.

*Preliminary Report*

Sustainable by design methods and criteria mapping

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## Abbreviations and Acronyms

| Abbreviation | Definition |
|---|---|
| ANP | Analytic network process |
| CAD | Computer Aided Design |
| CAE | Computer Aided Engineering |
| CBA | Cost-benefit analysis |
| CE | Circular Economy |
| Cefic | European Chemical Industry Council |
| ChemSec | International Chemical Secretariat |
| CSS | Chemicals Strategy for Sustainability |
| CVMN | Contingent valuation method |
| DG RTD | Directorate-General for Research and Innovation |
| EEA | European Environment Agency |
| EF | Ecological Footprint |
| ELCD | European reference Life Cycle Database |
| EMCC | European Materials Characterisation Council |
| EMMC | European Materials Modelling Council |
| EMMO | Elementary Multi-perspective Material Ontology |
| EoL | End of LIfe |
| EPLCA | European Platform on Life Cycle Assessment datasets |
| ESG | Environment, Social, Governance |
| ESRS | Environmental and sustainability rating systems |
| FAIR data | Findable, accessible, interoperable, and reusable data |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gas |
| GTP | Green Tribology Principles |
| H2020 | Horizon 2020 |
| HE | Horizon Europe |

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| Abbreviation | Definition |
|---|---|
| HPM | Hedonic pricing method |
| ILO | International Labour Organization |
| ITUC | International Trade Union Confederation |
| IRR | Internal Rate of Return |
| JRC | Joint Research Centre |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| cLCC | Conventional Life Cycle Costing |
| eLCC | Environmental Life Cycle Costing |
| sLCC | Societal Life Cycle Costing |
| LCSA | Life Cycle Sustainability Assessment |
| LCT | Life Cycle Thinking<br>Life Cycle Tribology |
| MCA | Multicriteria analysis |
| MCI | Material Circularity Index |
| MIPS | Material intensity per service unit |
| NPV | Net present value |
| OECD | Organisation for Economic Co-operation and Development |
| PBT substances | Persistent, bioaccumulative, and toxic substances |
| PEF | Product Environmental Footprint |
| PSIA | Product Social Impact Assessment |
| PR | Preliminary Report |
| R&I | Research & Innovation |
| SbD | Safe-by-design |
| SDGs | Sustainable Development Goals |
| SEA | Strategic environmental assessment |
| SEILA | Socio economic impact assessment |
| SETAC | Society of Environmental Toxicology and Chemistry |

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| Abbreviation | Definition |
|---|---|
| SHBD | Social Hotspot Database |
| SIA | Social impact assessment |
| SILCA | Product Social Impact Life Cycle Assessment database |
| S-LCA | Social Life Cycle Assessment |
| SRIP | Strategic Research and Innovation Plan |
| SSbD | Safe-and-Sustainable-by-Design |
| SSIA | Safe and Sustainable Innovation Approach |
| SusbD | Sustainable by Design |
| SW | Software |
| TCA | Travel cost analysis |
| TLR | Technology Readiness Level |
| UN | United Nations |
| UNEP | United Nations Environment Programme |
| VC | Value Chain |
| WBG | World Bank Group |

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# 1. Executive Summary

This preliminary report "Mapping sustainability by design" is part of the IRISS Project "**IRISS – International ecosystem for accelerating the transition to Safe and Sustainable-by-Design materials, products and processes"**. It aims to explore the **methods** applied in industry, in previous EU or national projects, as well as in scientific literature, to include **sustainability criteria,** at the design phase of the material processes and product development. It also intends to assess **the tools** used to develop products and processes, considering a **system approach,** to achieve safer, functional, recyclable, or degradable products maximizing lifetime and minimizing energy consumption. **Sustainability criteria** should focus on early stages of materials development, tailoring them to the intended use. Correlations need to be established between material behaviour along different Technology Readiness Levels (TRLs), exploring characterization and modelling tools capabilities. Sustainability criteria will include **material and product durability, strategies for minimising energy use** during material production or use and **minimising critical raw material use.** For materials likely to reach the environment, biodegradability and potential ecotoxicity will be part of the sustainability criteria.

In this report, the literature review of sustainability has been focused on updating the work previously performed by Caldeira et al., 2022 [1]. They reviewed the most relevant publications related to safety and sustainability dimensions, methods, tools, and criteria, and performed an analysis of the data compiled until 7th October 2021. Based on their study, the review presented herein has updated the information till February 2023. Besides, as the previous study was focused on chemicals, additional terms have been included, such as materials, biomaterials, or biobased materials. Then, a deeper analysis of the main existing SSbD frameworks identified has been performed. This information has been complemented with the results obtained from the **survey** launched within the IRISS network and the identified stakeholders, as well as with the analysis of the relevant identified **SSbD related EU projects.**

In this report, the work is divided into 6 main sections starting with an introduction to the concept of Safe and Sustainability by Design (SSbD), the description of the objectives of this preliminary report and the proposed methodology (chapter 2). Chapter 3 maps the sustainability frameworks, methodologies and tools beginning with section 3.1, which compares the five published SSbD frameworks on how to operationalize SSbD: a) the frameworks proposed by the EC Joint Research Centre (JRC), b) the European Environment Agency (EEA), c) the Organization for Economic Co-operation and Development (OECD), Working Party on Manufactured Nanomaterials (WPMN) under a policy and regulatory perspective, and d) the frameworks published from an industrial perspective by the Safe and Sustainable Innovation Approach (SSIA) Steering Group, of the European Chemical Industry Council (Cefic) and e) the International Chemical Secretariat (ChemSec). The **JRC framework** is the most comprehensive and detailed one (e.g., in recommended dimensions, parameters and tools), while the other approaches can be seen more as conceptual ones. Safety and environmental sustainability dimensions are covered in all regarded SSbD approaches, while all three sustainability pillars (environmental, social, economic) are only covered by JRC, OECD, and Cefic.

Chapter 3 includes a mapping of the three sustainability dimensions (environmental, social, economic) based on the analysis of the 55 documents identified during the literature review update. Section 3.2 focuses on the **environmental dimension (LCA)** and provides a summary of the literature review, as the detailed analysis has been conducted in the preliminary report PR*1.3 - Lifecycle Analysis Mapping*. Section 3.4 covers the **social dimension (S-LCA)** and analyses the main



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guidelines for S-LCA, namely the UNEP, 2020 Guidelines for Social Life Cycle Assessment of Products and Organizations [74] and the current Handbook for Product Social Impact Assessment (**PSIA**) [78]). The literature review concluded that the number of studies considering the social indicators proposed by the mentioned guidelines is increasing significantly, with **"Health and Safety of workers"** being the most used indicator. Concerning the databases, two main databases are frequently used by S-LCA practitioners: Social Hotspots Database (SHDB) and Product Social Impact Life Cycle Assessment database (**PSILCA).** Among the 55 studies analysed, three of them utilized the PSILCA database, while four used the SHDB database.

In life cycle sustainability assessment, the **economic** pillar is usually addressed through the Life Cycle Costing (LCC) methodology, analysed in section 3.5. Three different types of **life cycle cost** analysis need to be considered: conventional **LCC** (cLCC), environmental LCC (eLCC) and social LCC (sLCC). Life cycle cost is by far the predominant term reported in the studies, but several studies consider environmental externalities (eLCC), as an additional cost. However only isolated studies include the sLCC.

Section 3.6 describes **modelling and characterization tools**, paying special attention to the different tools for sustainable engineering design and manufacture of products. Sustainable engineering tools work in correlation with sustainability assessment with the aim of designing products that do not only satisfy technical requirements, but also environmental ones. Existing tools mainly focus on material and process selection for sustainability but there is a lack of dedicated engineering tools for holistic end-of-life concepts and circular economy aspects. High performance has a positive impact on the overall sustainability and tribology, is a tool that helps in the design of sustainable materials, products, and processes, assessing the functionality of a material/product for the selected application controlling the friction, and consequently increasing the energy efficiency during use.

In addition to the literature mapping, a survey was conducted to understand the status of SSbD application and competencies in both academia and industries. The survey results in each of the sustainability pillar, detailed in Chapter 4, align with the findings of the literature review. Similarly, chapter 5 analyses the sustainability aspects considered in seventeen on-going EU projects, showing a similar trend to the survey results.

The report ends with the conclusion (chapter 5). The Safe-and-Sustainable-by-Design (SSbD) concept is a central component of the EC Chemical Strategy for Sustainability, but there is still a need for a common understanding and practical implementation. Safety-related design principles are widely applied in the design phase, while the sustainability-related design principles show marginally lower application rates**.** Concerning the environmental assessment, some SSbD approaches recommend using the Product Environmental Footprint (PEF) assessment method. There has been an increasing interest from the chemical and materials stakeholders to implement Social LCA (S-LCA) in the sustainability studies, as well as in the inclusion of environmental externalities (eLCC) in LCC, but still case studies are very limited in comparison with the studies implementation LCA and LCC. The social and economic aspects show a low level of implementation and methodological maturity.

IRISS, along with the AMI2030 and SSbD EU Financed projects, can address these challenges, and promote progress in SSbD. Training and education are necessary to enhance SSbD skills among engineers, and support can be provided for eco-design capacities.

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# 2. Introduction

## 2.1 Sustainable development

**Sustainable development** is one of the core principles of sustainability, described as the capacity of humanity to evolve to meet current requirements "without sacrificing the ability of future generations to meet their own needs". Progress towards sustainable development is vital to preserve a balance between human activities and the ecosystem. In ISO Guide 82:2019, which provides guidelines for addressing sustainability in standards, sustainability is defined as "*state of the global system, encompassing the environmental, social and economic subsystems, in which the needs of the present are met without compromising the ability of future generations to meet their needs*" [1].

The concept of sustainability is continually evolving. Understanding and achieving a balance between environmental, social, and economic systems, ideally in mutually supporting ways, is considered essential for making progress towards sustainability. The achievement of sustainability is now recognized as **one of the most important considerations in all human activities.**

In the last decade, numerous methods have been developed to quantify and evaluate sustainability[2]. Assessing sustainability requires integrated approaches, able to model complex systems and to capitalize the best knowledge on impact assessment. Moreover, these approaches should allow for comparison between different options, be reproducible and transparent, highlighting trade-offs. The background approach is **Life Cycle Thinking (LCT),** which considers a system, such as a product, a service, or an organization, from cradle to grave, or in a more modern vision, from cradle to cradle. This concept integrates three dimensions into the sustainability assessment: environment, economy, and society. The most crucial methodologies in LCT are Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA), based on a life cycle perspective.

There are several assessment methodologies for assessing sustainable development. In 2021, Flour and Bokhoree [3] carried out a review on Sustainability Assessment Methodologies, using a bibliometric analysis approach based on Web of Science platform, covering the period from 2000 to 2020. A combination of keywords was employed to retrieve papers related to this topic. The keywords used were as follows: "**sustainability assessment tools**" OR "**sustainability assessment methodologies"** OR "**sustainability measurement techniques**". A total of 28 results were obtained from various papers related to sustainability assessment (see Table 1). The selected elements were based on the structure of the triple bottom line, which combines the environmental, economic, and social dimensions. They were ranked according to their applicability at different scales and the sustainability dimensions taken into consideration.

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*Table 1 - Sustainability Assessment methodologies (Table based on [3])*

| | Environmental | Economical | Social |
|---|---|---|---|
| Life Cycle Assessment (LCA) | √ | | |
| Dow Jones Sustainability Index (DJSI) | √ | √ | √ |
| Environmental Sustainability Index (ESI) | √ | | |
| Environmental Performance Index (EPI) | √ | | |
| Ecological Footprint (EF) | √ | | |
| Sustainable Society Index (SSI) | √ | √ | √ |
| Life Cycle Costing (LCC) | √ | | |
| Human Development Index (HDI) | | √ | √ |
| Environmental Impact Assessment (EIA) | √ | | |
| Sustainable National Income (SNI)] | √ | √ | |
| Social Life Cycle Assessment (S-LCA) | | | √ |
| Strategic Environmental Assessment (SEA) | √ | | |
| Index of Sustainable Economic Welfare (ISEW) | | √ | |
| National Sustainable Development Index (NSDI) | √ | √ | √ |
| Composite Sustainable Development Index (ICSD) | √ | √ | √ |
| Full Cost Accounting (FCA) | | √ | |
| Integrated Value Model for Sustainable Assessment (MIVES) | √ | √ | √ |
| Cost–Benefit Analysis (CBA) | √ | √ | √ |
| Genuine Progress Indicator (GPI) | | √ | |
| Life Cycle Sustainability Assessment (LCSA) | √ | √ | √ |
| System Dynamics (SD) | √ | √ | √ |
| Multi Criteria Decision Analysis (MCDA) | √ | √ | √ |
| Sustainability Assessment Model (SAM) | √ | √ | √ |
| Barometer of Sustainability (BS) | √ | √ | √ |
| Fuzzy Evaluation for Life Cycle Integrated Sustainability Assessment (FELICITA) | √ | √ | √ |
| Sustainability Assessment by Fuzzy Evaluation (SAFE) | √ | √ | √ |
| Fuzzy Logic Approach for Sustainability Assessment based on the Integrative Sustainability Triangle (FUZZY-IST) | √ | √ | √ |
| Adaptive Neuro-Fuzzy Inference System (ANFIS) | √ | √ | |

This study provided a review of various existing sustainability methodologies primarily applied at country level. Only few of them integrated the environmental, economic, and social dimensions.

With the absence of a truly integrative approach, sustainability assessment does not effectively assist decision-makers and the stakeholders. Efforts and programs aimed at measuring sustainability have become significant research topics as they impact various fields, including economic, environmental, and social. The severity and interlinkages of global crises present an unprecedented challenge. It is observed that very few approaches address the overall sustainability. Since it is complex in nature and difficult to measure, the use of appropriate elements to establish an assessment framework is

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essential. The way in which progress is assessed represents a key level in undertaking the root causes of sustainability.

There are many differences among existing frameworks concerning the ease of use, assessment procedure, and data availability. The indicators used are too general and with different scopes.

Nautiyal and Goel [4] analysed various methodologies for sustainability assessment:

- LCA: Life cycle assessment
- SEILA: Socio economic impact assessment
- SEA: Strategic environmental assessment
- CBA: Cost-benefit analysis
- TCA: Travel cost analysis
- SIA: Social impact assessment
- CVMN: Contingent valuation method
- HPM: Hedonic pricing method
- MCA: Multicriteria analysis
- MIPS: Material intensity per service unit
- ANP: Analytic network process
- ESRS: Environmental and sustainability rating systems

According to these authors, each methodology has its own peculiarities, constraints, and complexity. Figure 1 shows the elements that a sustainability assessment method must comprise: the scope and objectives of assessment, appropriate sustainability indicators, an assessment technique, and finally the interpretation and application of assessment. Their research demonstrated that sustainability assessment uses various qualitative approaches or data collection along with quantitative techniques to produce valuable outcomes. One of the significant challenges in this assessment is the tradeoff among society, economy, and environment. Table 2 represents a summary of the review performed by Nautival et al [4] of different sustainability assessment methods.

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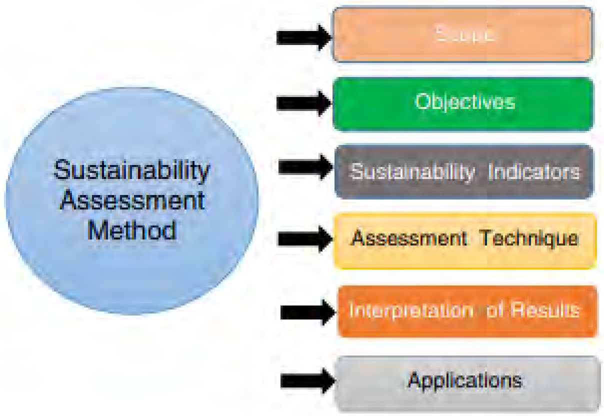


*Figure 1 – Elements of a sustainability assessment method (Figure taken from [4])*

*Table 2 - Comparison of sustainability assessment methods on the basis of some important criteria (Table taken from [4])*

| S. No. | Criteria | LCA | SEIA | SEA | CBA | TCA | SIA | CVM | HPM | MCA | MIPS | ANP | ESRS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Cover all domains of Sustainability | High | High | High | Medium | High | High | Medium | Medium | High | Medium | High | High |
| 2 | Approach to alternative scenarios | Medium | Medium | Medium | High | Medium | High | Medium | High | High | Medium | Medium | Medium |
| 3 | Ability to handle scarcity of data | High | Medium | Medium | Medium | Medium | High | Low | Low | High | Low | Medium | Medium |
| 4 | Engagement of stakeholders in all phases | Low | Low | Medium | Medium | High | High | Medium | Medium | High | Low | High | High |
| 5 | Clear assessment | Low | Medium | Medium | Medium | High | Medium | High | Low | Medium | Low | High | Medium |
| 6 | Clear interpretation of results | Low | Medium | Medium | Medium | High | Medium | High | Low | Medium | Low | High | Medium |
| 7 | Manage interrelationships | Low | Low | Low | High | Medium | Low | Medium | High | High | Medium | High | Medium |

More recently in 2022 Caldeira et al. [1] performed a review of safety and sustainability dimensions, aspects, methods, indicators, and tools. This study has been used as a starting point for the bibliographical review performed in this report. The results of this study are analysed more deeply in the section 3.2.

Another interesting review of sustainable assessment approaches has been performed in the frame of the ORIENTING project [5]. ORIENTING is a research project to develop an operational methodology for product Life Cycle Sustainability Assessment (LCSA). The main purpose of Orienting project is to integrate a life cycle approach that includes the analysis of environmental, social, and economic impacts.

## 2.2 Safe and Sustainable-by-Design (SSbD) concept

With the European Green Deal [6], the European Commission aims to position Europe as the first climate neutral continent by 2050. The Green Deal defines four interlinked policy goals that will drive the **transition to a sustainable economy and society**: **climate neutrality**, **biodiversity protection**, **circular economy, and a zero-pollution ambition for a toxic-free environment**. To achieve these goals, several strategies and action plans have been adopted, including the **Chemicals Strategy for Sustainability (CSS)** [7].

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The CSS has introduced a Strategic Research and Innovation Agenda for 2022. The **SRIP** (**Strategic Research and Innovation Plan for safe and sustainable Chemicals and Materials**) delivers on this second announcement and highlights the Research and Innovation (R&I) areas that are crucial for making chemicals and materials safer and more sustainable [8]. The life cycle approach proposed by SRIP is schematically represented in Figure 2. .

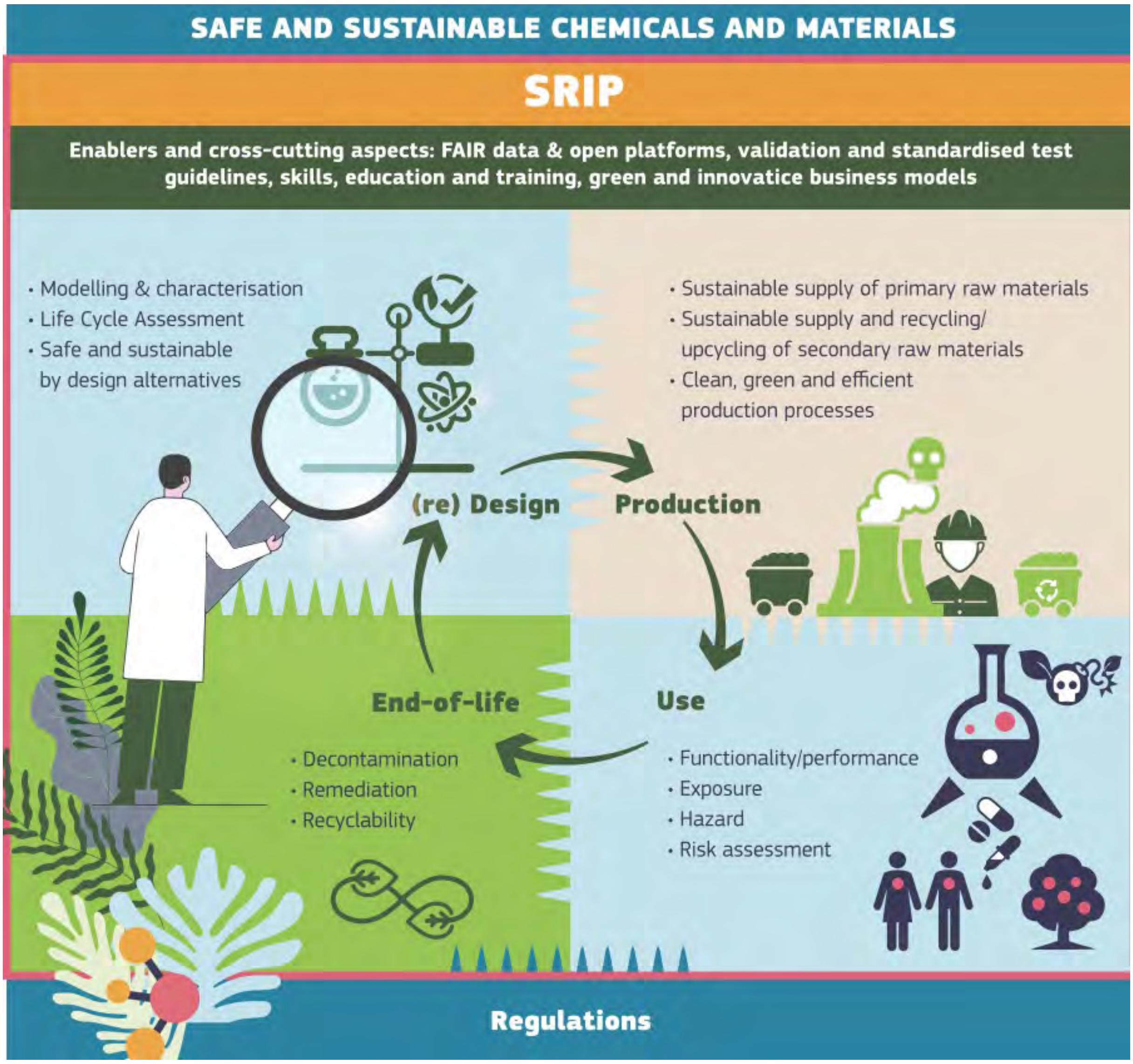


*Figure 2 - The life-cycle approach of the Strategic Research and Innovation Plan (SRIP). (Figure taken from [8])*

The Plan focuses on enabling and crosscutting aspects and the R&I needs in line with life cycle stages of chemicals and materials. As chemicals and materials are used in many different sectors and consumer goods, the identified R&I areas can also contribute to increasing the overall sustainability of these value chains and products.

The SRIP will support another R&I action announced in the CSS, the **Safe and Sustainable-by-Design (SSbD)** framework and criteria. This framework sets out criteria on how to **assess safety and sustainability** of a chemical or material **across its lifecycle**.

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The concept of **SSbD** lies at the core of this multidimensional transition. It aims to ensure that chemical materials and products **are designed, produced, and used** in a way that avoids harm to both people and the environment. The **Sustainability** criteria should cover **environmental, social, economic aspects, with safety being included in all of them**. That means chemicals, materials and products that are safe for humans and environment and benefits all dimensions of sustainability. The transition towards SSbD chemicals and materials would thereby contribute to several Sustainable Development Goals (SDGs) as shown in Figure 3.

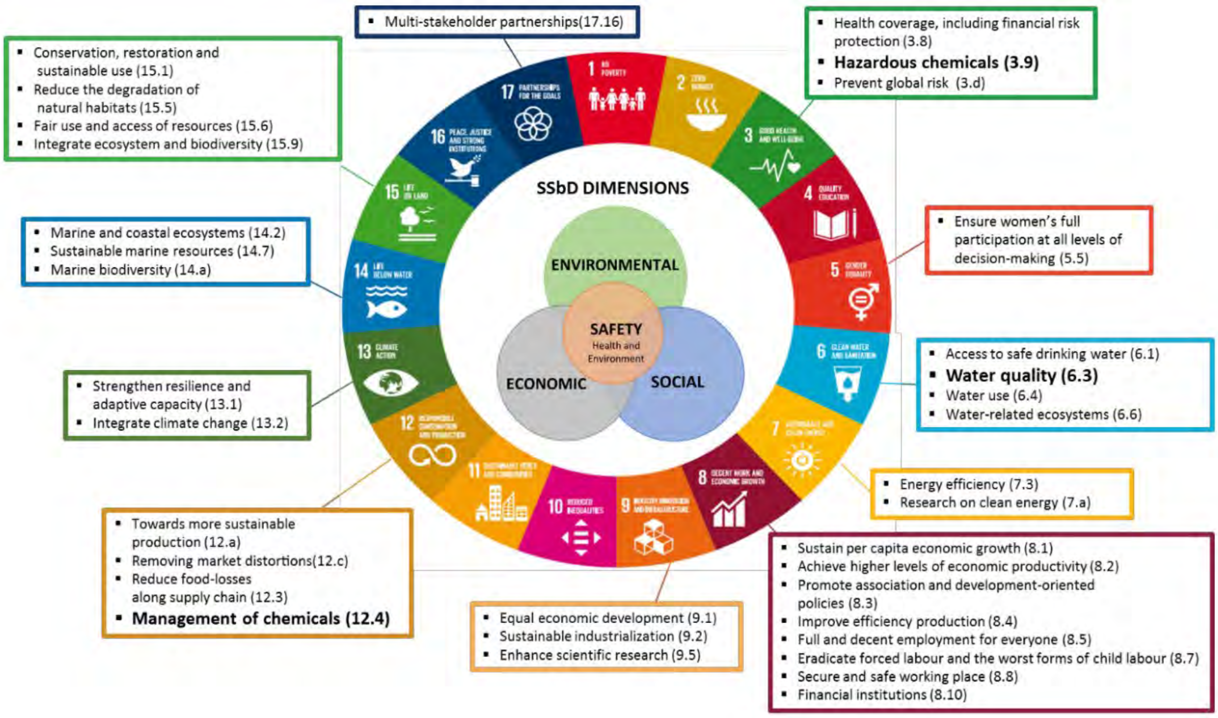


*Figure 3 - Sustainability dimensions considered in the review performed by the JRC in 2022 (Figure taken from [1])*

The **safety** concept is transversal to all sustainability dimensions (environmental, social, and economic) and it is related to the **absence of unacceptable risk** (in line with REACH art 68 (EU, 2006)) **for both humans and the environment,** ideally ensured by the **absence of intrinsic hazard properties of chemicals.**

The CSS action foresees the development of a framework to define SSbD criteria for chemicals and materials. The EC Joint Research Centre (JRC) has proposed a first framework [9]. There are different approaches and frameworks that define SSbD criteria for chemicals and materials and give their view on how to operationalize the SSbD concept. These approaches will be analysed in chapter 3.

## 2.3 Objectives and Methodology

This preliminary report PR1.2 includes the results from the activities conducted in task 1.2 "Sustainable-by- Design" of the Work Package (WP) 1 of the IRISS project. WP 1 aims to obtain a complete overview of SSbD methods and criteria. Previous EU projects, along with other research and activities in the domains of safe by design (SbD) and SSbD, including life cycle assessment (LCA)

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methodologies, serve as vital inputs. These elements form the basis for the implementation and application of SSbD within the framework proposed by the JRC report (Caldeira et al., 2022) [9]. The recommended methodology and SSbD criteria will be mapped against to state-of-the-art approaches for product and process development across different project value chains (VCs) at all stages of product development and innovation processes.

Considering the main elements of a framework, information sources and the perspective of the mapping, the whole work has been structured as follows:

**1.- Information source.** WP1 considers three main information sources for the global mapping:

- Scientific literature
- Surveys
- EU or national projects

**2.- Elements for the definition of SSbD criteria.** They are depicted in Figure 4 and can be mapped under different scopes:

- **Framework** is the alignment of different assessment methodologies for a specific purpose: Directives, ecolabels, initiatives, etc.
- **Methodologies** and related standards to assess the different dimensions of safety and sustainability: Risk Assessment, LCA, LCC, etc.
- **Indicators:** magnitudes for impact assessment. Ecotoxicity, children labour, etc.
- **Methods**: measurement methods, models, software tools and databases to get the numerical value of the different indicators.

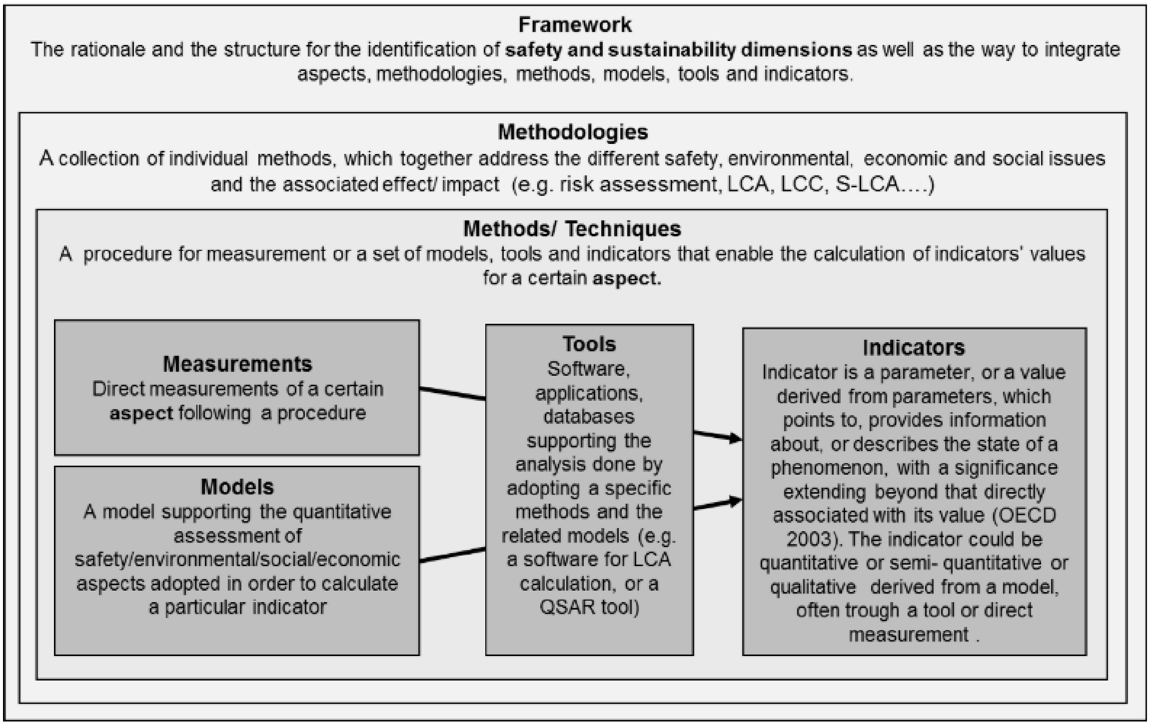


*Figure 4 - Conceptual representation of the elements to be considered in the development of a framework for the definition of criteria for SSbD chemicals and materials. LCA (Life Cycle Assessment), LCC (Life Cycle Costing), S-LCA (Social Life Cycle Assessment). Figure taken from [1]*

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**3.- Mapping perspective.** The different framework elements can be mapped considering three perspectives:

- **Pillars:** safety, environmental, social and techno economic sustainability.
- **Life cycle stage:** considering both technical and biological cycles, the different framework elements can be mapped concerning the life stage where they apply: production, use and recycling/disposal.
- **Values chains:** Automotive, energy materials, electronics, construction, home & personal care, packaging, fragrances, etc.

The mapping work of WP1 is split into four tasks. **Task 1.1** and **Task 1.2** focus on the Safety and Sustainability aspects, subsequently. However, the sustainability dimension is very extensive in two aspects: Life Cycle Analysis and Circular Economy. For this reason, another two specific tasks have been developed:

-**Task 1.3:** focuses on the detailed LCA methodologies, standards, and tools for environmental sustainability.

-**Task 1.4:** focuses on the way that the different frameworks are considering the life stage, strategies for a circular economy and value chains where they apply.

Figure 5 represent WP1 mapping structure, considering the different frameworks, methodologies, indicators and tools.

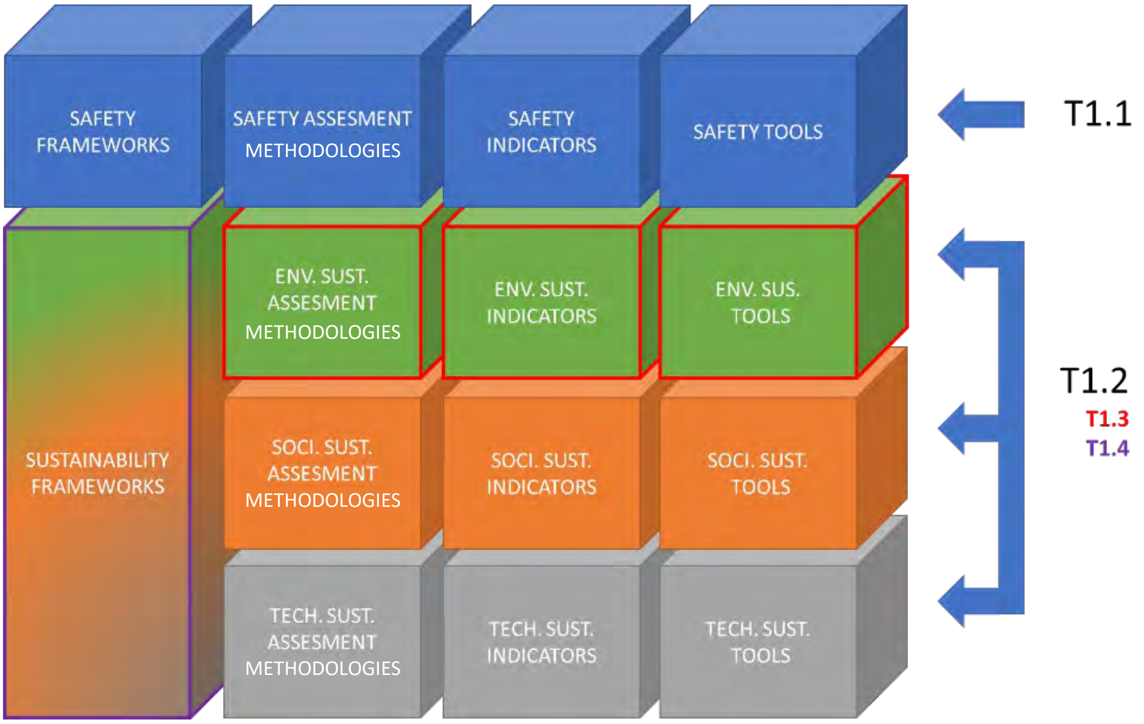


*Figure 5 - WP1 mapping structure considering the mapping of different frameworks, methodologies, indicators and tools. Blue boxes are for the Safety dimension (Task 1.1). Green, orange and grey boxes are for the environmental, social and tecno-economical dimensions, respectively. Task 1.2 considers the whole scope of sustainability. Task 1.3 is focused on the LCA methodology with its own indicators and tools (boxes with red borders). T1.4 is focused on the circularity aspects of the sustainability frameworks (boxes with violet borders).*

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# 3. Mapping of sustainability frameworks, methods, tools, and criteria

## 3.1 Comparison of the most relevant SSbD frameworks

### 3.1.1 Overview of SSbD frameworks

Within WP3, a comparison of published SSbD approaches was conducted regarding a wide range of aspects, including design principles, implementation strategies, safety and sustainability assessment parameters, tools and identified gaps. The comparison has been submitted to an open-access publication by Apel et al., 2023 [10] and it is also available on IRISS SharePoint. This section describes the main outcomes of these identified SSbD approaches in terms of sustainability aspects.

An inventory of the **SSbD approaches** published from a **policy, regulatory and industrial perspective** is illustrated in Table 3. This inventory includes the EC Joint Research Centre (JRC), the European Environment Agency (EEA), the Organization for Economic Co-operation and Development (OECD) Working Party on Manufactured Nanomaterials (WPMN), Safe and Sustainable Innovation Approach (SSIA) Steering Group, the European Chemical Industry Council (Cefic) and the International Chemical Secretariat (ChemSec).

Of the analysed SSbD approaches, the **JRC framework** is the most **comprehensive and detailed** (e.g., in recommended dimensions, parameters and tools), while the **other approaches** are more as **conceptual.**

*Table 3 - Inventory of SSbD approaches*

| Approach | Title | Reference |
|---|---|---|
| ***Policy/Regulatory Perspective*** | | |
| EC Joint Research Centre (JRC) | Safe and Sustainable by Design chemicals and materials - Framework for the definition of criteria and evaluation procedure for chemicals and materials | (JRC, 2022) [9] |
| European Environment Agency (EEA) | Designing safe and sustainable products requires a new approach for chemicals | (EEA, 2021) [11] |
| Organization for Economic Co-operation and Development (OECD) Working Party on Manufactured Nanomaterials (WPMN) Safe Innovations Approach (SIA) Steering Group | Sustainability and Safe and Sustainable by Design: Working Descriptions for the Safer Innovation Approach. | (OECD, 2022) [13] |
| ***Industrial Perspective*** | | |
| European Chemical Industry Council (CEFIC) | Safe and Sustainable-by-Design: Report Boosting innovation and growth within the European chemical industry<br>Safe and Sustainable-by-Design: A Transformative Power | (CEFIC, 2021) [14]<br>(CEFIC, 2022) [15] |
| International Chemical Secretariat (ChemSec) | Safe and Sustainable by Design Chemicals | (ChemSec, 2021) [16] |

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## 3.1.2 Descriptions of SSbD frameworks

**European Commission (EC) Joint Research Centre (JRC)**

Based on the review of safety and sustainability dimensions, aspects, methods, indicators, and tools performed by Caldeira et al. [1], the EC JRC has developed a framework for the definition of **SSbD criteria and evaluation procedures** for chemicals and materials [9]. In this framework, SSbD is defined "*as a pre-market approach to chemicals and materials design that focuses on providing a function (or service), while avoiding volumes and chemical and material properties that may be harmful to human, health, and the environment, in particular groups of chemicals likely to be (eco)toxic, persistent, bio-accumulative, or mobile. Overall sustainability should be ensured by* ***minimizing the environmental footprint of chemicals and materials*** *in relation to climate change, resource use, and protecting ecosystems and biodiversity, adopting a lifecycle perspective*".

The framework recommends a two-phase approach (Figure 6):

- A **(re)-design phase** that proposes guiding design principles to support the integration of safety and sustainability aspects into the product design. While the design principles are interrelated, three of them are primarily concerned with human and environmental safety, while the other five principles focus on sustainability aspects.
- A **safety and sustainability assessment** phase that addresses chemical safety, direct toxicological/ecotoxicological impacts, and aspects of environmental, social, and economic sustainability in a stepwise hierarchical approach.

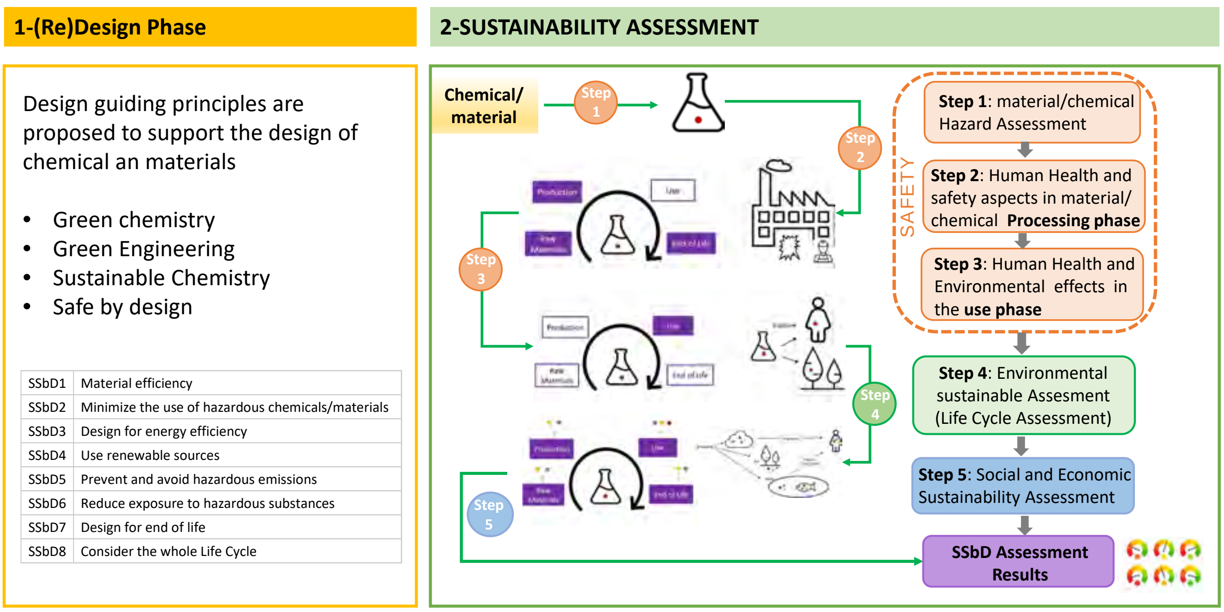


*Figure 6 - SSbD assessment workflow proposed in the framework developed by JRC (Figure taken from [9])*

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**European Environment Agency (EEA)**

The European Environment Agency (EEA) published a briefing on SSbD products that focused on the design stage of a product. The EEA defines SSbD as ***"a pre-market design approach** whereby the objectives of minimizing the use of hazardous chemicals, reducing greenhouse gas emissions, and fostering the reuse and recycling of materials in a circular economy are built into product design*" [11].

The proposed approach focuses on products and consists of four steps (Table 4). In the first step, a **multidisciplinary design team** focuses on the **function that a product delivers** (rather than the form) to allow for a wide range of possible candidates. Sustainability goals should be built into the product design right from the start. In the second step, the **potential impacts** of the different candidates **throughout the life cycle** should be mapped. The recommended **safety and sustainability dimensions** are *chemical safety, resource use and circularity, greenhouse gas emissions and impacts on ecosystems*. In the third step, the performance of the candidates along the different environmental dimensions is assessed, e.g., using the **Product Environmental Footprint** methodology developed by the JRC. In the fourth step, the most sustainable candidate is chosen based on its **scoring performance**. To provide a basis for consistent approaches across the industrial sectors, the EEA calls for **harmonized methodologies** and **minimum performance requirements** against safety and sustainability goals.

**OECD WPMN SSIA Steering Group**

In 2020, the **OECD Working Party** on **Manufactured Nanomaterials** (WPMN) published a report on the Safe Innovation Approach (SIA) which combines the concept of **Safe(r)-by-Design (SbD)** with Regulatory Preparedness (OECD, 2020). Due to the need to include more sustainability aspects to comply with the planetary boundaries, the WPMN agreed to move **from SbD and SIA towards SSbD** and the Safe and Sustainable Innovation Approach (SSIA). Therefore, the WPMN published working descriptions on Sustainability and Safe and Sustainable by Design in 2022 (OECD, 2022) [13]. This working description was developed in **co-creation by the 22 delegations including 17 countries that are part of the OECD WPMN SSIA** Steering Group.

In the working description, SSbD is described "*as an approach that* **focuses on providing a function** *(or service), while* ***avoiding*** *onerous* ***environmental footprints*** *and chemical properties that may be harmful to human health or the environment*" (OECD, 2022) [13]. The basic aim is to identify and minimize the safety and sustainability issues early in the innovation phase while keeping in mind the entire life cycle. The working description specifies three pillars of design for SSbD in nanotechnology with respective safety and sustainability aspects that need to be addressed (Figure 7). The three pillars are:

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I) Safe and Sustainable material/chemical/product
II) Safe and Sustainable production
III) Safe and Sustainable use and end-of-life.

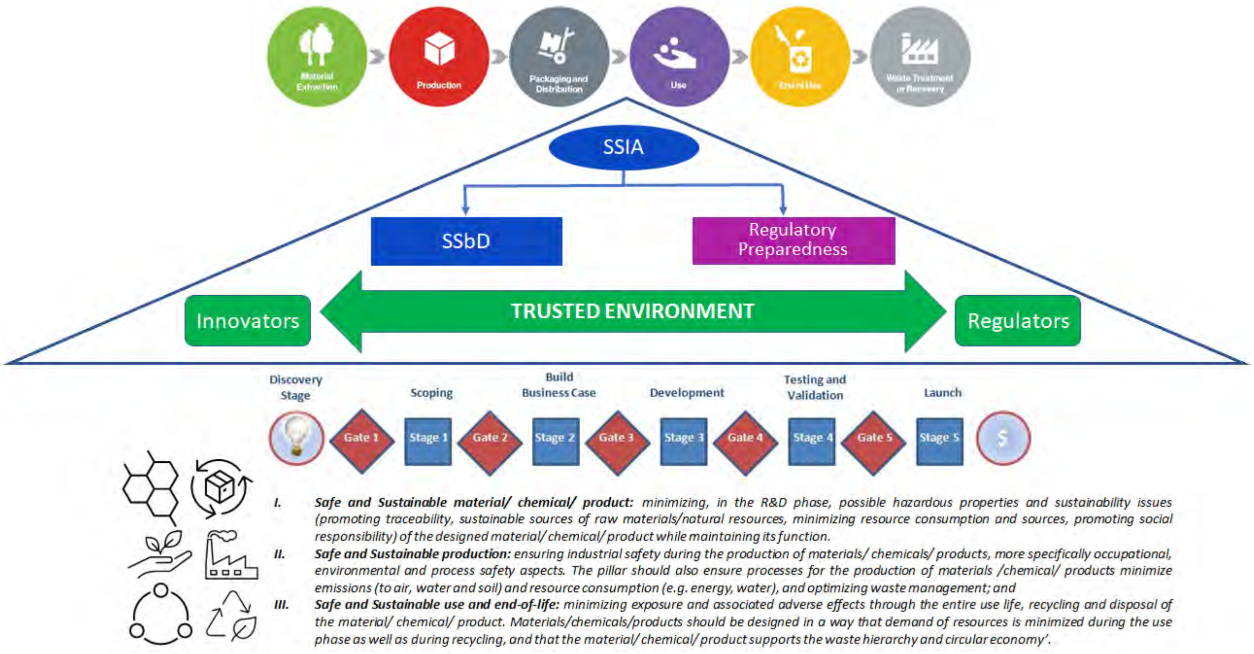


*Figure 7 - SSbD pillars identified by the OECD WPMN SSIA SG (Figure taken from [10])*

**Regulatory preparedness** refers to the capacity of regulators, including policymakers, to anticipate the regulatory challenges, particularly human and environmental safety, and sustainability challenges. This requires that regulators become aware of and understand innovations early enough to take appropriate action, and that appropriate regulatory tools are modified or developed as needed. Regulatory Preparedness helps to ensure that innovative materials and products undergo suitable (and if appropriate, adapted) safety and sustainability assessment before entering the market. Regulatory Preparedness requires dialogue and knowledge-sharing among regulators and between regulators and innovators, industry, and other stakeholders. This communication and interaction help regulators to anticipate the need for new or modified regulatory tools and **reduce the uncertainties for innovators and industry associated** with the future development of the safety and sustainability legislation and regulations applicable to emerging technologies [17].

**CEFIC**

In 2021 and 2022, Cefic published two reports on how **SSbD is defined by the chemical industry** and how to bring SSbD from a mere concept into practice ([14],[15]). Combining the definitions given in the reports, SSbD is "*an iterative process guiding innovation and the placement on the market of chemicals, materials, products, processes, and services that are safe, and deliver environmental, societal, and/or economical value through their applications. Those chemicals, materials, products, and technologies enable accelerating the transition towards a circular economy and climate-neutral society and preventing harm to human health and the environment throughout the life cycle. In scope are new chemicals, materials, products, processes, and services, as well as re-designing existing ones*". **The scope** explicitly covers both **new and existing chemicals, materials, products, processes, and services.**

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Cefic proposed a stage-gate process to implement SSbD into the innovation process based on **guiding design principles and assessment criteria on a product-application level**. The safety and sustainability assessment dimensions are divided into focus dimensions, **minimum requirements**, and additional dimensions; the latter can be included in the assessment or not **depending on the intended use and related exposure.** Every focus dimension is linked to a design principle. Cefic also highlights the requirement for a clear guidance on how to deal with trade-offs and **identify several further research and innovation needs,** e.g., **SSbD toolbox development**.

**ChemSec**

In 2021, ChemSec published a position paper on safe and sustainable by design chemicals (ChemSec, 2021) [16]. Their view on SSbD is heavily focused on the **phase-out of hazardous chemicals** as hazardous chemicals can never be safe and sustainable as they have negative impacts on human health and the environment and disrupt a circular economy. ChemSec proposes to implement SSbD criteria in a stepwise approach following a clear timeframe. This opens the possibility to include the most important criteria right away and gives the industry time to prepare and gather data for future criteria. They propose to include criteria as follows:

Year 1: **Hazardous properties** of chemicals and $CO_2$ emission,

Year 4: **Water use and waste in production** and

Year 7: **Impacts on ecosystems** and **basic social dimensions.**

### 3.1.3 Assessment dimensions

Safety and environmental sustainability dimensions are covered in all regarded SSbD approaches, while **all three sustainability pillars** (environmental, social, economic) are only **covered by JRC, OECD and Cefic.** It must be noted that **the number of proposed dimensions differs between** approaches since some do not recommend specific parameters and/or indicators for the assessment of the dimensions as **they only conceptional.**

Cefic divides the recommended safety and sustainability dimensions into two minimum requirements (that need to be fulfilled), seven focus dimensions (that are needed to fulfil the Green Deal Goals) and additional dimensions. The latter are chosen based on the intended product-application-combination. **Cefic further includes corporate requirements and stakeholder expectations as additional dimensions.**

Concerning the environmental assessment, most SSbD approaches **recommend using the Product Environmental Footprint (PEF) methodology** that assesses all aspects considered in the EU CSS [18], which are *ecosystem & biodiversity, pollution, resources, climate change* and *toxicity.* The PEF is only seen as a temporary solution until a SSbD specific guideline is available [9]. As *biodiversity loss* is only indirectly assessed in the PEF, the JRC framework suggests adding it as a further parameter as well as ***ecotoxicology for terrestrial, marine, soil, and sediment organisms*** to consider beyond freshwater organisms in the assessment.

The **social and economic aspects** show a **low level of implementation and methodological maturity** [9]. Social aspects are only included in the SSbD approaches by JRC, Cefic and OECD. While all three also cover the economic dimension, **Cefic is the only one to propose economic parameters** for the

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assessment. Due to this low maturity level, the **JRC sees the social and economic assessment step in an exploratory phase.**

Table 4 shows the comparison of different SSbD approaches from a policy/regulatory perspective (EC Joint Research Centre, JRC; European Environmental Agency, EEA; Organization for Economic Co-operation and Development (OECD) Working Party on Manufactured Nanomaterials (WPMN) Safe Innovations Approach (SIA) Steering Group) and from an industrial perspective (European Chemical Industry Council, Cefic; International Chemical Secretariat, ChemSec).

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*Table 4 - Sustainability aspects covered in the different SSbD approaches from a policy/regulatory perspective (EC Joint Research Centre, JRC; European Environmental Agency, EEA; Organisation for Economic Co-operation and Development (OECD) Working Party on Manufactured Nanomaterials (WPMN) Safe Innovations Approach (SIA) Steering Group) and from an industrial perspective (European Chemical Industry Council, Cefic; International Chemical Secretariat, ChemSec). Table based on [10]*

| | Policy/Regulatory Perspective | | | Industry Perspective | |
|---|---|---|---|---|---|
| **Aspects and Parameters** | **JRC** | **EEA** | **OECD WPMN SSIA** | **Cefic** | **ChemSec** |
| **Scope** | Chemicals/materials and associated processes | Products | Nanomaterials and advanced materials; material/ chemical/ product/service and associated processes | Chemicals, materials, products, processes, and services (and technologies[1]) | Chemicals (materials and products) |
| | Pre-market and on the market | Pre-market | Pre-market | Pre-market and on the market | (Not specified) |
| **Framework structure** | Stepwise approach<br>1. (Re-)Design phase<br>2. Safety and Sustainability Assessment phase | Stepwise approach in an iterative process<br>1. Identifying options for product delivery<br>2. Mapping the potential impacts of product options throughout the life cycle<br>3. Assess sustainability performance throughout the lifecycle | (Not specified) | Stepwise approach in an iterative process<br>1. Performance and functionality need<br>2. Assessment Dimensions<br>3. Design Principles<br>4. Comparative Assessment<br>5. Trade-offs | (Not specified) |

[1] only first report

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| | Policy/Regulatory Perspective | | | Industry Perspective | |
|---|---|---|---|---|---|
| **Aspects and Parameters** | **JRC** | **EEA** | **OECD WPMN SSIA** | **Cefic** | **ChemSec** |
| | | 4. Selecting the most sustainable product option: scoring and minimum performance criteria product's life cycle | | | |
| **Assessment dimensions** | Safety aspects, environmental, social, and economic aspects<br><br>Hierarchical approach:<br>1. Safety aspects<br>2. Environmental,<br>3. Social,<br>4. Economic aspects | Safety and environmental aspects | Safety aspects, environmental, social and economic aspects | Safety aspects, environmental, social, and economic aspects Additionally, two other dimensions<br>• Corporate requirements<br>• Stakeholder expectations | Safety aspects, environmental and social aspects |
| **Tools Mentioned** | **Safety dimensions**<br>• CLP Regulation<br>• REACH<br>• New approach methodologies (NAMs)<br>• ECHA Guidance, substance substitution tools and Information on Chemicals<br>• OECD Guidance and Substitution and Alternatives Assessment Toolbox | **Safety dimensions**<br>• OECD guidance and guidelines<br><br>**Environmental dimensions**<br>• PEF | **Safety dimensions**<br>• OECD guidelines and its hazard/risk assessment tools<br>• SIA<br><br>**Environmental dimensions**<br>• LCA | **Safety dimensions**<br>• REACH<br>• CLP<br><br>**Environmental dimensions**<br>• LCA using ISO standards and Greenhouse Gas (GHG) Protocol | **Environmental dimensions**<br>• LCA's using ISO 14067 for Carbon Footprint<br>• GHG Protocol<br>• PEF |

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| | Policy/Regulatory Perspective | | | Industry Perspective | |
|---|---|---|---|---|---|
| **Aspects and Parameters** | **JRC** | **EEA** | **OECD WPMN SSIA** | **Cefic** | **ChemSec** |
| | • SCIP Database<br>• SIA toolbox<br>• SubSelect<br>• GHS Column Model<br>**Environmental dimensions**<br>• Environmental pressure measurement<br>• Life Cycle Assessment (LCA) with Product Environmental Footprint (PEF) Methods (climate change, ecotoxicity and human toxicity, resource use, etc.)<br>• US EPA's GREENSCOPE<br>**Social dimensions**<br>• Social LCA<br>• Social Impact Assessment<br>• Social and Human Capital Protocol<br>• Social Footprint<br>**Economic dimensions**<br>• Production cost<br>• Profitability<br>• Life Cycle Costing (LCC) | | **Social and Economic dimensions**<br>• Socio-Economic Analysis (SEA) | **Social dimensions**<br>• WBCSD Chemical Industry Methodology for Portfolio Sustainability Assessments (PSA) | |

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| | Policy/Regulatory Perspective | | | Industry Perspective | |
|---|---|---|---|---|---|
| **Aspects and Parameters** | **JRC** | **EEA** | **OECD WPMN SSIA** | **Cefic** | **ChemSec** |
| **Environmental dimensions** | *Estimation of impacts posed by chemicals in all areas of concern including:*<br>• human morbidity and mortality from chemical exposure;<br>• biodiversity losses from chemical exposure;<br>• other environmental impacts associated with the life cycle of chemicals e.g., climate change, ozone layer depletion, eutrophication, acidification, resource depletion, water consumption.<br><br>**16 Environmental Footprint (EF) impact categories:**<br>• Toxicity<br>o Human toxicity, cancer effects<br>o Human toxicity, non-cancer effect<br>o Ecotoxicity freshwater<br>• Climate change<br>o Climate change<br>• Pollution | *Mapping impacts throughout the life cycle*<br>• Resource use and circularity<br>o Resources consumed<br>o Potential for end-of-life recovery for reuse and/or recycling<br>• Greenhouse gas emissions<br>o Energy consumption<br>o Potential greenhouse gas emissions<br>o Fuels used in production processes and waste management/ recycling processes<br>• Impacts on ecosystems | *Derived from the design principles:*<br><br>*Material/chemical/ product*<br>• Traceability<br>• Sustainable sources of raw materials/natural resources<br>• Resource consumption and sources<br><br>*Production processes*<br>• Emissions (to air, water, and soil)<br>• Resource consumption (e.g., energy, water)<br>• Waste management | • Climate change mitigation<br>• Energy consumption (min. ecological footprint)<br>• Resource use of Renewable and Circular feedstock<br>• Biodiversity and ecosystems impacts<br>• Reduction of emissions into air, water, soil<br>• Sustainable use and protection of water | • $CO_2$ emissions<br>• Water use<br>• Waste in production<br>• Impact on ecosystems and biodiversity |

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| | Policy/Regulatory Perspective | | | Industry Perspective | |
|---|---|---|---|---|---|
| **Aspects and Parameters** | **JRC** | **EEA** | **OECD WPMN SSIA** | **Cefic** | **ChemSec** |
| | o Ozone depletion<br>o Particulate matter/Respiratory inorganics<br>o Ionising radiation, human health<br>o Photochemical ozone formation<br>o Acidification<br>o Eutrophication, terrestrial<br>o Eutrophication, aquatic freshwater and marine<br>• Resources<br>o Land use<br>o Water use<br>o Resource use, minerals, and metals<br>o Resource use, energy carriers<br><br>Suggested Additions:<br>• biodiversity loss<br>• Ecotoxicology for terrestrial, marine, soil, and sediment organisms (not only for freshwater organisms) | o Damage during resource extraction<br>o Emissions of pollution<br><br>Reference to the *Product Environmental Footprint method* to assess:<br>• Resource use<br>• Impact on climate and ecosystems<br>• Impacts on health from air pollution | *<u>Use and end-of-life</u>*<br>• Resources during the use phase and recycling<br>• Waste hierarchy<br>• Circular economy | | |

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| | Policy/Regulatory Perspective | | | Industry Perspective | |
|---|---|---|---|---|---|
| **Aspects and Parameters** | **JRC** | **EEA** | **OECD WPMN SSIA** | **Cefic** | **ChemSec** |
| **Social dimensions** | **Workers**<br>• Child labour<br>• Fair salary<br>• Forced labour<br>• Health and Safety<br>• Freedom of association and collective bargaining<br>• Working hours<br>• Equal opportunities/ discrimination<br><br>**Local community**<br>• Community engagement<br>• Local employment<br><br>**Consumers**<br>• Health and safety<br>• Responsible communication | (not included) | Promoting social responsibility<br>• social welfare[3]<br>• human health safety[3]<br>• respect for human rights, including equality and education[3] | **Society**<br>• Health & Safety<br>• Hunger (no completion to the food chain) & Poverty<br>• Human rights/child labour/forced labour<br>• Affordability & Competitiveness<br>• Working conditions remuneration, gender equality, fair salary...)<br>• Public Health | Basic social dimensions (not further specified) |
| **Economical dimensions** | Reference to different *Life Cycle Costing (LCC)* approaches, e.g.<br>• conventional LCC (cLCC)<br>• environmental LCC (eLCC)<br>• societal LCC (sLCC) | (not included) | Ensuring economic growth and innovation within | • Profitability<br>• Production cost<br>• Life cycle cost<br>• Resilience<br>• Economic and technical sovereignty | (not included) |

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| | Policy/Regulatory Perspective | | | Industry Perspective | |
|---|---|---|---|---|---|
| **Aspects and Parameters** | **JRC** | **EEA** | **OECD WPMN SSIA** | **Cefic** | **ChemSec** |
| | • circular economy-related approaches | | the planetary boundaries[2] | • Creation of Jobs | |

[2] Working description of Sustainability

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## 3.2 Literature review – Methodology and first mapping screening

As mentioned in the introduction (section 2.1) in 2022, Caldeira et al. [1] performed a review of safety and sustainability dimensions, aspects, methods, indicators, and tools. A total of **119** "**frameworks**" (approaches proposing how to consider different dimensions of sustainability when comparing alternative chemicals, products, or services) were considered. Out of these, 57 were proposed by academia, 15 were certification schemes, 13 were proposed by industry, 11 were EU legislation (or proposals), and 10 were proposed by governmental agencies (Table 5).

*Table 5 - Overview of the area of application of the SSbD documents reviewed by Caldeira et al. [1], and the types of organization proposing them (Table taken from [1])*

| Area of application | Academia | Industry | NGOs | EU legislation (or proposal) | Governmental agencies (-related) | Certification organisations | International organisations | Total |
|---|---|---|---|---|---|---|---|---|
| **Chemicals** | | | | | | | | **71** |
| Generic | 23 | 3 | 4 | 3 | 8 | 2 | 4 | 47 |
| Solvents | 17 | 7 | - | - | - | - | - | 24 |
| Fluorinated GHG (F-gases) | - | - | - | 1 | - | - | - | 1 |
| **Products** | | | | | | | | **26** |
| Generic | 3 | 3 | - | 1 | 2 | 5 | - | 14 |
| Energy products | 1 | - | - | 3 | - | - | - | 4 |
| Financial products | - | - | - | 1 | - | - | - | 1 |
| Construction products | - | - | - | | - | 1 | - | 1 |
| Electronics | - | - | 1 | 1 | - | 1 | 1 | 4 |
| Bio-based products | 1 | | - | | - | - | - | 1 |
| Cosmetics | - | - | - | - | - | 1 | - | 1 |
| **Materials** | | | | | | | | **14** |
| Generic | 4 | - | - | - | - | - | - | 4 |
| Nanomaterials | 2 | - | - | - | 1 | - | 1 | 4 |
| Plastics | - | - | - | - | - | 1 | 1 | 2 |
| Textiles | - | - | - | - | - | 4 | | 4 |
| **Services** | | | | | | | | **6** |
| Suppliers' selection | 1 | - | - | 1 | - | - | - | 2 |
| Waste management | 2 | - | - | - | - | - | - | 2 |
| Transport systems | 1 | - | - | - | - | - | - | 1 |
| Soil remediation | 2 | - | - | - | - | - | - | 2 |
| **Total** | **57** | **13** | **5** | **11** | **11** | **15** | **7** | **119** |

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These 119 frameworks were deeply analysed providing information on the sustainability dimensions and aspects covered by the framework and the area of application (Table 6).

***Table 6 - Combination of dimensions considered by the frameworks and respective number and application area (shaded cell means that the dimension was covered). Table taken from [1]***

| Number of frameworks | Safety | Environmental | Social | Economic | Area of Application |
|---|---|---|---|---|---|
| 9 | | | | | Products, chemicals |
| 14 | | | | | Chemicals, electronics, textiles, cosmetics |
| 34 | | | | | Products, chemicals, energy, plastics |
| 1 | | | | | Products |
| 3 | | | | | Energy, chemicals, transport systems |
| 4 | | | | | Products, chemicals, textiles |
| 11 | | | | | Products, chemicals |
| 30 | | | | | Products, chemicals, energy, plastics |
| 2 | | | | | Nanomaterials, chemicals |
| 11 | | | | | Chemicals, nanomaterials, electronics |

Only **9 frameworks considered aspects for all four dimensions**, while most frameworks considered various combinations of dimensions, with safety (101 out of 119) and environmental (105 out of 119) dimensions being the most frequently included ones. The social dimension was considered by 31 frameworks and the economic dimension by 60. Especially for these two dimensions, indicators proposed were mostly conceptual, listing elements to be included without reporting the operational methods or approaches to address them qualitatively or quantitatively. 34 frameworks considered safety, environmental and economic dimensions.

The main results of the review were the following:

- A few existing frameworks encompass **the four dimensions of sustainability (safety, environmental, economic, and social).**
- **Many frameworks are purely conceptual,** listing elements to be included but without reporting the operational methods or approaches to address qualitatively or quantitatively the issues at stake.
- In most of the frameworks, **safety considerations refer to legislative requirements**.
- **Life cycle considerations** are often mentioned and integrated into the frameworks, with **different levels of detail** in terms of **models and indicators to be adopted.**
- Indicators regarding the **social dimension were the least considered** in the reviewed literature but recent guidelines could be used for addressing this dimension in the future.


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- Some frameworks provide tables **ranking chemicals** based on **threshold criteria for selected aspects.**

- Finally, some frameworks are **complemented by operational tools** that allow ranking chemicals, materials or products **based on specific criteria.**

In this report, an updated review of the relevant publications on sustainability methods, tools, and criteria, is provided, based on the previous work by Caldeira et al. [1]. They performed a compilation and review of the most relevant publications related to safety and sustainability dimensions, methods, tools, and criteria. Their literature review was performed via Scopus on the 7th of October 2021 focusing on chemicals. Besides, as the previous study was focused on chemicals, **additional search terms have been included such as materials, biomaterials, or biobased materials.** The search string used by Caldeira et al. was defined as follows in Table 7.

***Table 7 - Search terms used by Caldeira et al. [1] in Scopus.***

| |
|---|
| TITLE-ABS-KEY ( ( "alternatives assessment" OR "chemicals alternative assessments" OR "alternatives analysis" OR "substitution assessment" OR "chemicals assessment" OR "solvent selection" OR "solvents selection" OR "solvent design" OR "safe and sustainable" OR "social LCA" OR "life cycle costing" OR "life cycle cost" ) AND ( "chemical" OR "chemicals" OR "solvent" OR "solvents" ) AND ( "framework" OR "frameworks" OR "guide" OR "guides" OR "methodology" OR "methodologies" OR "tool" OR "tools" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) |
| *Search performed on the **7th of October 2021.** The search was conceptualized with the purpose of missing the minimum number of studies possible. As a result, **a corpus of initial 713 documents were retrieved**. The inclusion/exclusion of the documents was based on their titles and abstracts. When this was not sufficient, the main text was also scrutinized.* |

As mentioned, from the total of 119 “frameworks” considered, 57 were from academia. The 713 documents they obtained via the Scopus search were screened regarding the other sustainability dimensions than safety. They selected only documents presenting decision frameworks focusing on integrating at least two sustainability dimensions (being the four dimensions: safety, environment, society, and economy). Documents discussing or applying frameworks focusing on only one dimension were excluded, except for a few documents presenting frameworks for analyzing the safety dimension.

**The present study updates** the literature search on **Scopus on the 9th of February 2023,** covering additional aspects to those considered by Caldeira et al. Thus, their focus was on chemicals and solvents, and the current mapping has included terms related to other kind of materials (e.g., biomaterials, biobased). The search string was also characterised by further terms concerning frameworks (e.g., software, indicator), sustainability topics (LCSA) or sectors and applications (e.g., packaging, food).

First, a bibliometric analysis was performed to have an overview on the attention paid to the sustainability methods, tools, and criteria since 1998. Using the search string in Table 8, the evolution in the number of publications is shown in the chart in Figure 8. The first results were obtained in 1998 so it was selected as the first year for the analysis.

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*Table 8 - SCOPUS search string proposed for the IRISS sustainability mapping process, without considering the three sustainability dimensions.*

| |
|---|
| ( TITLE-ABS-KEY ( "alternatives assessment" OR "chemicals alternative assessments" OR "alternatives analysis" OR "substitution assessment" OR "chemicals assessment" OR "solvent selection" OR "solvents selection" OR "solvent design" OR "safe and sustainable" OR "social LCA" OR "life cycle costing" OR "life cycle cost" ) AND TITLE-ABS-KEY ( "durability" OR "extend* lifespan" OR "extend* life span" OR "recycl*" OR "circular*" OR "safe and sustainable by design" OR "SSbD" OR "sustainab*" OR "LCSA" OR "Life Cycle Sustainability Assessment" OR "sustainability assessment*" ) AND TITLE-ABS-KEY ( "chemical*" OR "solvent*" OR "material*" OR "biomaterial*" OR "biobased*" OR "bio-based*" ) OR "packag*" OR "electronic*" OR "metal*" OR "building*" OR "construction" OR "plastic*" OR "fibre*" OR "automotive" OR "transport" OR "vehicle*" OR "batterie*" OR "food" OR "agricultur*" OR "agro*" OR "energy" ) AND TITLE-ABS-KEY ( "framework*" OR "guide*" OR "methodolog*" OR "tool*" OR "measurement*" OR "model*" OR "indicator*" OR "software" OR "app*" OR "method*" OR "technique*" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) |

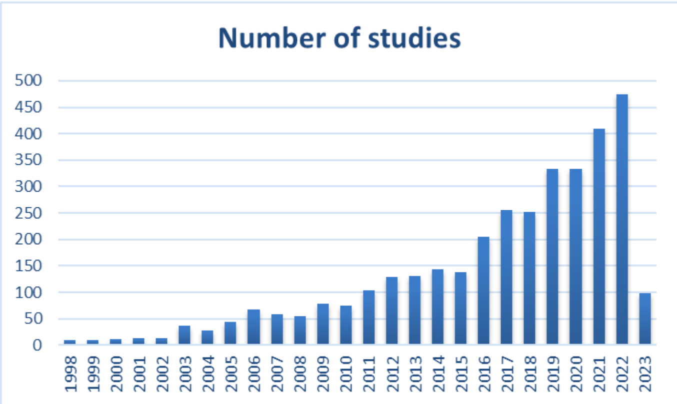


*Figure 8 - Number of studies published within the last 26 years considering the search terms in Table 8.*

This first search resulted in **more than 500 results for 2022 and 2023** (after the publication by Caldeira et al.). Then, additional terms were introduced in the string to have a more specific view of the number of publications on each sustainability dimension. The economic, environmental, and social dimensions were considered separately. Their corresponding search strings are provided in Annex I.

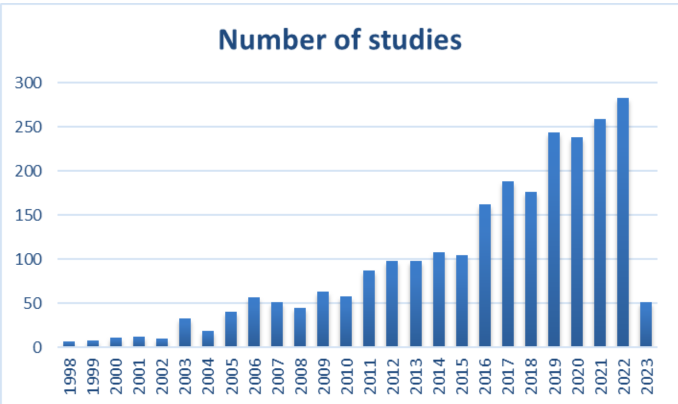


*Figure 9 - Number of studies published within the last 26 years considering only the economic dimension (search string in Annex I, Table 40) Publications for 2023 only considered until 9th of February.*

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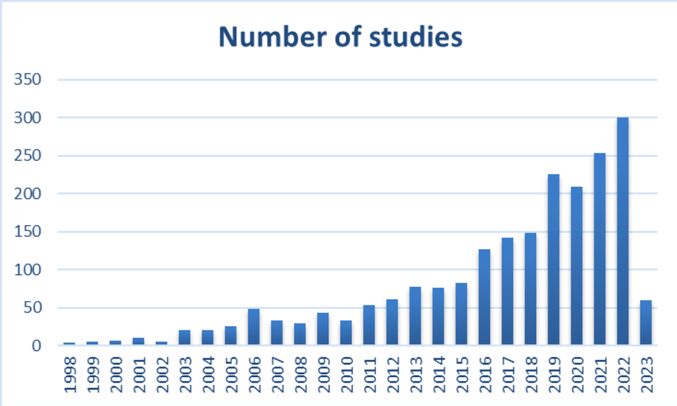


*Figure 10 - Number of studies published within the last 26 years considering only the environmental dimension (search string in Annex I, Table 41)*

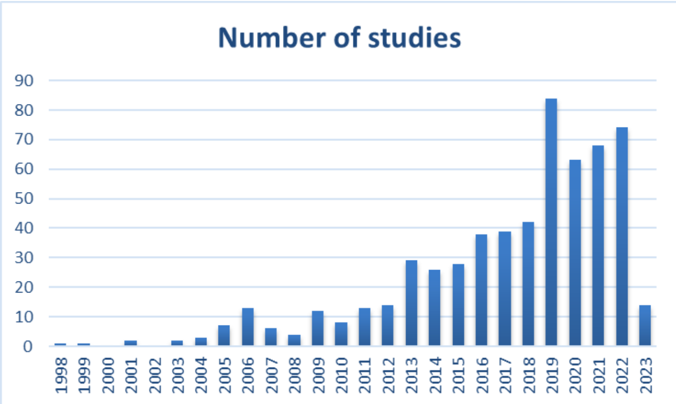


*Figure 11 - Number of studies published within the last 26 years considering only the social dimension (search string in Annex I, Table 42)*

By introducing more specific search terms for each sustainability dimension, the total number of results analysed was even greater than that obtained from the first search. Therefore, an additional search was performed including all three dimensions.

The figures above enabled however to have some conclusions on the evolution of the number of publications:

- Historically, the economic dimension has attracted most of the attention but in the last two years, **more studies** concerning the **environmental dimension are observed.**
- The most significant increase in the number of studies published is observed from 2018 to 2019, considering the three dimensions separately. Amongst them, **the largest increase is in the social dimension.** However, the number of studies in this dimension **is still quite small,** around the fourth part of both environmental and economic ones.
- Considering the different figures of studies published in 2023, we envisage that they remain growing and follow a trend similar to that observed since 2020.

The figures obtained from each search are provided in Table 9. The number of studies obtained in 2022 and 2023 are marked in blue colour as they are not included in the previous study from Caldeira et al.


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*Table 9 - Number of studies published within the last 26 years for the search strings considered.*

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SEARCH #1: SSbD** | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
| | 9 | 10 | 11 | 14 | 13 | 36 | 28 | 44 | 67 | 59 | 55 | 79 | 75 |
| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 [3] |
| | 103 | 128 | 131 | 143 | 138 | 205 | 255 | 252 | 334 | 334 | 409 | **474** | **98** |
| **SEARCH #2: SSbD + ECONOMIC DIMENSION** | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
| | 7 | 8 | 11 | 12 | 10 | 33 | 19 | 40 | 57 | 51 | 45 | 63 | 58 |
| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| | 87 | 98 | 98 | 108 | 105 | 162 | 188 | 176 | 244 | 238 | 259 | **283** | **51** |
| **SEARCH #3: SSbD + ENVIRONMENTAL DIMENSION** | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
| | 4 | 5 | 7 | 10 | 6 | 21 | 20 | 26 | 48 | 33 | 29 | 43 | 33 |
| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| | 54 | 61 | 77 | 76 | 83 | 127 | 142 | 149 | 226 | 209 | 254 | **300** | **60** |
| **SEARCH #4: SSbD + SOCIAL DIMENSION** | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
| | 1 | 1 | 0 | 2 | 0 | 2 | 3 | 7 | 13 | 6 | 4 | 12 | 8 |
| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| | 13 | 14 | 29 | 26 | 28 | 38 | 39 | 42 | 84 | 63 | 68 | **74** | **14** |

The final search terms included in the literature review for the sustainability mapping (this report), which covered at the same time the three dimensions, are detailed in Table 10 below. The evolution in the number of publications is as shown in the chart in Figure 12, and the figures obtained from each search are provided in Table 11.

*Table 10 - New SCOPUS search string proposed for the IRISS sustainability mapping process.*

( TITLE-ABS-KEY ( "alternatives assessment" OR "chemicals alternative assessments" OR "alternatives analysis" OR "substitution assessment" OR "chemicals assessment" OR "solvent selection" OR "solvents selection" OR "solvent design" OR "safe and sustainable" OR "social LCA" OR "life cycle costing" OR "life cycle cost" ) AND TITLE-ABS-KEY ( "durability" OR "extend* lifespan" OR "extend* life span" OR "recycl*" OR "circular*" OR "safe and sustainable by design" OR "SSbD" OR "sustainab*" OR "LCSA" OR "Life Cycle Sustainability Assessment" OR "sustainability assessment*" ) AND TITLE-ABS-KEY ( "chemical*" OR "solvent*" OR "material*" OR "biomaterial*" OR "biobased*" OR "bio-based*" ) OR "packag*" OR "electronic*" OR "metal*" OR "building*" OR "construction" OR "plastic*" OR "fibre*" OR "automotive" OR "transport" OR "vehicle*" OR "batterie*" OR "food" OR "agricultur*" OR "agro*" OR "energy" ) AND TITLE-ABS-KEY ( "framework*" OR "guide*" OR "methodolog*" OR "tool*" OR "measurement*" OR "model*" OR "indicator*" OR "software" OR "app*" OR "method*" OR "technique*" ) AND TITLE-ABS-KEY ( "LCC" OR "life cycle cost*" ) AND TITLE-ABS-KEY ( "environment*" ) AND TITLE-ABS-KEY ( "social*" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) )

[3] 2023, refers to 9 February 2023

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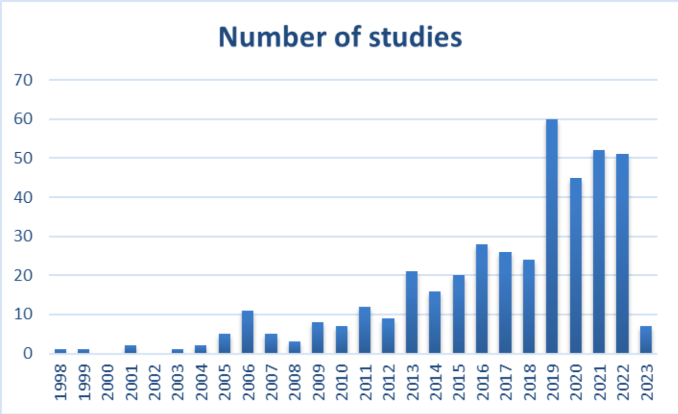


*Figure 12 - Number of studies published within the last 26 years considering the search terms in Table 10.*

*Table 11 - Number of studies published within the last 26 years for the search strings considered.*

| SEARCH #5: SSbD + ECONOMIC, ENVIRONMENTAL & SOCIAL DIMENSIONS | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1 | 0 | 2 | 0 | 1 | 2 | 5 | 11 | 5 | 3 | 8 | 7 |
| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| | 12 | 9 | 21 | 16 | 20 | 28 | 26 | 24 | 60 | 45 | 52 | 51 | 7 |

As a result, a corpus of initial 58 documents were retrieved. As expected, the number of results obtained was significantly reduced in comparison to the large number of documents analysed by Caldeira et al. This was due to the limitation to 2022 and 2023 for our screening, and the addition of more search fields to introduce the terms for each sustainability dimension. They were connected by the operator "AND", which resulted in fewer possible combinations. All the data and literature analysis performed were compiled in Excel sheets, which are provided in Annex I. From the list of 58 references, three of them were not available for downloading to the IRISS consortium members. Thus, they could not be considered for further analysis, but are listed in the search results in Annex I.

To screen the remaining 55 documents, their titles and abstracts were reviewed. It was confirmed that all of them covered a minimum of two sustainability dimensions and many included three dimensions. The full list with the 55 references in this mapping can be found in Section 7-References (subsection "Scopus search").

The analysis of the documents was conducted in terms of:

- **Sustainability dimensions** and areas of application covered
- The **methods, databases and software tools used** for impact assessment
- The **LCA stages and Circular economy aspects** considered
- The **environmental, social, and economic** indicators.

Taking the tables proposed by Caldeira et al. as a basis, a first screening of the Sustainability dimensions linked to the Areas of application covered was conducted. The areas of application were selected to be consistent with those listed in other sections of this report, and also considering the research fields covered by the different studies. The areas proposed are as follows:

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1. Construction
2. Energy (materials, supply systems and batteries)
3. Electronics and ICT
4. Automotive and Transport
5. Food systems
6. Agriculture, Forestry and Fishing
7. Packaging
8. Metals
9. Waste management
10. Community, Social and Personal services
11. Personal care
12. Bio-based products
13. Products (not specified)

In a few studies, it was difficult to assign only one area of application. The criteria, when more than one area was possible to consider, was to select the most specific one. For instance:

- For papers focused on "biobased asphalt" we assigned "Construction" instead of "Bio-based products".
- For "HDPE bottle": "Packaging" instead of "Plastics".
- For "solid waste recycled building insulation materials" we selected "Construction" instead of "Waste management".

The documents obtained via the Scopus search were screened regarding the sustainability dimensions (environmental, social, and economic). However, safety was also considered by two of the studies analysed and it is also shown in Table 12.

*Table 12 - Combination of dimensions considered by the studies and respective number and application area (shaded cell means that the dimension was covered)*

| Number of studies | Safety | Environmental | Social | Economic | Area of Application |
|---|---|---|---|---|---|
| 2 | | | | | Construction, Energy (materials, supply systems and batteries). |
| 36 | | | | | Construction; Energy (materials, supply systems and batteries); Electronics and ICT; Automotive and Transport; Food systems; Agriculture; Packaging; Waste management; Community, Social and Personal services; Bio-based products. |
| 19 | | | | | Construction; Energy (materials, supply systems and batteries); Electronics and ICT; Food systems; Metals; Waste management; Personal care; Products (not specified). |

Compared to the results obtained in the literature review performed by Caldeira et al., we observe herein that the number of studies considering the social dimension has significantly increased in the last two years: from 31 out of 119 frameworks to 38 out of 55 in the current mapping, which is

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consistent with the results in the bibliometric analysis. Our focus was not on safety, however, we obtained 2 studies covering this dimension as well. For the studies considering two dimensions, only the combination covering the environmental and economic aspects was observed.

The number of studies published on each application area and the dimensions they cover are included in the tables 13- 15 below. The studies are identified by their authors.

***Table 13 - Number of studies obtained in the "Construction" application area and sustainability dimensions covered.***

| Study | Safety | Environmental | Social | Economic | Number of studies |
|---|---|---|---|---|---|
| Amini Toosi et al. [19] | | | | | |
| Corona et al. [20] | | | | | |
| Di Ruocco et al. [21] | | | | | |
| Ding Y. [22] | | | | | |
| Ferreira et al. [23] | | | | | |
| Larsen et al. [24] | | | | | |
| Larsen et al. [25] | | | | | |
| Mahmoud et al. [26] | | | | | |
| Mohamed et al. [27] | | | | | |
| Qiao et al. [28] | | | | | |
| Sánchez-Garrido et al. [29] | | | | | 21 |
| Scolaro and Ghisi [30] | | | | | |
| Soust-Verdaguer et al. [31] | | | | | |
| Sutantio et al. [32] | | | | | |
| Sutantio et al. [33] | | | | | |
| Tempa et al. [34] | | | | | |
| Van Cauteren et al. [35] | | | | | |
| Yuliatti et al. [36] | | | | | |
| Zhang et al. [37] | | | | | |
| Zhao and Li [38] | | | | | |
| Zhou et al. [39] | | | | | |

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*Table 14 - Number of studies obtained in the "Energy (materials, supply systems and batteries)" application area and sustainability dimensions covered.*

| Study | Safety | Environmental | Social | Economic | Number of studies |
|---|---|---|---|---|---|
| Barahmand and Eikeland [40] | | | | | |
| Haase et al. [41] | | | | | |
| Li et al. [42] | | | | | |
| Nubi et al. [43] | | | | | |
| Ramos and Rouboa [44] | | | | | |
| Rezazadeh Kalehbasti et al. [45] | | | | | 11 |
| Salim et al. [46] | | | | | |
| Sevindik and Spataru [47] | | | | | |
| Tushar et al. [48] | | | | | |
| Wijayasekera et al. [49] | | | | | |
| Yang et al. [50] | | | | | |

*Table 15 - Number of studies obtained in rest of the application areas and sustainability dimensions covered.*

| Study | Safety | Environmental | Social | Economic | Area of Application | Number of studies |
|---|---|---|---|---|---|---|
| Mele and Campana [51] | | | | | Electronics and ICT | 3 |
| Olsthoorn et al. [52] | | | | | | |
| Roci et al. [53] | | | | | | |
| Caraman et al. [54] | | | | | Automotive and Transport | 3 |
| Sarkar et al. [55] | | | | | | |
| Stefanini and Vignali [56] | | | | | | |
| Degieter et al. [57] | | | | | Food systems | 3 |
| Peña et al. [58] | | | | | | |
| Stefanini and Vignali [59] | | | | | | |
| Maffia et al. [60] | | | | | Agriculture, Forestry and Fishing | 2 |
| Stillitano et al. [61] | | | | | | |
| Papo and Corona [62] | | | | | Packaging | 1 |
| Jayawardane et al. [63] | | | | | Metals | 1 |

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| Study | Safety | Environmental | Social | Economic | Area of Application | Number of studies |
|---|---|---|---|---|---|---|
| Daniela-Abigail et al. [64] | | | | | Waste management | 4 |
| Sauve et al. [65] | | | | | | |
| Xiao et al. [66] | | | | | | |
| Zhang et al. [67] | | | | | | |
| Gulcimen et al. [68] | | | | | Community, Social and Personal services | 2 |
| Kazemi et al. [69] | | | | | | |
| Rizan et al. [70] | | | | | Personal care | 1 |
| Allotey et al. [71] | | | | | Bio-based products | 2 |
| Collotta et al. [72] | | | | | | |
| Singh and Sarkar [73] | | | | | Products (not specified) | 1 |

"Construction" and "Energy (materials, supply systems and batteries)" are the most widely studied areas, with 21 and 11 publications available, respectively.

Concerning the total of 13 areas of application listed above, we have found research articles addressing the three sustainability dimensions in 10 of them. Only the areas of "Metals", "Personal Care", and "Products (not specified)" are represented by studies not considering the social dimension. Therefore, in general, the three sustainability dimensions are considered in different areas and value chains (Figure 13).

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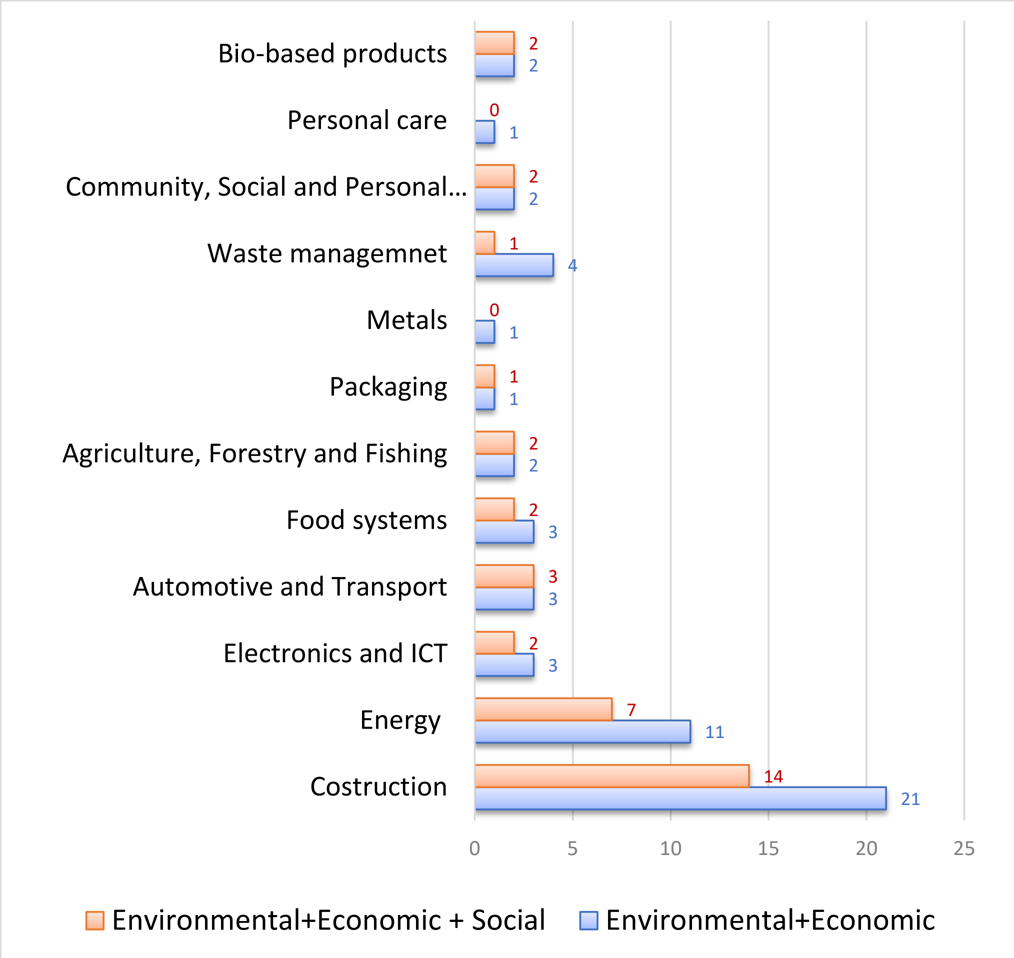


*Figure 13- Number of studies per application area considering environmental and economic dimensions (blue) and all sustainability dimensions (red).*

## 3.3 The Environmental dimension: LCA (Life Cycle Assessment)

The Lifecycle Environmental assessment will be deeply analysed in Task 1.3, therefore, this section just includes the summary of the literature review. For more details go to preliminary report PR*1.3 -Lifecycle analysis mapping.*

**Impact assessment methods, databases, and software**

The elements screened herein were selected to be consistent with those listed in other sections of this report, such as the 'Survey on the mapping of SSbD initiatives'. The number of studies published on each subject is included in Table 16.

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*Table 16 - Number of studies obtained in the analysis of Impact assessment methods, databases, and software.*

| Impact assessment methods | | | | |
|---|---|---|---|---|
| **PEF** | **ReCiPe** | **CML** | **Impact World+** | **USEtox** |
| 4 | 17 | 13 | 1 | 3 |

| Databases | | | | |
|---|---|---|---|---|
| **ECOINVENT** | **EPLCA** | **USLCI** | **LCA Food DK** | **ELCD** |
| 24 | 0 | 1 | 0 | 1 |

| Software | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **SimaPro** | **Gabi** | **OpenLCA** | **Umberto** | **TEAM** | **Activity-browser** | **Brightway 2** | **QSAR models** | **Ecochain** |
| 20 | 10 | 7 | 3 | 0 | 0 | 0 | 0 | 0 |

*PEF: Product Environmental Footprint; EPLCA: European Platform on Life Cycle Assessment datasets; USLCI: U.S. Life Cycle Inventory Database; ELCD: European reference Life Cycle Database.*

*Total number of studies: 55*

Among the reviewed studies, the most **frequent impact assessment methods** are **ReCiPE and CML**. **Ecoinvent** is the database most largely applied in LCA inventory analysis. Within software tools, **SimaPro** is the most frequent with twice the number of results obtained for Gabi. OpenLCA and UMBERTO are also used often to support studies.

The review of databases and software performed by Caldeira et al. listed several ready-to-use online resources, which were focused on the safety aspect of chemicals, materials, or products. Hence, they would not be comparable with the tools reported herein, that aim at mapping sustainable by design methods and criteria. Their literature review covered the impact assessment methods within different aspects analysed for the environmental sustainability dimension. The most cited models for addressing the indicators they considered were Recipe 2016, USEtox and CML (from the most to least popular). This is consistent with the results found herein, which in addition shows also that the **PEF method is gaining attention** as a sustainability metric.

## <u>Environmental indicators</u>

Regarding the analysis of the environmental indicators considered in the literature review performed, the number of results obtained is shown in Table 17 below.

*Table 17 - Number of studies obtained in the analysis of Environmental indicators (Scopus search described in Section 3.2)*

| Environmental indicators | | | | | | |
|---|---|---|---|---|---|---|
| **Ecotoxicity** | **Acidification** | **Eutrophication** | **Climate change** | **Global warming** | **GHG emissions** | **Ozone depletion** |
| 18 | 21 | 24 | **30** | **26** | **27** | 18 |
| **Human toxicity** | **Fossil resources** | **Mineral resources** | **Land resources** | **Water resources** | **Land use** | **Resource use** |
| 22 | 3 | 1 | 2 | 2 | 17 | 8 |

*Total number of studies: 55*

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The most used indicators in the studies analysed herein are **"Climate change", "GHG emissions" and "Global warming",** which are covered in around half of the publications.

Caldeira et al. reported "Global warming potential" as the most cited one among the indicators used within the climate change category, used in 56 frameworks out of the 119 analysed. They defined Global warming as the phenomenon of an increase in average global temperatures (which may be natural but also due to greenhouse gas (GHG) emissions), leading to climate change, with potential impacts on ecosystems and biodiversity, human health, and resource availability.

The **"Climate change"** indicator was found to be the most reported herein (30 publications out of 55). Therefore, more attention is being paid to climate change issues in the last years for products in general.

"Eutrophication", "Human toxicity" and "Acidification", are used often in the frameworks reviewed by Caldeira et al. and remain among the most applied environmental indicators, based on the results obtained in this study.

**LCA stages and Circular economy considerations**

The LCA stages and circular economy considerations were selected in line with those listed in other sections of this report and considering also the most cited in the literature. Table 18 provides the number of results found.

*Table 18 - Number of studies obtained in the analysis of LCA stages and Circular economy considerations.*

| LCA stages | | | | | | |
|---|---|---|---|---|---|---|
| Raw material extraction | Production/ Processing/ Manufacturing Stage/Phase | Use/Consume Stage/Phase | End of life | Disposal | Recycling | Reuse |
| 15 | 16 | 18 | 29 | 39 | 37 | 24 |

| Circular economy considerations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Durability | Reusability | Repairability | Renewable | Recycled content | Lifespan | Recycling | Recovery | Valorization | MCI |
| 14 | 24 | 8 | 29 | 4 | 11 | 37 | 28 | 6 | 3 |

*MCI: Material circularity index*

*Total number of studies: 55*

Concerning LCA stages, **"Disposal" and "Recycling"** are the most frequent phases considered by the studies analysed, followed by **"End of life".** This would be reasonable given the attention that circularity concepts are gaining attention in the last few years, which means that these final stages should be integrated into the life cycle of products.

A specific analysis of the LCA stages mapped herein was not performed in the report by **Caldeira et** al. They reviewed the "Resources, processing- and product-related aspects" by organising them into four sections, addressing (i) Type and quantity of resources, and efficiency of the production process, (ii) Circularity aspects, (iii) Biodegradability, and (iv) Energy efficiency/consumption. Within the circularity aspects, they observed that recyclability is considered a key feature for chemicals. Herein, the **recycling stage** is also one of the most cited, **but the "Reuse" concept** is also widely

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considered. This is in line with the circular economy concept for products in general, where reuse is preferred to recycling. In terms of the circular economy considerations studied in this mapping, **"Recycling" is the most cited as expected.** The terms **"Renewable", "Recovery" and "Reusability" are gaining attention, together with "Durability", which is considered in 14 out of the 55 publications analysed.**

## 3.4 Sustainability Social dimension: S-LCA

**Introduction to S-LCA**

The United Nations Environment Programme (UNEP) defines the **Social Life Cycle Assessment** (S-LCA) as a methodology to assess the **social impacts of products and services** across their life cycle (e.g., from the extraction of raw material to the end-of-life phase, e.g. disposal) [74]. It offers a systematic assessment framework that **combines quantitative as well as qualitative data.** S-LCA provides information on social and socio-economic aspects for decision-making, with the prospect of improving the social performance of an organization and ultimately the well-being of stakeholders.

In terms of social metrics in international law and global policy, there are four common standards used in practice:

- **Universal Declaration of Human Rights:** proclaimed by the United Nations General Assembly in 1948. It establishes fundamental human rights to be universally protected and is widely recognized as having paved the way for the adoption of more than seventy human rights treaties.
- **OECD guidelines on labour standards and economic integration,** to govern working conditions.
- **ILO labour standards,** developed by the International Labour Organization since 1919, are essential in the international framework for ensuring that the growth of the global economy provides benefits for all.
- **Sustainable Development Goals (SDGs),** 17 internationally agreed goals by all UN Member states to be reached by 2030.

Furthermore, on 23 February 2022, the European Commission adopted a proposal for a Directive on corporate sustainability due diligence [75]. The aim is to foster sustainable and responsible corporate behaviour and to anchor human rights and environmental considerations in companies' operations and corporate governance. The new rules will ensure that businesses address the adverse impacts of their actions, including in their value chains inside and outside Europe.

The first guidelines for S-LCA were launched by UNEP in 2009, within the Life Cycle Initiative [76]. In the foreword included in the 2020 edition [74], they state that researchers and practitioners have used these **Guidelines to assess the social and socio-economic impacts of products and services over their lifecycle**. They also observed that since then, the practice of S-LCA has evolved from a small circle of academic practitioners to one that **now includes stakeholders from industry, policy makers, and business.**

In this context, a recent study by Maffia et al. [60] highlights the long way to reach the scientific maturity of S-LCA procedures, even though they are widely applied in different sectors (agriculture, bioenergy, transport, water management, chemical products, electronics, etc.). **S-LCA allows** to

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identify key issues, assesses, and tells the story of **social conditions in the production, use and disposal of products.** On the other hand, critical questions remain to be resolved concerning methods, frameworks, paradigms, and indicators to compare different products or products belonging to the same product sector and make improvements where necessary. Other authors have emphasized this gap as well [41], when comparing the level of development, application, and harmonization of the social assessment *vs*. the environmental assessment methodologies. S-LCA is fragmented with only general theoretical concept, for which empirical data are widely missing. The framework provided by the UNEP guidelines needs to be agreed and standardized, with indicators explicitly defined for different case studies. **The UNEP guidelines** are currently a landmark in the field of social assessment, but the indicators proposed so far are often assessed based on **qualitative information** rather than quantitative, **given the nature of the social aspects** under assessment.

In addition, the **Social Value Initiative** running from 2013 [77], intends to be a cross-sector initiative to lead guidance on measuring the social impacts of products and services, in a way that is recognised for its high quality, credibility and business viability. Its purpose **is to improve the lives of workers, users and local communities** by better insights that enables more balanced decision making. The Initiative has been funded by various companies, with results and deliverables that are non-proprietary and available **under a Creative Commons licence**. The current Handbook for Product Social Impact Assessment (PSIA) [78] was published in 2020 and is considered their fifth iteration, which has been tested by the companies in several case studies.

Some important differences between the **UNEP initiative** and the **Social Value Initiative** are found in the way they address the social metrics and the social topics. The guidelines from **UNEP are based on six social and socio-economic impact categories** with 40 subcategories, whilst **PSIA proposes four social topics** and 25 subcategories (Table 19 and Table 20).

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*Table 19 - List of stakeholder categories and impact subcategories proposed in the UNEP guidelines (Table taken from [74])*

| Worker | Local community | Value chain actors (not including consumers) | Consumer | Society | Children |
|---|---|---|---|---|---|
| 1. Freedom of association and collective barganing<br>2. Child lbor<br>3. Fair salary<br>4. Working hours<br>5. Forced labor<br>6. Equal opportunities/discrimination<br>7. Health and safety<br>8. Social benefits/social security<br>9. Employment relationship<br>10. Sexual harassment<br>11. Smallholders including farmers | 1. Access to material resources<br>2. Access to immaterial resources<br>3. Delocalization and migration<br>4. Cultural heritage<br>5. Safe and healthy living conditions<br>6. Respect of indigenous rights<br>7. Community engagement<br>8. Local employment<br>9. Secure living conditions | 1. Fair competition<br>2. Promoting social responsibility<br>3. Supplier relationships<br>4. Respect of intellectual property rights<br>5. Wealth distribution | 1. Health and safety<br>2. Feedback mechanism<br>3. Consumer privacy<br>4. Transparency<br>5. End-of-life responsibility | 1. Public commitments to sustainability issues<br>2. Contribution to economic development<br>3. Prevention and mitigation of armed conflicts<br>4. Technology development<br>5. Corruption<br>6. Ethical treatment of animals<br>7. Poverty alleviation | 1. Education provided in the local community<br>2. Health issues for children as consumers<br>3. Children concerns regarding marketing practices |

*Table 20 - Social topics per stakeholder group addressed in the PSIA guidelines (Table taken from [78])*

| Social topics for workers | Social topics for local communities |
|---|---|
| 1.1 Occupational health and safety<br>1.2 Remuneration<br>1.3 Child labour<br>1.4 Forced labour<br>1.5 Discrimination<br>1.6 Freedom of association and collective bargaining<br>1.7 Work-life balance | 3.1 Health and safety<br>3.2 Access to material and immaterial resources<br>3.3 Community engagement<br>3.4 Skill development<br>3.5 Contribution to economic development |
| **Social topics for users** | **Social topics for small-scale entrepreneurs** |
| 2.1 Health and safety<br>2.2 Responsible communication<br>2.3 Privacy<br>2.4 Affordability<br>2.5 Accessability<br>2.6 Effectiveness and comfort | 4.1 Meeting basic needs<br>4.2 Access to services and inputs<br>4.3 Women's empowerment<br>4.4 Child labour<br>4.5 Health and safety<br>4.6 Land rights<br>4.7 Fair trading relationships |

In the tables 21-23 below a **comparative analysis of the social topics** covered by these two initiatives is provided:

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- Social topics covered in the UNEP initiative and the Social Value Initiative, within the same impact categories.
- Social topics covered in the UNEP initiative and the Social Value Initiative but addressed in different manners or within different impact categories.
- Social topics addressed only by one of these initiatives.

*Table 21 - Social topics covered both in the UNEP and PSIA guidelines within the same impact categories.*

| Workers | Local communities | Consumer/Users | Small-scale entrepreneurs |
|---|---|---|---|
| Freedom of association and collective bargaining<br>Child labour<br>Fair salary / Remuneration<br>Working hours / Work-life balance<br>Forced labour<br>Equal opportunities / discrimination<br>Health and safety | Access to material resources<br>Access to immaterial resources<br>Community engagement<br>Health and safety | Health and safety<br>Feedback mechanism / Responsible communication / Transparency<br>Consumer privacy | Child labour<br>Fair trading relationships |

*Table 22 - Social topics covered in the UNEP and PSIA guidelines, addressed differently or within different impact categories.*

| Workers | Local communities | Value chain actors | Society | Small-scale entrepreneurs |
|---|---|---|---|---|
| Social benefits / Social security<br>Sexual harassment<br>Smallholders including farmers | Respect of indigenous rights<br>Secure living conditions<br>Contribution to economic development | Fair competition<br>Supplier relationships | Contribution to economic development | Meeting basic needs<br>Access to services and inputs<br>Land rights |

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*Table 23 - Social topics covered only by UNEP or PSIA guidelines.*

| Workers | Local communities | Value chain actors | Consumer/Users | Society | Children | Small-scale entrepreneurs |
|---|---|---|---|---|---|---|
| Employment relationships | Delocalisation and migration<br>Cultural heritage<br>Local employment<br>Skills development | Respect of intellectual property rights<br>Wealth distribution | End-of-life responsibility<br>Affordability<br>Accessibility<br>Effectiveness and comfort | Public commitment to sustainability issues<br>Prevention and mitigation of armed conflicts<br>Technology development<br>Corruption<br>Ethical treatment of animals<br>Poverty alleviation | Education provided in the local community<br>Health issues for children as consumers<br>Children concerns regarding marketing practices | Women's empowerment<br>Health and safety |

**In terms of social metrics references,** UNEP establishes a **five-point scale** for social performance of the stakeholder groups on context- dependent inventory indicators, providing generic guidance for indicators (Figure 14).

| Scale level | Description |
|---|---|
| +2 | Ideal performance. Best in class |
| +1 | Beyond compliance |
| 0 | Compliance with local and international laws and/or basic societal expectations |
| -1 | Slightly below compliance level |
| -2 | Starkly below compliance level |

***Figure 14 - Generic ascending reference scale for social performance evaluation proposed in the UNEP guidelines (Figure taken from [74])***

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In the PSIA methodology, data about each social topic is interpreted with **a scale considering dynamic evolution**. Figure 15 shows the generic reference scale.

| | |
|---|---|
| +2 | best in class, continuous improvement |
| +1 | beyond generally acceptable situation, continuous improvement |
| 0 | generally acceptable situation, |
| -1 | unacceptable situation but improving |
| -2 | unacceptable situation, no improvement |

*Figure 15 - Generic scale to assess social performance in the PSIA guidelines (Figure taken from [78])*

In addition**, this generic scale proposed in the PSIA methodology** has been adapted for each topic in the Social Topics Report [79], which includes metrics designed specifically for **every social topic, linked to specific indicators per performance level.** An example is provided in Figure 16, related to the reference scale for Occupational Health and Safety within the social topics for workers.

| | Definition of the scale level | Performance Indicators |
|---|---|---|
| +2 | The company is best in class compared to its peers on OHS performance | • Credible statistics show the OHS performance is best in class compared to its peers in the same sector and region, and this performance has improved over at least 3 years<br>• Credible statements from NGOs, unions and workers that confirm this |
| +1 | The company has a management system in place to pro-actively and continuously improve the working culture, beyond an acceptable level and can show tangible results of these efforts. | • Documents that provide a credible description of management system to promote continuous improvement of health and safety and the results of these efforts<br>• Credible statements from NGOs, unions and workers that confirm this |
| 0 | Working conditions and working culture are adequately protecting occupational health and safety, which includes that equipment, the use of personal protection equipment, the prevention of harassment are conforming to the state of the art regarding safety and exposure. | • Documents like audits that show compliance with national standards, see for example the Global ILO LEGOSH database for OECD countries<br>• Documents that show certification schemes/standards on health and safety, audits. |
| -1 | There has been a neglect in the working conditions (culture) regarding the maintenance and promotion of occupational health and safety, which results in high accident rates and deteriorating health conditions of workers, but the company or facility has developed a corrective action plan with clear timeline for completion. | • While the company is in an area where this situation often occurs according to statistics, there is evidence that the company has started to address the situation with a clearly defined timeline.<br>• There are incidents of complaints, lawsuits and other signals but they have been significantly reduced during the last 3 years |
| -2 | There is a neglect in the working conditions (culture) regarding the maintenance and promotion of occupational health and safety, which results in high accident rates and deteriorating health conditions of workers. | • Complaints, lawsuits and other signals<br>• Absence of positive information, while the company is in an area, where the risk of bad occupational health and safety situations often occurs according to generic statistics. |

*Figure 16 - Specific reference scale to assess Occupational Health and Safety in the social topics for workers (Figure taken from [79])*

To describe the data collection strategy for the assessment, there are many data sources available that can be classified into different categories.

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- **Publicly available:** with open access, such as national and global statistics organizations.
- **Primary or internal data:** obtained directly from the value chains that are being analysed, in the form of questionnaires, company audits, or interviews.
- **LCA databases:** using a common metric to describe to social risks in a sector and/or company.
- **Service providers:** data offered under subscription by a company.

Further details are provided below on the most widely used public data sources, LCA databases, and service providers.

***Publicly available data sources and main topics addressed***

- **Organization for Economic Cooperation and Development (OECD**): Agriculture, development, economy, education, energy, environment, finance, government, health, innovation and technology, jobs, society.
- **International Labour Organization (ILO):** Labour supply, working conditions, poverty and inequality, competitiveness, industrial relations, selected groups.
- **United Nations (UN):** topics on Sustainable Development Goals, economy, environment, geospatial aspects, and population and society.
- **The World Bank Group (WBG):** Education, gender, health, labour, and social protection.
- **World Economic Forum:** Global risk, energy, social mobility, gender, competitiveness.
- **International Trade Union Confederation (ITUC):** Civil liberties, right to establish or join unions, Trade union activities, Right to collective bargaining, Right to strike.
- **World Intellectual Property Organization (WIPO):** IP and trademark at regional and country level.
- **Amnesty international:** armed conflict, arms trade, business and human rights, child labour and child soldiers.
- **Transparency international statistics:** corruption in public sector (bribery), diversion of public funds, effective prosecution of corruption cases to adequate legal framework, access to information, legal protection for whistle-blowers, journalists, and investigators.
- **Wage Indicator living wages database with three wage indicators:** Minimum Wage, Living Wage, Actual Wage.

<u>Social LCA databases</u>

There are two main databases, the Product Social Impact Life Cycle Assessment database (PSILCA) and the Social Hotspots Database (SHDB).

- **PSILCA** [80] is developed by GreenDelta to provide transparent and up-to-date information on social aspects of products over their life cycles, for different industry sectors and commodities and for 69 qualitative and quantitative indicators. It allows calculation and assessment of the social impacts of products along the products' entire life cycles, considering global supply chains and services, and to detect social hotspots.

- **The SHDB** [81] is developed by NewEarth B aiming to foster greater collaboration in improving social conditions worldwide by providing the data and the tools necessary for improved visibility of social hotspots in product supply chains. Its last update is version 4 (2019) covering 4 Stakeholder categories, 6 Social impact categories, 26 Sub-categories, 160 indicators and 244 countries.

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Both PSILCA and SHDB are based on global Input Output databases with added social indicators, oriented to identify risks (less on positive impacts), and defining data per working hour. Worker hours are related to 1$ of process output.

***Service providers***

Service providers sell specific data to research companies, sectors, and countries. This type of data involves considerable investment compared to social LCA databases, which can be used at a lower price. The most relevant options are as follows:

- **Ecovadis** [82]: provides company specific primary data including risk level and scorecard based on an online questionnaire. The scorecard illustrates performance across 21 indicators in four themes (environment, labour and human rights, ethics, and sustainable procurement).
- **SMETA by Sedex** [83]: provides company specific primary data by self-assessment surveys and audits that are conducted by third parties.
- **RepRisk** [84]: offers company specific secondary data, with risk management and compliance solutions, mainly to prevent and manage business conduct risks.
- **Datamaran** [85]: also offering secondary data, using artificial intelligence to analyse the relevance of each topic, providing positive and negative information.
- **Maplecroft** [86]: provides secondary data, offering quantitative risks indices and mapping technology, with global risk datasets covering more than 150 environmental, social, political, and economic issues

Depending on the specific case study, different data collection strategies will be designed, and the most appropriate data sources will be selected. When conducting a social LCA, it is of utmost importance to define the goal and scope of the study and the type of data required. For instance, PSILCA and SHDB would be interesting to provide the number of risk hours in a specific sector, but if we intend to provide a risk score per sector, the sources offered by the Service providers might be more useful.

**<u>Summary of Literature review</u>**

In terms of the analysis of the social indicators considered in the literature review performed, the number of results obtained is shown in Table 24 below.

*Table 24 - Number of studies obtained in the analysis of Social indicators (Scopus search described in Section 3.2)*

| Social indicators | | | | | | |
|---|---|---|---|---|---|---|
| **Poverty** | **Corruption** | **Child labour** | **Forced labour** | **Fair salary/wage** | **Working hours** | **Local employment** |
| 5 | 3 | 5 | 2 | 4 | 5 | 6 |
| **Health and Safety (workers)** | **Health and Safety (consumers)** | **Freedom of association** | **Collective bargaining** | **Equal opportunities** | **Discrimination** | **Community engagement** |
| **11** | **9** | 3 | 2 | 4 | 4 | 4 |

*Total number of studies: 55*

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The results obtained confirm the increase in the attracted interest by the social dimension of sustainability in the last two years, observed in the general literature review described previously.

The number of studies considering social indicators is increasing significantly, with **"Health and Safety of workers"** being the most used indicator, in 11 out of 55 publications. In the report by Caldeira et al., the most often used indicator was **"No child labour"** with 11 out of 119 frameworks.

Regarding the different indicators screened, Caldeira et al. showed a major attention to those related to Human rights ("No child labour", "No forced labour", "Discrimination prevention"), Labour rights ("Working hours" and "Fair wages") and Occupational health & safety. In this study, **"Health and safety" indicators both for workers and consumers** are the most reported, so considerations about Occupational health & safety and Customer protection aspects are taken into consideration. **"Local employment"** is also found of interest in the studies analysed, which is included in the Supply chain responsibility aspect. The other categories proposed by Caldeira et al. to analyse the social dimension were Human rights and Labour rights, which are also quite represented in the publications studied herein. In comparison, they reported much less attention to the indicators related to Supply chain responsibility and Customer protection.

**Database**

Concerning the databases two main databases are frequently used by S-LCA practitioners, **PSILCA and SHBD**. Within the analysed studies, three of them used the PSILCA database and four of them used the SHBD database.

## 3.5 Techno-economical dimension

Economic sustainability refers to multiple aspects related to techno-economic feasibility, operational costs, etc. Moreover, there are important considerations to be made in the context of **SSbD such as the 'availability' of raw materials**, as chemicals/materials cannot be declared SSbD if the raw materials to produce them are **not renewable or are (very) scarce and extracted and processed in an unsustainable manner**. **Economic aspects play a role when there is a need to rank chemicals and materials based on SSbD** criteria (even if they are not SSbD) [9].

### 3.5.1 Life Cycle Costing (LCC)

**Introduction**

In life cycle sustainability assessment, the economic pillar is usually addressed through the **Life Cycle Costing (LCC)** methodology. As the name suggests, LCC is a technique that assesses costs over the life cycle of a product or a system. LCC belongs to the group of sustainability methodologies that focus on flows in connection with the production and consumption of goods and services. They focus on evaluating different flows in relation to various products or services instead of for example regions or nations. LCC is an economic approach that sums up the "total costs of a product, process or activity discounted over its lifetime". It is associated with **all costs occurring from purchase to disposal and can include the costs of externalities (the environmental costs).** The idea is that the purchase price often does not reflect the full costs caused by a product over its whole life cycle and hence is not a sufficient indication.

The Society of Environmental Toxicology and Chemistry (SETAC) distinguishes three different types of **life cycle cost analyses: conventional LCC, environmental LCC and social LCC** [87]. Conventional LCC, also termed financial LCC, is the original method, Environmental LCC is aligned with LCA in

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terms of system boundaries, functional unit, and methodological steps. Lastly, environmental and societal LCC includes monetarization of other externalities, including both environmental impacts and social impacts.

While the LCA methodology has been standardized and can be applied to any product, for **conventional LCC,** there are only standards for **some sectors** including ISO 15663 [88] for **petroleum and gas**, ISO 15686-5 ([89],[90]) **for building and constructed assets** as well as some **general standards,** such as IEC 60300-3-3, BS 3843, AS/NZS 4536.

For **environmental LCC** the work of the scientific working group within SETAC on LCC resulted in the **LCC methodology described** in Hunkeler et al. [87], while **societal LCC is still at an early stage** of development, and more research work is required [91].

- **The conventional LCC (cLCC),** which focuses on internal costs (cost directly involved in the life cycle of the product) and is a pure economic evaluation taking into consideration the different stages in a life cycle approach. LCC is mainly applied as a decision-making tool, to support the acquisition of capital equipment and long-lasting products with high investment.

- **The environmental LCC (eLCC),** which extends the LCC by including environmental externalities[4] and a comprehensive multistakeholder perspective, for example, producers and consumers – including externalities that are anticipated to be internalized in the decision-relevant future. These costs must relate to real money flows. For example, in the case of the car, this means that anticipated extra taxes on pollution from fuel combustion might be included in the operational cost. Unlike the conventional LCC, which is industry driven, environmental LCC was rather developed to support LCA in the sense that it covers the economic dimension and helps identify hot spots in terms of both cost and environmental impacts.

- **The societal LCC (sLCC),** further extends eLCC by including additional externalities associated with the life cycle of a product. Therefore, sLCC assesses all costs associated with the life cycle of a product that are covered by anyone in society, whether today or in the long-term future. The perspective of sLCC comprises the society overall (locally, as well as nationally and internationally), also including governments.

More recent applications of **cLCC** also adopt a **circular economy perspective** by including multiple life cycles. Indeed, since the circular economy was established as one of the leading strategies towards a sustainable built environment (European Commission, 2015 [92], 2020 [93]), an increasing number of LCC studies started to apply more holistic approaches that consider products as a composite of components and parts with **different and multiple use cycles** (Bradley et al. [94]; Jansen et al. [95]). These novel approaches are especially relevant when comparing products designed for a **circular built environment to "business-as-usual" products and are here referred to as Circular Economy LCC (CE- LCC).** Table 25 shows an overview of the different variants of life cycle costing.

[4] external costs (also termed externalities) are value changes caused by a business transaction, which are not included in its price, or value changes caused as side effects of the economic activity.

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*Table 25 - Comparison of the different variants of life cycle costing (Table taken from [91])*

| | Conventional LCC | Environmental LCC | Societal LCC |
|---|---|---|---|
| **Goal** | The assessment of all life cycle costs that are directly covered by the main producer or user in the product life cycle | The assessment of all life cycle costs that are covered by all stakeholders connected to the product life cycle | The assessment of all life cycle costs that arecovered by anyone in the society |
| **Definition of the life cycle** | Economic lifetime, often excluding end-of-life | Complete life cycle | Complete life cycle |
| **Perspectives** | Mainly one stakeholder,either manufacturer or user | One or more stakeholders connectedto the life cycle | Anyone in the society, often includes governments |
| **Reference unit** | Product or project | Functional unit | Functional unit |
| **Types of costs** | Internal costs of one stakeholder, focusingmainly on acquisition and ownership costs | Internal costs of stakeholders connected to the life cycle, plus external costs and benefits expected to be internalized such as $CO_2$ taxes | Internal costs of all actors plus external costs, i.e. impacts that production or consumption have on third parties |
| **Adjustment to inflation** | Yes | Yes | Yes |
| **Discounting of results** | Consistent, with discount factors between 5-10% | No. Discounting the results of the LCC would make the analysis inconsistent with the steady-state assumption of LCA | Consistent but usuallylow discount factors (<3%) |

Degieter et al. [96] performed a systematic review of methods and findings of 92 LCC studies in the agri- food sector. In most of the analysed papers, the type of LCC was not mentioned in 61 papers (Figure 17). In the studies that mention the type of LCC (31, one paper applies two different types of LCC), conventional LCC is most often referred to (21 papers), followed by environmental LCC (nine papers) and finally societal LCC (two papers). The lack of studies including a societal life cycle cost analysis might be caused by the difficulties associated with conducting a societal LCC, such as the risk of double counting (when LCA is complemented by LCC, the costs of environmental externalities should not be included in the LCC) and methodological difficulties with regards to internalizing externalities (which externalities should be internalized? How externalities can be internalized? etc.). They concluded that there was no clear distinction between LCC types and that there is a need for standardized definitions for the different LCC types, which researchers can follow when conducting an LCC. The number of studies that included externalities for the life cycle cost analysis is still very limited due to methodological difficulties, indicating the need for further research. In addition, a standardized methodology for social life cycle assessment (sLCA), to assess the third pillar of sustainability, is still missing.

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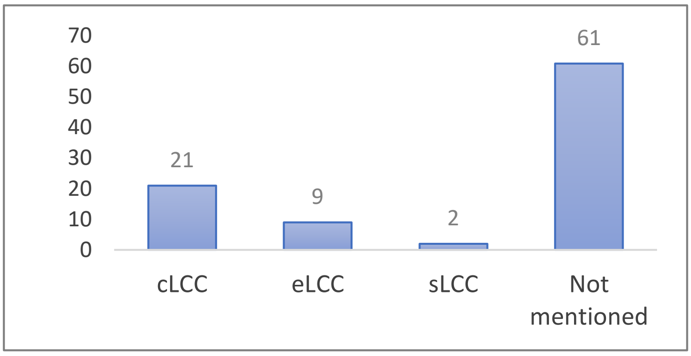


*Figure 17 - Number of studies according to LCC type (Figure taken from [96])*

Within ORIENTING Project, a literature review was conducted in March 2021 to identify and describe economic assessment approaches for potential use within LCSA (Life Cycle Sustainability Assessment) framework [97]. The summary of the literature search results is given in Figure 18. Four categories of results are distinguished: (1) Reviews, (2) Applications and Case Studies, (3) Theoretical Definitions and Methodology, (4) Integration within LCSA framework. Every scientific article identified has been assigned to one single category only.

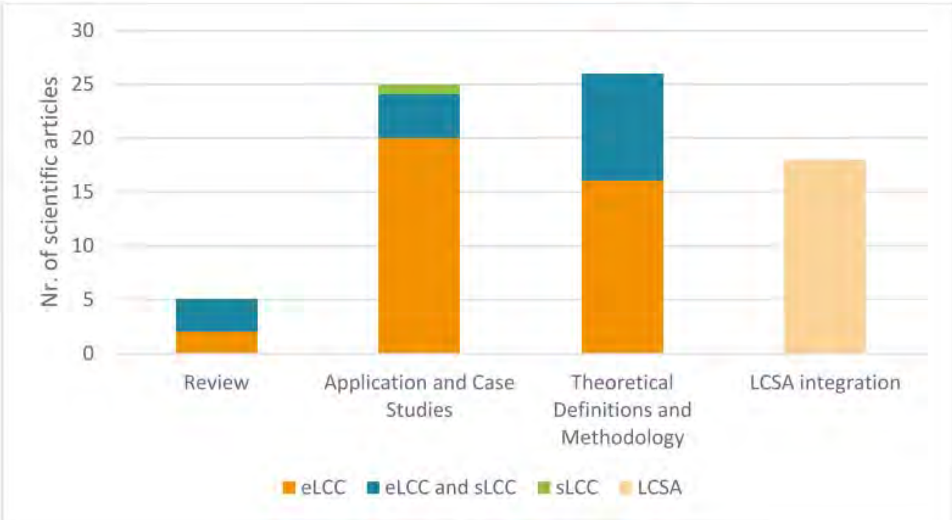


*Figure 18 - Number of studies according to LCC type, taken from ORIENTING project [97]*

More than 70 publications have been identified as of March 2021 considering eLCC and their integration within the LCSA. The utilization of sLCC is rarely explicitly addressed in the reviewed literature. Sun et al. [98] employed sLCC for evaluating fuel cell vehicles as compared with conventional gasoline vehicles. Except for this single case study, it was not possible to find scientific articles that specifically analysed, described, or applied this methodology. Rather, sLCC is described, sometimes only marginally, within works related to broader LCC or Sustainability Assessment when socio-economic.

Regarding the economic approaches mapped in this literature review, Life cycle cost is by far the predominant term reported in the studies, only 2 studies explicitly mention the cLCC, sLCC and the eLCC (Figure 19). However even though e-LCC is not mentioned, several studies consider environmental externalities.


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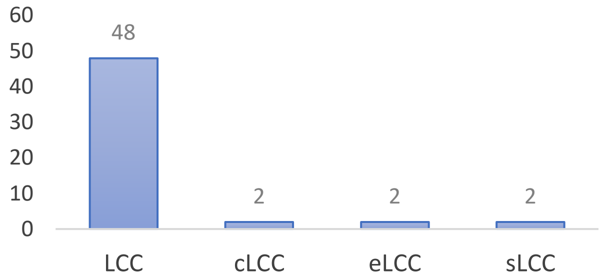


*Figure 19 - Number of studies according to LCC type, found in the current literature review*

**Data for Inventory Analysis**

The availability of reliable cost data is crucial to perform a realistic life cycle cost analysis. Gathering financial data can be time-consuming and will depend on the collaboration with involved companies and institutions.

Financial data can be very sensitive, especially if the results are intended to be published. In these cases, most of the data must be gathered from other independent data sources and references.

Besides, inventory data are very time and space sensitive. During the inventory phase, costs should be quantified in one currency and be based on a common year. In a different location, identical products may be of completely different value, and costs may need to be paid in a different currency, with floating exchange rates. Similarly, at a different time, prices and costs may have been changed, thus requiring the use of proper inflation rates to adjust them.
***Examples of public databases are shown in***

Table 26 giving an overview of different cost categories. These data are published at least annually. However, the scope of each database is different, and it is important to check each data source in terms of comprehensiveness, validity for different regions, currencies, and time to ensure that the data are comparable, while also taking the goal and defined scopeinto account.

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*Table 26 - Public database for life cycle cost data [91]*

| Type | Scope | Name | Link |
|---|---|---|---|
| Crude oil | Sectors, monthly, country | International Energy Agency | www.iea.org/statistics/topics/ priceandtaxes |
| Plastics | Global, weekly | The Plastic Exchange | www.theplasticsexchange. com |
| Marine fuel oils | Sector, daily, global | Ship and Bunker´s | www.shipandbunker.com/ prices |
| Chemicals | Sector, daily, global | ICIS, Part of RELXGroup | www.Icis.com/chemicals |
| Metals | Sector, daily, global | London Metal Exchanges | www.lme.com |
| Commodities | Sector, yearly, global | United Nations | www.comtrade.un.org/data |
| Inflation | Sector, country, monthly | World Bank | www.data.worldbank.org |
| Wages | Sector, country, yearly | International Labour Organization | www.ilo.org |
| Currency exchange rates | Yearly, monthly | World Bank | www.data.worldbank.org |
| Power, gas, coal,oil | Daily | European Stock Exchange | www.eex.com/en |

**Indicators**

Unlike environmental analysis, in which there is a greater consensus in the determination of indicators, the economic analyses still lack a set of commonly accepted indicators (Visentin et al. [99]).

Alejandrino et al. [100] conducted a systematic review of 100 articles of case studies including the three dimensions of sustainability. Figure 20 shows the indicators used in the reviewed studies, being “cost” the most common one. However, other indicators were identified: revenues, profit, price, net present value (NPV), added value, payback time, investment, internal rate of return (IRR), contribution to gross domestic product (GDP), risk, financial incentives, and unidimensional impact scores.

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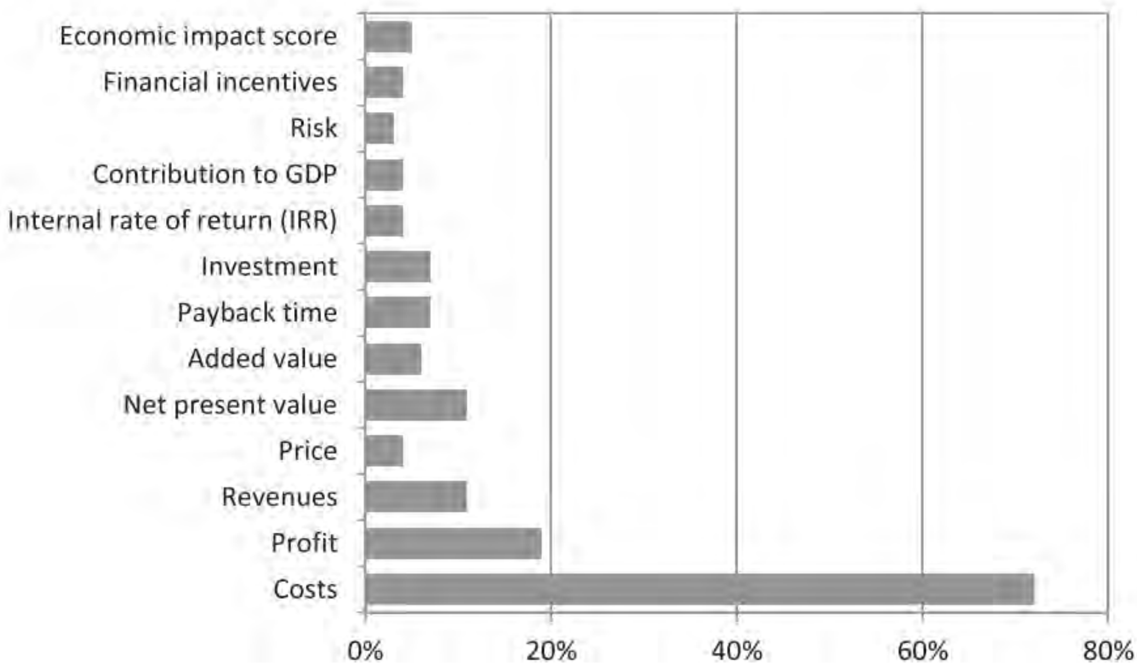


*Figure 20 - LCC impact categories according to Alejandrino et al. review [100] (Figure taken from [100])*

Visentin et al. [99] performed a bibliographical analysis of 105 publications corresponding to the period 2008-2019 and identified the most used economic indicators (Figure 21). Unlike the environmental dimension indicators, which consider complex environmental mechanisms, the indicators in the economic dimension are, in most cases, direct. The necessary data are often information about production and the actors involved. In the economic area, the main indicators used are electricity costs, operating and maintenance costs, raw material, and production and capital costs. Only some studies consider the environmental costs associated with the environmental impacts of the company, such as atmospheric emissions.

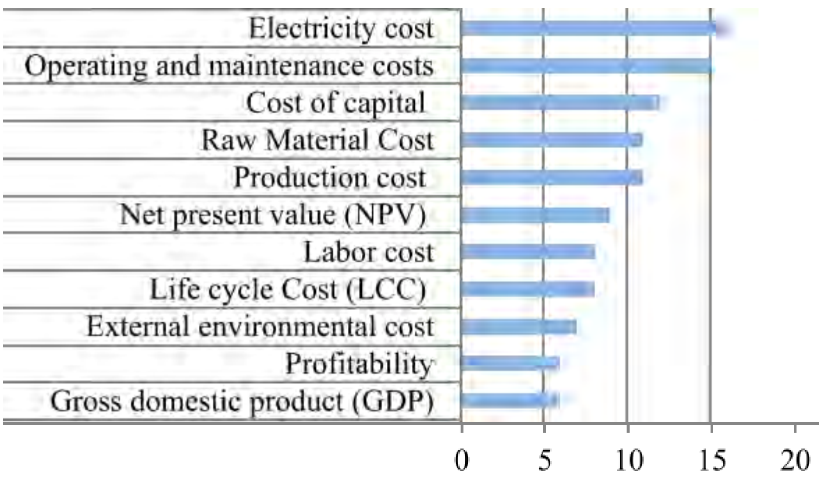


*Figure 21 - Economic indicators most used according to Visentin et al. [99] (Figure taken from [99])*

In general, LCC approaches focus on the estimation of total cost, as key indicator (Alejandrino et al. [100]), along with its leading cost components such as raw material, energy, labour cost etc. Only few applications extend the scope of LCC studies to include financial indicators.

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However, the evaluation of economic performance of different alternatives requires additional company-specific data such as the revenues and cash flow schedule. Retrieving this information does not only require extra effort but can also translate into confidentiality issues.

**External cost-Monetization**

The traditional LCC, assessing internal cost is part of the usual business administration. Similar to cLCC, eLCC can be used to detect cost drivers and potential for improvement opportunities throughout the life cycle of a product. However, eLCC's scope is larger, as it includes also (monetized) environmental externalities projected to be internalized. These might include e.g., future waste management cost, emission controls or environmental taxes and/or subsidies. In addition, eLCC usually takes a more future-oriented approach (i.e., during the design phase) compared to the more retrospective cLCC conducted for existing products [87].

For the e-LCC and sLCC a crucial part of the economic assessment lies in the quantification of externalities through monetization. Monetary valuation is the practice of converting measures of social and biophysical impacts into monetary units.

For the monetary valuation of environmental impacts and related environmental aspects, as needed when carrying out eLCC and sLCC, several approaches can be followed (ISO 14008 [101], Arendt et al. [102]), each one coming with different data requirements.

ISO 14008 [101] specifies a methodological framework for the monetary valuation of environmental impacts and related environmental aspects. Environmental impacts include impacts on human health, and on the built and natural environment. Environmental aspects include releases and the use of natural resources.

Arendt et al. [102] provided an overview of currently applied monetization methods in LCA. namely **Ecovalue12, Stepwise2006, LIME3, Ecotax, EVR, EPS**, t**he Environmental Prices Handbook, Trucost and the MMG-Method**. These nine methods were compared quantitatively and qualitatively, yielding results for 18 impact categories (27):

*Table 27 Impact categories proposed by [102]*

| | | |
|---|---|---|
| Climate change | Acidification | Mineral Resources |
| Ozone Depletion | Freshwater Eutrophication | Fossil Resources |
| Photochemical oxidation | Marine Eutrophication | Water use |
| Particulate Matter | Human Toxicity | Land Use |
| Ionizing Radiation | Terrestrial Ecotoxicity | Land Transformation |
| | Freshwater Ecotoxicity | Soil Organic Matter |
| | Marine Ecotoxicity | |

Monetary factors for the same impact category range mostly between two orders of magnitude for the assessed methods, with some exceptions (e.g., mineral resources with five orders of magnitude). Among the qualitative criteria, per capita income, and thus the geographical reference, has the biggest influence on the obtained monetary factors. When the monetization methods were applied to the domestic yearly environmental damages of an average EU citizen, their monetary values ranged between 7941.13 €/capita (Ecotax) and 224.06 €/capita (LIME3).

Overall, they concluded that current monetization methods in LCA use a wide variety of monetary valuation approaches. Therefore, varying monetary damage values are obtained. Practitioners


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should especially pay attention to the coherence of the underlying reference region of monetization methods and their case study.
In Europe, there are also damage's cost factors that have been derived in the context of the Externalities of Energy. The so-called "**ExternE methodology**" [103] was created to better quantify the social and environmental damages of energy, especially those provoked by air pollution coming from energy production and consumption. There are also damage cost factors derived from related European or national research that monetizes air pollution emissions as the Air quality appraisal: damage cost guidance (updated 2023) [104] and Environmental Prices Handbook (2018) [105]. However, these data are often time- and site-dependent/specific.

In conclusion, one of the key aspects is to seek for a comprehensive methodological framework where links between life cycle stages and stakeholder perspectives are thoroughly described. To this aim, the eLCC seems to be the main framework to consider as it does not only include, by definition, all the product's life cycle stages but also the consideration of soon-to- be-internalized externalities. It will be critical to establish how economic metrics should complement the social and environmental results. To do so, a first step consists in defining the economic indicators of interest to policymakers and then, ensuring that these do not overlap with metrics provided in LCA or S-LCA when calculating aggregated scores. While single scores can facilitate a decision-making process to prioritize choices, they come with some limitations in terms of transparency and interpretation (by experts).

**Main economic indicators identified in the literature review**

Regarding the economic indicators mapped in the literature review, the number of results obtained is shown in Table 28

*Table 28 - Number of studies obtained in the analysis of Economic indicators (Scopus search described in Section 3.2)*

| Economic indicators | | | | | |
|---|---|---|---|---|---|
| **Purchase cost** | **Production cost** | **Investment cost** | **Capital cost** | **Raw material cost** | **Labour cost** |
| 6 | **13** | **17** | 12 | 3 | **14** |
| **Electricity cost** | **Operating and maintenance costs** | **Externality cost** | **External cost** | **Monetization** | **Waste cost** |
| 5 | 4 | 0 | 6 | 5 | 2 |
| **Recycling cost** | **Revenues** | **Financial incentives** | **Minimum selling price** | **Profitability** | **Net present value** |
| 3 | 13 | 1 | 3 | **12** | **20** |
| **Added value** | **Payback period** | **Willingness to pay** | **Internal rate of return (IRR)** | **Gross Domestic Product (GDP)** | |
| 6 | 11 | 4 | 8 | 8 | |

*Total number of studies: 55*

In addition, **"Net present value", "Investment cost" and "Labour cost"** are, amongst others, frequently used indicators in the publications analysed. Although Caldeira et al. did not include all of them in the categories proposed, they could be classified within the **Production cost** and **Profitability economic aspects**. The indicator they reported as "Externality cost", considered by 6 frameworks out of 119, is found in this study as "External cost" in 6 publications out of 55. In

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addition, indicators belonging to other aspects are gaining more attention in the last years, such as "Willingness to pay", classified as a Market-related criteria. It was covered in only one of the frameworks analysed by Caldeira et al. (out of 119), and herein it is found in 4 out of 55 publications. These frameworks mainly looked at production or purchase costs (with 11 and 18 results, respectively, out of 119) and, to a lesser extent, profitability, externality costs and market-related criteria.

## 3.6 Modelling and characterization tools

In the process of developing sustainable chemicals, materials, products and processes, the implementation of **SSbD** principles plays an important role. The concept of SSbD focuses on avoiding potential adverse health and environmental effects at an early stage of material and product development. It involves analyzing sustainability during its life cycle, facilitating reuse, recycling, and the implementation of circular models.

One of the key aspects to improve sustainability in the use stage is to increase the **durability of materials** (**extending their lifetime)** as well as to improve their **energy efficiency** (reducing friction) in use (as also envisaged by the circular economy).

The concept of **extending the lifetime** of a product is also part of the circular economy and the **9R strategy** (schematized in Figure 22**).**

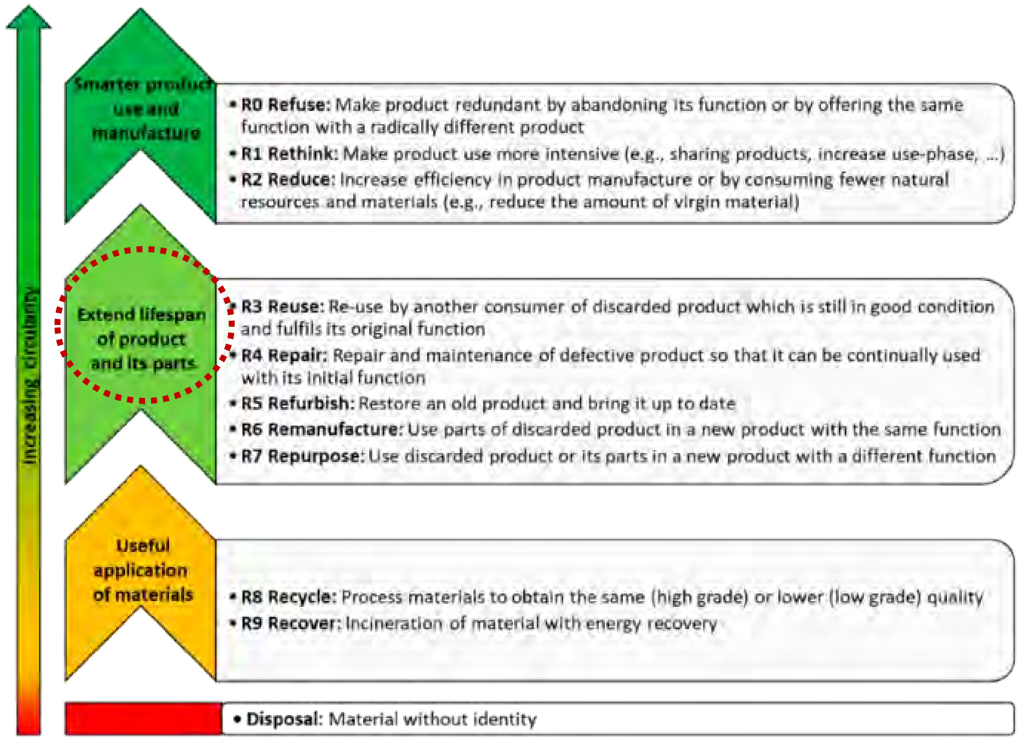


*Figure 22 - The 9R Framework of Circular Approaches (Figure taken from [106])*

One of the principles of the SSbD concept is that the materials and products should always be assessed also in relation to their **application or use phase,** as the benefits and sustainability performance are in the end-product and can occur at any moment across the entire life cycle. In setting assessment criteria and assessing product-applications, one needs to differentiate between

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industrial use, professional uses, consumer use and other uses (e.g., pharmaceutical ingredients, R&D) [107].

The Strategic research and innovation plan for safe and sustainable chemicals and materials (**SRIP)** [8] highlights the R&I areas crucial for making chemicals and materials safe and sustainable.

The Plan focuses on enabling and crosscutting aspects and the R&I needs in line with life cycle stages of chemicals and materials. As chemicals and materials are used in many different sectors and consumer goods, the identified R&I areas can also contribute to increasing the overall sustainability of these value chains and products.

According to SRIP one of the key points in the development of SSbD is the **modelling and characterization.** Models and advanced characterization play an important role in the design of chemicals and materials. To support the assessment of performance and functionality, molecular modelling can be applied to quantitatively describe and predict physical and chemical characteristics of systems.

In a similar way for material, products and components, **Tribology can provide interesting information to the SSbD criteria referring to the use phase ensuring the functionality** of a **material/product for the selected application(s**), controlling the friction, and consequently increasing the **energy efficiency** of the system, and **taking also into account the wear resistance, durability and repairability.**

In the design of materials and operation parameters for energy efficient use of a system (e.g. Braking, machining, walking, transmissions), tribology plays a key role. Tribology helps to optimize both operation parameters and design of material system and select the materials, lubricants, or surface treatments for energy efficient operation of the system.

According to the analysis performed by Lawrence Livermore National Laboratory, that details the sources of energy production in America in 2021, how the energy is used and how much waste exists, less than 32% of the total primary energy produced is used [108] (see Figure 23). A great amount of energy is lost due to friction.

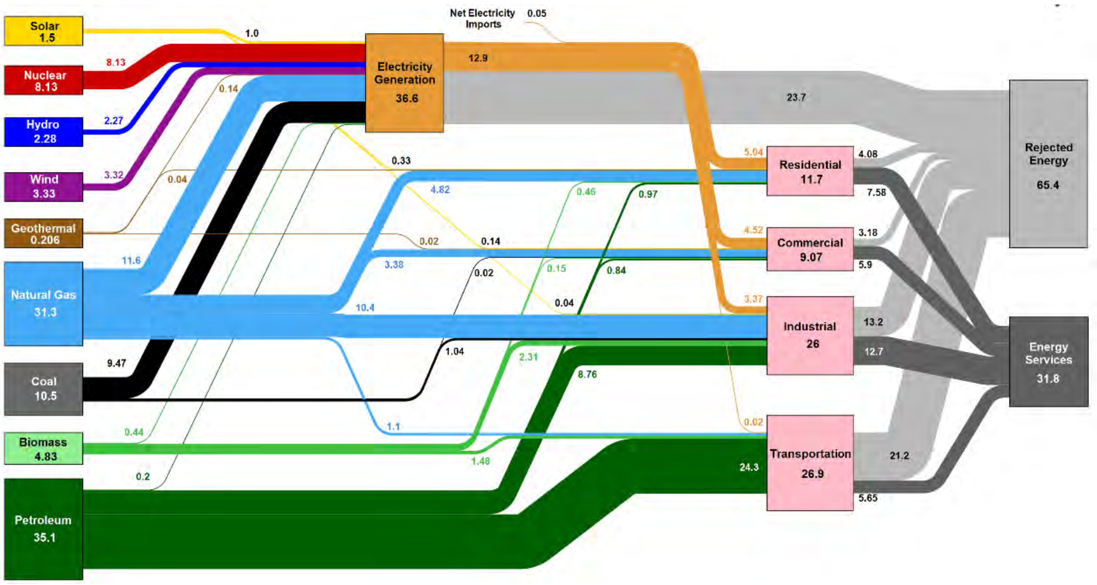

*Figure 23 - Estimated U.S. energy consumption in 2021 (Figure taken from [108])*


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Minimizing friction lost and, quantifying the wear and durability, has gained a lot of researchers' attention, as it reduces carbon footprint and greenhouse gas emissions without altering normal operational conditions of a running system. This leads to reduced carbon emissions in terms of monetary and ecological factors, which are the key to tribological sustainability.

The SRIP [8] identified several areas in **modelling and characterization** were research and innovation are needed:

- **Characterization**: develop models for multi-modal, multi-scale and multi-dimensional phase spaces (i.e., representations of the possible states of the system) for the characterization of chemicals and materials.

- **Optimization:** develop more robust, interoperable, and adaptive models for multi-objective optimization of different requirements for a chemical or material e.g., **performance, functionality, durability, safety, and sustainability**

- **Prediction**: establish models for specific matrices for the assessment of the impact of chemicals and materials (e.g., fate and transformation) and connect these to the in-silico simulation tools to assess the influence of the chemicals and materials on people and the environment. Develop simulation tools generating future scenarios predicting the functionality, safety and sustainability of new chemicals and materials and the processes needed to produce and recover them.

- **Design:** develop models that provide alternatives during the design phase and create a database of suitable safer alternatives, considering future regulatory requirements. Develop models considering findings from the recycling and disposal of existing chemicals and materials to redesign chemicals and materials from secondary raw materials to achieve the same or enhanced functionalities.

- **Degradation assessments:** develop test methods and analytical tools to assess the degradation of material. It is necessary to reproduce failure mechanisms during use, to predict their behavior at laboratory scale, and select the best materials solutions.

- The **environmental representativeness** across all life cycle stages should be improved, with special attention to use and end of life as well as consideration of substances difficult to test (e.g., endocrine disrupting, persistent, bioaccumulative and toxic (PBT) substances) and advanced materials (e.g., nanomaterials, microplastics)

The Materials 2030 initiative [109] proposes the development of a materials database as a key action to accelerate digitalization in product innovation**.** The objective is twofold:

- To **design novel materials for given specifications** at a speed unattainable in the usual process of discovery where targeted development is difficult, and breakthroughs are often unpredictable.

- T**o manage and control material behavior and data over the material´s value chains and along the entire lifetime**. Data obtained in production, laboratory control and use phase and during End of Life (EoL)- process will be key to increase efficiency and reliability of the material design to minimize the environmental impact through waste, reduction extended lifetimes and to optimize towards circular material flows and materials for the planet.

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### 3.6.1 Management of data

In this section, some extracts of text of *The Materials 2030 initiative* [109] are summarized below.

Initial steps in terminology, classification, and data documentation for multiperspective materials modelling and characterization workflows have been done, establishing the now widely accepted data structures MODA [110] and CHADA [111], respectively. Europe is leading the way in ontology-based data documentation of materials and manufacturing due to the development of the EMMO ontology framework [112].

The availability, transparency and access to data are key factors for success; therefore, some important initiatives are added in different European countries such as:

- Germany: Platform Material Digital PMD[113], NFDI-MatWerk (Nationale Forschungsdateninfrastruktur für Materialwissenschaft & Werkstofftechnik) [114] , FAIRmat (Findable, Accessible, Interoperable, and Reusable Data Infrastructure for Condensed Matter Physics and the Chemical Physics of Solids)[115], etc.
- France: DIADEM – Discovery Acceleration for the Deployment of Emerging Materials [116]
- At European level: the European Materials Modelling Council (EMMC), European Materials Characterization Council (EMCC), as an example.

Due to the lack of ontologies able to capture the multi-perspective nature of materials science and applications, EMMC and related projects developed a physics, semiotics and mereotopology based top level ontology for applied sciences called EMMO (Elementary Multi-perspective Material Ontology). Industry Commons projects are developing best practices for ontology-based data documentation (Onto Commons [117]) and a data marketplace (DOME 4.0 [118]), The full potential of the effective exploitation of the rich and rapidly growing amount of data in materials science, transformation, use and re-use until the end of life still needs to be harvested. (Figure 24)

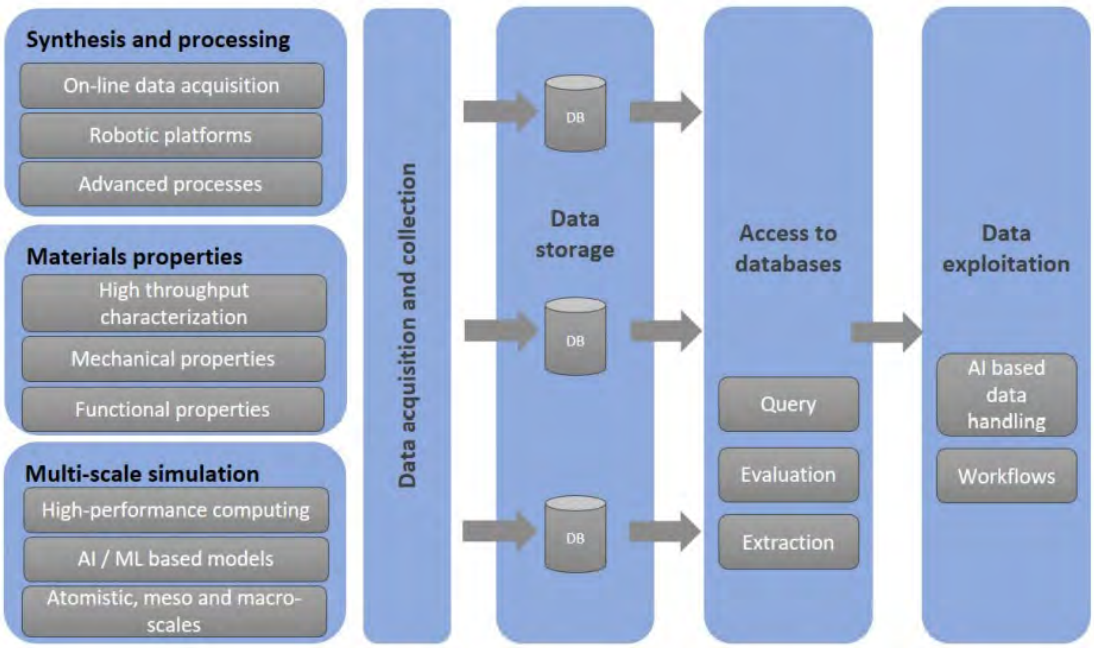


***Figure 24 - Efficient pathways for harvesting relevant data originating from synthesis and processing, characterization, and simulations will need to be created and managed (Figure taken from [109])***

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**The future initiative should be a (common) data space**, based on the 'embryonic' data spaces emerged in the manufacturing sector, having a focus on data sharing for circularity in line with the Circular Economy Action Plan, involving organizations from the circular economy (e.g., reuse, repair, and remanufacturing, refurbishing, and recycling companies to improve circularity and secondary use of the materials).

Advanced materials development requires multiple sources of data and knowledge, based on digital and innovative methodologies, **including modelling, characterization, production, and testing technologies for the advanced materials lifecycle** (development, production, use, recycle).

High-throughput characterization: compositional, structural, mechanical, **functional properties and durability, as well as in situ or operando characterization**, will generate large databases. **New advanced characterization instruments and protocols are needed**, developing the interphase with the cloud, to store and analyse the information, independently of the physical testing.

### 3.6.2 Engineering tools for implementation of sustainability at design stage

This chapter analyses engineering tools that support or guarantee sustainability of finished products. Product development in this sense does not describe the development of new materials, but of products which use these advanced materials. SSbD, "by design", should be an element of all development activities, from consumer goods, consumer electronics, automotive and transport in general, white wares etc. as well as for machines, components, and subcomponents in industrial manufacturing.

The scope of the assessment lies on SSbD in model- and simulation-driven design with informed and evidence-based materials selection within a tools landscape of multi-objective optimisation, with the objective to design sustainable products and manufacturing processes. Consequently, this chapter analyse how technology can be leveraged, at the design stage, for sustainable development.

*"Eighty percent of product life costs in the aerospace industry are locked in at the concept design phase, when materials and manufacturing decisions are made, and the efficiency of the overall system is revealed. That's why it is critical to integrate eco design processes during this phase, ensuring the embodied energy and $CO_2$ associated with materials and their manufacturing are identified and optimized so that the final product can be understood in terms of its sustainable impact with minimal time or cost constraints"* [119].

Advanced virtual product engineering employs Computer Aided Designs (CADs) with multi-physics simulation tools. As an example, the workflow of product and process design proposed by Tekniker is shown in Figure 25.


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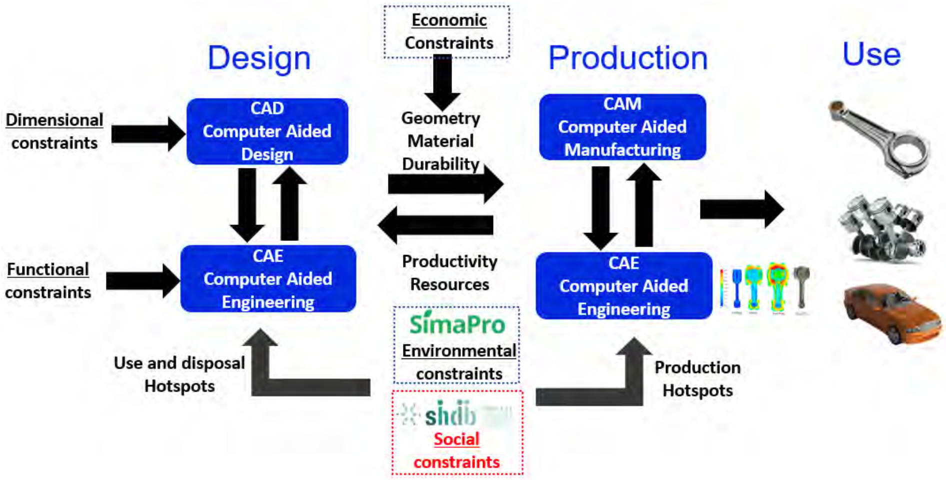


*Figure 25 - Concept of Sustainable by design production (source Tekniker)*

To ensure the sustainability of the finished product, an extra loop for LCA is included. However, LCA of materials, components, or products are costly and time-consuming, which represents a serious barrier in time-to-market-controlled developments. A citation from EU project PLEIADES, "*An LCA for just one material could take six weeks. Aerospace manufacturers probably have several thousands of bills of materials for their aircraft*". To assigning reference eco data from already existing materials and to process data at the design stage can massively reduce the time and money spent on sustainable products development [120].

#### *3.6.2.1 Technical support and tools for SSbD at the product design stage*

More and more companies are relying on digital prototyping in product development. With the help of simulation software, development teams set up virtual prototypes, which are designed to fulfil the product (or component) requirements e.g., for mechanical load and stiffness, chemical or heat resistance, etc. Furthermore, development teams can also digitally optimize production processes. Additional SW modules provide a cost assessment, so functionality, performance, manufacturability, and cost are predictively set to the product specifications.

Modern design tools include sustainability, ecological footprint, and environmental parameter calculations / predictions. Hence, the virtual prototype can be adjusted, modified, re-designed, and optimised to reach better properties and functionality while minimising the environmental footprint. Figure 26 shows an example of a sustainable design of a product, where the digital protype is optimized towards environmental footprint with the support of SSbD.

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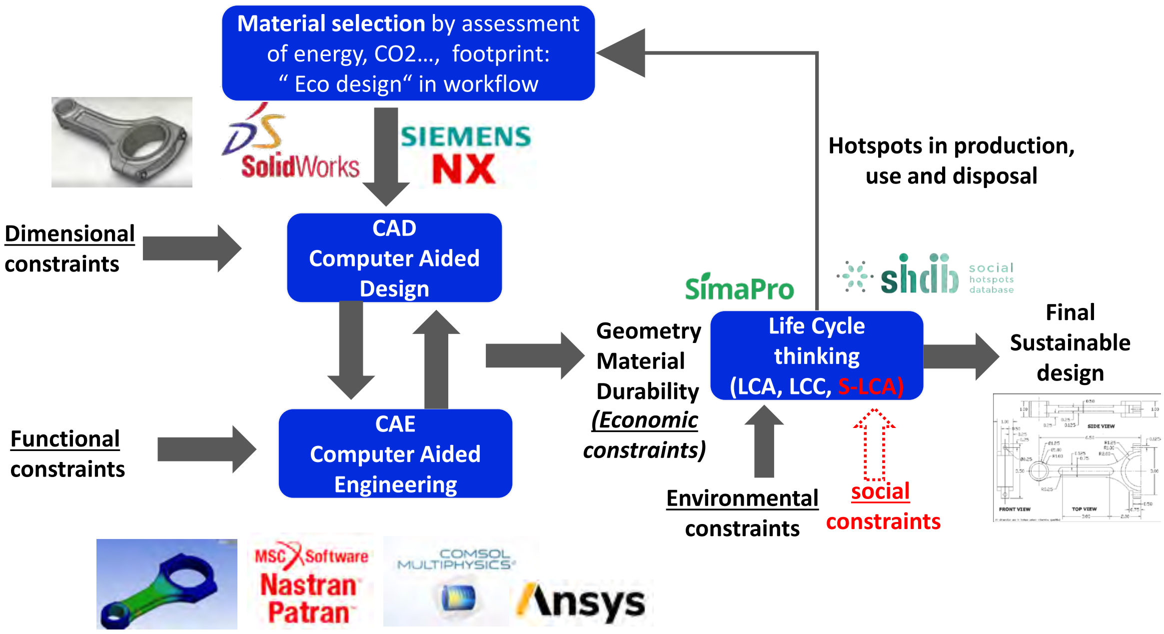


*Figure 26* - **Example of sustainable design of a product with extended workflow: the digital prototype is optimized towards environmental footprint with the help of SSbD tools supporting "Materials and process selection"** ***(source Tekniker)***

The most prominent feature of SSbD software tools is Materials Selection: Making evidence-based decisions on the choice of sustainable materials. The latest SSbD tools can provide values for the product's or component's materials for:

- Carbon footprint
- Climate impact (Ecoinvent metrics)
- Energy consumption: at raw materials level, including embedded energy
- Manufacturing energy consumption
- Energy consumption during useful life
- Water consumption
- Air and other resources
- Screening against Restricted Substances (eg. Critical or harmful materials)

The SSbD tool handles trade-offs between the virtual prototypes' performance, eco parameters, and costs; or between the different eco parameters. In many cases, the parameter "% recyclate used" can also be provided.

A second group of important SSbD properties of a newly designed product include

- Product design fit for Circular Economy
- Reduced packaging
- Product design supporting easy recycling
- Repair-friendly design
- Design for (partly) re-use, re-furbishing
- Enable recovery of valuable materials
- End of Life (EoL) concept

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Virtual prototypes can support and enable answers to these challenges, but today it is mostly the engineering teams that make the necessary design decisions at this stage. Large enterprises provide internal guidebooks on CE-friendly design for their engineers and development teams; one route to CE is modular design. Concept "many identical parts" beneficial for re-use.

One of the methods that can be used to assess sustainability at the materials design phase is to carry out appropriate accelerated tests at the level of the materials design (e.g., fatigue, tribological tests, ageing) to assess material degradation behaviour simulating the working conditions during the use in the application. This information can be used to select and improve the materials, surface treatments, lubricants, increasing lifetime, guarantee during use, while reducing maintenance costs. An example of the inclusion of materials data properties, durability and performance at the design phase is shown in Figure 27.

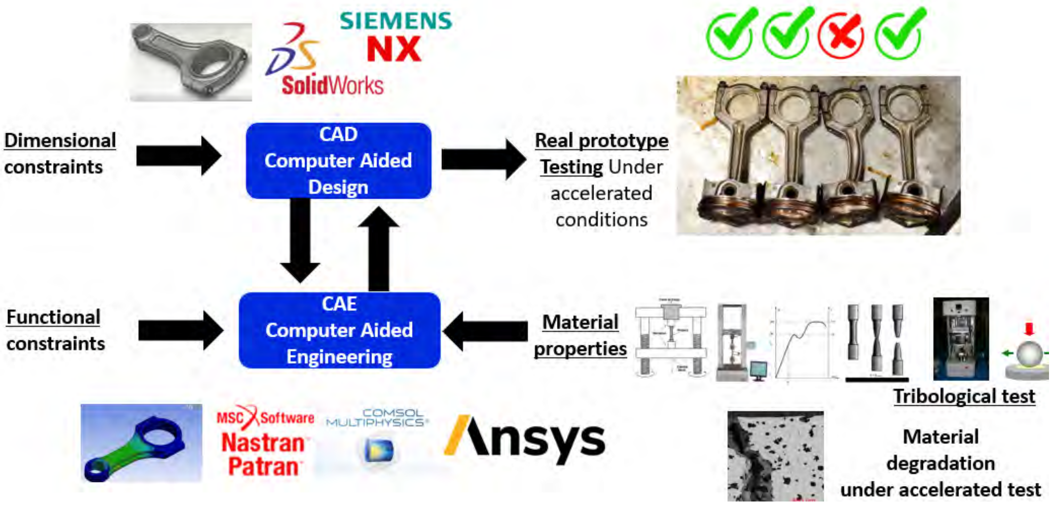


*Figure 27 - Inclusion of materials data properties, durability, and performance at design phase (source Tekniker)*

### 3.6.2.2 Needs of reliable data

In order to compute eco impacts and footprints, the virtual-prototype-based SSbD software (SW) tools require reliable materials and process data. Materials data are fundamental but also can include sensitive information. General access to public materials data bases do not cover all material classes and specifics. Especially for advanced materials, physical, chemical, environmental, or cost data is often proprietary and protected know-how for in-house use only. Commercially available eco data of materials come from:

- Data bases of the SW providers. Example: ANSYS Materials Universe™ - 4.000 commercially available materials (also processes) with access to environmental data; Global Polymer Additives – over 15.000
- Dedicated materials data bases considering environmental aspect, like Ecoinvent

The Advanced Materials Initiative AMI2030 [108] is currently working on Roadmap and Strategic R&I Agenda for the materials ecosystem of Europe. An essential part of AMI2030 is the merging of computational and experimental material science with data science: Materials digitization. Under this umbrella, the need of sharing of environmental data of materials, old and new, has been

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highlighted. Interoperability of data needs to be assessed as highlighted by AMI2030 WG1 stakeholders.

### 3.6.2.3 *Inclusion of sustainability modules into engineering software SSbD Software vendors*

Most of the leading Computer Aided Engineering (CAE) software (SW) providers offer sustainability modules that compute the environmental parameters of a product under development.

- **ANSYS GRANTA**: the ANSYS CAE products in connection with the appropriate data base provide $CO_2$, energy, and resources information; materials selection with Ashby maps Ansys | Engineering Simulation Software [121]
- **ALTAIR:** e.g., sustainability by light-weight design; sustainable building practices Altair Simulation 2022 [122]
- **Siemens NX:** sustainability enhancement by use of Digital Twin [123]
- **Solid Works:** Module SUSTAINABITILY with environmental impact and interactive dashboard for $CO_2$, energy (SOLIDWORKS Sustainability - 2022 - SOLIDWORKS Help) [124]

### 3.6.2.4 *SSbD tools at work in digital prototyping: The project PLEIADES*

The design, development, and prototyping of a complex product like a gas turbine requires the simultaneous handling of thousands of parts and subcomponents. The list of specifications and performance requirements is long. In the EU-sponsored project PLEIADES [125], a collaborative project within Clean Sky 2 (2016-2020), additional targets were set for the developers: besides the requirements of performance and cost, the digital prototypes were designed with minimal environmental footprint. Energy, $CO_2$, and material resources were considered. Rolls-Royce aerospace teamed up with a consortium including. ANSYS, with the objective of 'Sustainable and Green Engines'. For instance, materials selection for critical components was done interactively on "digital prototype" level, using environmental footprint data of alternative solutions. By "playing" with various options of materials, processes, and designs, the trade-offs of different solutions could be compared. While the actual results of this work are confidential and proprietary, the design principles for sustainable products have pilot character: One of the aims of PLEIADES was to develop industry-focused **eco-design tools** that support real engineering workflows, thereby supporting engineers to make better decisions and assure sustainability.

Citations from project report: "*Over four years, from August 2016 to December 2020, the Ansys Materials team analysed, developed, and tested a workflow for industrial eco design to evaluate the environmental and sustainability impacts of aircraft components during the concept design phase. Rolls-Royce provided in-house specifications, material, and process data that were stored in the Ansys Granta MI Enterprise materials information management software suite*."

"*Rolls-Royce was very pleased with the work produced by the Ansys-led consortium as part of the CleanSky 2 PLEIADES program to build a solution for integrating eco-design best practices within aerospace engineering workflows,"* says Amandeep Singh Mhay, Engineering Specialist of Materials Data at Rolls-Royce [119].

This EU project is one of the very rare case studies with successful implementation of SSbD tools in the workflow of complex product development. The fact that it took four years to achieve the project objectives (integrating eco design in the workflow) makes it transparent how much work


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still needs to be done. IRISS will offer to share SSbD case studies and best practices across all industry sectors addressed by the project.

### 3.6.3 Sustainability and tribology, Green Tribology Principles (GTP)

Sustainability has become a topic of critical importance in the last decade. Technology plays a significant role in the battle against climate change to save our planet. The development of new technologies may lower pollution, reduce raw material exploitation, and improve efficiency. Due to its intrinsic trans-sectorial nature, tribology has drawn the attention of the supporters of sustainability. Tribology is the science and engineering of interacting surfaces in relative motion. It includes the study and application of the principles of friction, lubrication and wear. Tribology affects the efficiency of innumerable fields, e.g., automotive, industry, biomedical, and aerospace, among others; its contribution to sustainable development may be consistent and different strategies may be employed. This discipline allows the environmental, economic, and social impacts to be decreased in a wide range of applications following the same strategies ([130],[131]).

Green Tribology is a novel area of science and technology related to sustainability and tribology, pursuing the efforts of the scientific community for a sustainable future through the optimization of the tribosystems. It can be viewed as an interdisciplinary topic which includes classical tribology, chemical engineering, materials science, energy, green lubrication, and environmental sciences, with the purpose of improving the efficiency of processes (cleaner production) and machine components by controlling the friction, reducing the wear and dangerous pollutions, to protect the environment and improve the quality of life.

Recent investigations report that "[…] *by applying for advances in Green Tribology in terms of new surfaces, materials and lubrication technologies, the total global energy loss in tribological systems could be decreased by 18% in the next 8 years and up to 40% in the next 15 years. An additional advantage of environmentally friendly Green Tribology is a significant reduction in carbon dioxide emissions and economic costs*" [132].

Green tribology can be viewed in the broader context of two other 'green' areas: green engineering and green chemistry. The US Environmental Protection Agency defines green engineering as "*the design, commercialization, and use of processes and products in a way that reduces pollution, promotes sustainability, and minimizes risk to human health and the environment without sacrificing economic viability and efficiency*" [133].

Another related area is green chemistry which is defined by the US Environmental protection Agency as "*the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal*" [134].

In 2010, Nosonovsky and Bhushan [131] published a pioneering work formulating the 12 principles of green tribology based on the 12 principles of green chemistry [135] and the 12 principles of green engineering [136]. These 12 Green Tribology principles (GTPs) became the basis of the sustainable aspects of this discipline. Table 29 summarizes the green chemistry principles and green engineering principles.


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*Table 29 - Green chemistry and green engineering principles (Table based on [135] and [136])*

| Green Chemistry Principles [135] | Green Engineering Principles* [136] |
|---|---|
| 1. It is better to prevent waste than to treat or clean up waste after it is formed. | 1. Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous. |
| 2. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product | 2. It is better to prevent waste than to treat or clean up waste after it is formed |
| 3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment. | 3. Separation and purification operations should be designed to minimize energy consumption and material use |
| 4. Chemical products should be designed to preserve efficacy of function while reducing toxicity. | 4. Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency |
| 5. The use of auxiliary substances should be made unnecessary wherever possible and innocuous when used | 5. Products, processes, and systems should be "output pulled" rather than "input pushed" using energy and materials. |
| 6. Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure | 6. Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition |
| 7. A raw material of feedstock should be renewable rather than depleting wherever technically and economically practicable | 7. Targeted durability, not immortality, should be a design goal. |
| 8. Unnecessary derivatization should be avoided whenever possible | 8. Design for unnecessary capacity or capability solutions should be considered a design flaw |
| 9. Catalytic reagents are superior to stoichiometric reagents. | 9. Material diversity in multicomponent products should be minimized to promote disassembly and value retention |
| 10. Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products | 10. Design of products, processes, and systems must include integration and interconnectivity with available energy and material flows. |
| 11. Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances | 11. Products, processes, and systems should be designed for performance in a commercial "after-life." |
| 12. Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires | 12. Material and energy inputs should be renewable rather than depleting. |

** As proposed by Anastas and Zimmerman in March 2003 [136]. In May of the same year, the participants discussed and modified the principles during the Green Engineering: Defining the Principles conference, reducing the number to nine [137].*

The 12 principles of green tribology proposed by Nosonovsky and Bhushan [131] were as follows:

**1- Minimization of heat and energy dissipation**. (Friction is the primary source of energy dissipation). Most of the energy dissipated by friction is converted into heat and leads to heat pollution of the atmosphere and the environment. The control of friction and friction minimization, which leads to both energy conservation and prevention of damage to the environment owing to heat pollution, is a primary task of tribology.

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**2- Minimization of wear** is the second most important task of tribology that has relevance to green tribology. In most industrial applications, wear is undesirable. It limits the lifetime of components and therefore creates the need for their recycling. Wear can also lead to catastrophic failure. In addition, wear creates debris and particles that contaminate the environment and can be hazardous for humans in certain situations. For example, wear debris generated after human joint-replacement surgery is the primary source of long-term complications in patients.

**3- Reduction or complete elimination of lubrication and self-lubrication**. Lubrication is a focus of tribology since it leads to the reduction of friction and wear. However, lubrication can also lead to environmental hazards. It is desirable to reduce lubrication or achieve the self-lubricating regime, where no external supply of lubrication is required.

**4- Natural lubrication** (e.g., vegetable-oil-based) should be used, when possible, since it is usually environmentally friendly.

**5- Biodegradable lubrication** is especially recommended when there is a risk of lubricant losses, to avoid environmental contamination.

**6- Sustainable chemistry and green engineering principles** should be used for the manufacturing of new components for tribological applications, coatings, and lubricant.

7-**Biomimetic approaches** should be used whenever possible. These include biomimetic surfaces, materials, and other biomimetic and bioinspired approaches since they tend to be smart and more ecologically friendly.

**8-Surface texturing** should be applied to control surface properties. Conventional engineered surfaces have random roughness, and the randomness is the factor that makes it extremely difficult to overcome friction and wear. On the other hand, many biological functional surfaces have complex structures with hierarchical roughness, which defines their properties. Surface texturing provides a way to control many surface properties relevant to making tribo-systems more ecologically friendly.

**9- Environmental implications of coatings** and other methods of surface modification (e.g., texturing, shot penning) should be investigated to avoid using or generating harmful products during processing or during product use (e.g., through particles release).

**10- Design for degradation of surfaces**, coatings and tribological components. Like green chemistry applications, the ultimate degradation/ utilization should be taken into consideration during design phase.

**11- Real-time monitoring**, analysis, and control of tribological systems during their operation should be implemented to prevent the formation of wear debris or hazardous substances. Online sensors can be used to monitor wear, ageing, corrosion, and component health.

**12- Sustainable energy applications** (should become the priority of the tribological design as well as engineering design in general)

More recently in 2022 Freschi et al. [130] have reviewed the 12 principles of green tribology to fathom the developed research related to sustainability and tribology. They suggested different approaches and innovations as references, pursuing the efforts of the scientific community for a sustainable future through the contribution also of tribosystems. Figure 28 shows the relations and

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influences of green chemistry principles and the green engineering principles on the green tribology principles proposed.

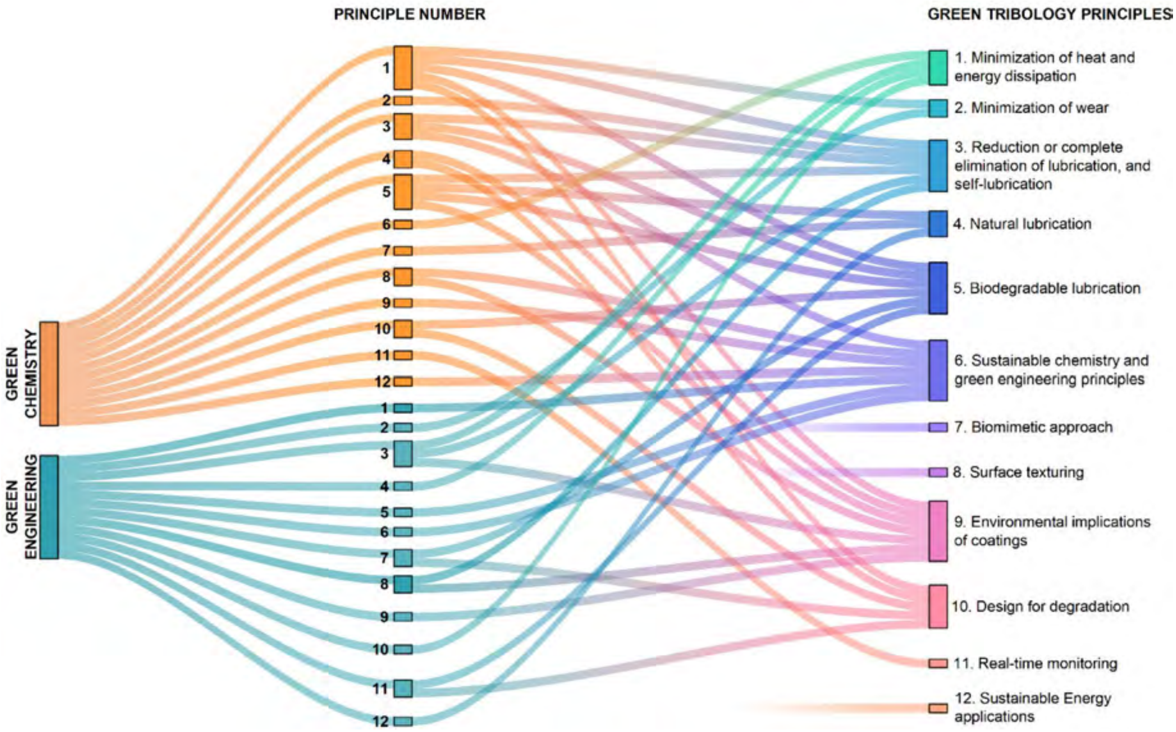


*Figure 28 - Sankey diagram of the proposed relations and influences of the green chemistry principle and the green engineering principles on the green tribology principles (Figure taken from [130])*

Green tribology principles fall within the green path previously traced by the green chemistry and green engineering principles. Besides providing sustainable strategies for tribological systems, the added value indicates a crucial field where tribology can strongly make a difference, that is, renewable energy production.

However, it is important to highlight the difference in the concepts of “Green” and “Sustainable”. Although they are directly linked, Sustainability offers a holistic approach including other aspects apart from the “Green” principles. Further analysis on the concepts of “Green Chemistry” and “Sustainable Chemistry” are provided in IRISS preliminary report PR1.4.

### 3.6.4 Laboratory tests and modelling

Usually, before deploying components in service, lab-scale tests are carried out to predict the lifetime of such components in services. Different labs (i.e., research groups) approach this in different ways depending on the availability of resources and expertise. These physical experiments help to identify a material/material and lubrication system that are appropriate to be used in each system with increased efficiency. Though lab-scale tests are most widely used and offer reliable results, it is not free from some flip sides [138]. For examples, lab-scale tests requires both equipment, experimental setup, and manpower. Frequently, lab-scale tests are performed in accelerated mode and small-scale which may risk overlooking time or size effects. To overcome


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such limitations, it is important to reproduce the failure mechanism at laboratory scale, and to combine experiments with computer-based simulations.

To simulate today's complex tribo-contact scenarios, a methodological breakdown of a complex design problem into simpler sub-problems is essential to achieve acceptable simulation outcomes. This also helps to manage iterative, hierarchical systems within given computational power. Kurdi et al. [139] reviewed recent trends of simulation practices in tribology to model tribo-contact scenario and LCA with the help of simulation. Together they analysed the pros and cons of both physical experiments and simulation approaches, their interdependencies and how one approach can benefit the other. An extension of the simulation approach, together with experimental data, can lead towards LCA of components which will provide us with a better understanding of the efficient usage of limited resources and conservation of both energy and material resources.

For a given tribo-system, there are several individual components termed as tribo-elements. Each of the tribo-elements performs its functions in a synchronized manner to operate the system, which involves the transfer of energy and material. Transfer of energy and material increases wear and causes poor performance of the system, which can be minimized by applying proper lubrication and/or selection of materials such as coatings. This will, in turn, lead to conservation of material and energy.

In LCA of tribology lubrication, energy conservation, environmental conservation, and recycling of tribo-elements form the base of a rectangular pyramid that leads to the conservation of energy at the apex of the pyramid [140][141]. Pyramidical representation of these interrelated factors is also known as life cycle tribology (LCT). Thus, by careful analysis of the lifespan of each tribo-elements, innovative and creative tribo-techniques can be used in design to extend the lifespan of a given tribo-system.

The LCA of any tribo-system is directly and indirectly influenced by several participating factors such as the wear-resistant behavior of the system, lubricating behavior, extending life span by lubricating and re-furbishing the components [142]. These factors are usually built into any tribo-system. The transformation of material and energy consumption during tribological interaction defines the performance and life cycle of that system.

Controlling friction and, therefore, wear, has gained a lot of researchers' attention, as it reduces carbon footprints and greenhouse gas emission without altering normal operational conditions of a running system. This leads to reduced carbon emissions in terms of monetary and ecological factors, which are the key to tribological sustainability.

Tribologists should work together by combining the resources of experimental, simulation, and LCA towards the growth and implementation of sustainable tribology not only for research purposes, but also from commercial applications point of view.

In the field of tribology, it is worth mentioning the activities carried out with the EU project i-TRIBOMAT[5] , which aims to establish a Sustainable Open Innovation Test Bed for intelligent Characterisation, paving the way for new collaborative approaches in sharing infrastructure, competences, and data for the benefit of the European industry, in order to support industrial innovation, to improve the efficiency of materials up-scaling and transform new materials into world-wide competitive products. i-TRIBOMAT services combine conventional laboratory level tribotests, and experimental surface characterization techniques with Artificial Intelligence tools,

[5] https://www.i-tribomat.eu

such as database searches, computer simulation and modelling, which allow up-scaling laboratory test results to infer friction and wear behaviour of real components.

**Corrosion**

Another important issue to consider when selecting a material or designing a component is the corrosion resistance properties, which can greatly influence the performance and durability of a product. Corrosion has a huge economic, environmental and sustainability impact on virtually all aspects of construction materials. The annual cost of corrosion worldwide was estimated to exceed US$2.5 trillion in 2016, which translates to 3 to 4% of the Gross Domestic Product (GDP) of industrialized countries according to NACE IMPACT study report [143]. Thus, the economic and environmental impact of corrosion is significant. The corrosion of metallic materials involves their dissolution and formation of corrosion products which, depending on their composition, can have elements that could lead to the pollution of waters, agricultural soils, plants, animals, aquatic life, and human health [144][145][146][147]

In addition to causing severe environmental damage and threats to public safety, corrosion disrupts operations and requires extensive repair and replacement of failed assets. The replacement of corrosion-deteriorated materials implies material extraction from nature, with its subsequent environmental damage [148][149][150][151]

The goal of the fight against corrosion is to guarantee the predetermined life of a structure, component, or device at minimum cost, considering both the investment and maintenance costs. The solution must also be compatible with environmental regulations, allowing recycling of components at the end of their life. To reduce the huge cost and the environmental impact of corrosion and enhance the sustainability of materials used in different industrial applications, available corrosion control practices such as proper material design and selection, the use of corrosion inhibitors, coatings, cathodic protection etc., are recommended. These preventive measurements could lead to savings of between 15 and 35% of the cost of corrosion [152] , which translates to between US$375 and $875 billion annually. Corrosion mitigation and control is still one of the burning issues for researchers in industries and academia. Some progress and advancements in the fight against corrosion, in terms of corrosion resistant material development, corrosion mitigation strategies and monitoring are being carried out. Furthermore, great effort has been made in the development of advanced materials for corrosion protection, cathodic protection, corrosion inhibitors, advanced coating, computational corrosion science, artificial intelligence, and machine learning in corrosion research.

To avoid or prevent unpredictable failures, coatings have been successfully used to minimize corrosion losses in steel structures. However, the environmental impact of the composition and production methods of coatings should also be considered. The coating industry is nowadays trying to replace toxic paint components such as lead or copper by more environmentally friendly elements, as well as extending the lifetime of the coatings. This will lead to more sustainable protective solutions that could lower the dissolution of paints and the release of its composing elements, while protecting the metallic materials. Furthermore, an enlarged duration of a coating/metal pair, will constitute the reduction of maintenance and repair operations and their relative costs and impact both in the production of new materials and the pollution that those operations could produce.

Corrosion tests can be performed for evaluating the behavior of materials and coatings under different environmental conditions, performing accelerated degradation tests such as the salt spray test (ISO 9227/ASTM B117) or under specific temperature, humidity, or condensation conditions.

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Tests can be carried out in a single climatic chamber following a specific standard (ISO 2812, ISO 6270, ISO 12944, ISO 16474, etc.) or using custom test cycles combining several chambers order to reproduce specific working conditions depending on the environment of the materials/coatings under study. The corrosion behavior can be evaluated with the traditional salt spray tests (ISO9227/ASTM B117) as well as by means of electrochemical corrosion tests under different techniques as electrochemical noise, linear and cyclic potentiodynamic polarization, and/or impedance tests. The corrosion rate can be determined using potentiostatic measurements and/or impedance measurements in different corrosive atmospheres/media. Electrochemical noise and impedance measurements can be used if needed as a non-destructive measurement to determine the corrosion mechanism. All these tests can be complemented with different analytical techniques such as Inductively Coupled Plasma (ICP), etc.

# 4. Survey on the mapping of Safe and Sustainable by Design (SSbD) initiatives

## 4.1 Introduction

Within WP1, an online survey was designed to collect information from IRISS partners and stakeholders, who were asked to participate via email. A transcript of the survey is included in Annex B of PR1.5.

This chapter maps industrial practice, research, and education in terms of sustainability based on the WP1 survey replies. In total, in total, **87 valid responses** were recorded. The replies within the sustainability block are analysed in the specific section of this preliminary report PR1.2). Safety blocks discussion is included in PR1.1, LCA block is included in PR1.3, circular economy is included in PR1.4 and Skills aspects are included in PR1.5.

The background of the responding organizations is shown in Figure 30 and Figure 31. Organizations from 19 countries responded to the survey, including:

- companies (n = 37; 43%),
- research and technology organizations (n = 22; 25%),
- academic institutions such as universities (n = 13; 15%),
- business or industry associations (n = 4, 5%),
- public authority individual citizens (n = 2; 2%),
- clusters/platforms/networks (n = 2; 2%),
- other non-governmental organizations (NGOs) (n = 2; 2%),
- and other organization types that were not further specified (n = 5; 6%).

The responding companies were mostly large companies (n = 25; 67%), followed by small and medium enterprises (SMEs) (n = 11; 30%) and start-ups (n = 1; 3%).

The responders are working in a wide range of sectors with the chemical sector (n = 37; 43%) being the most represented in this survey (Figure 31).

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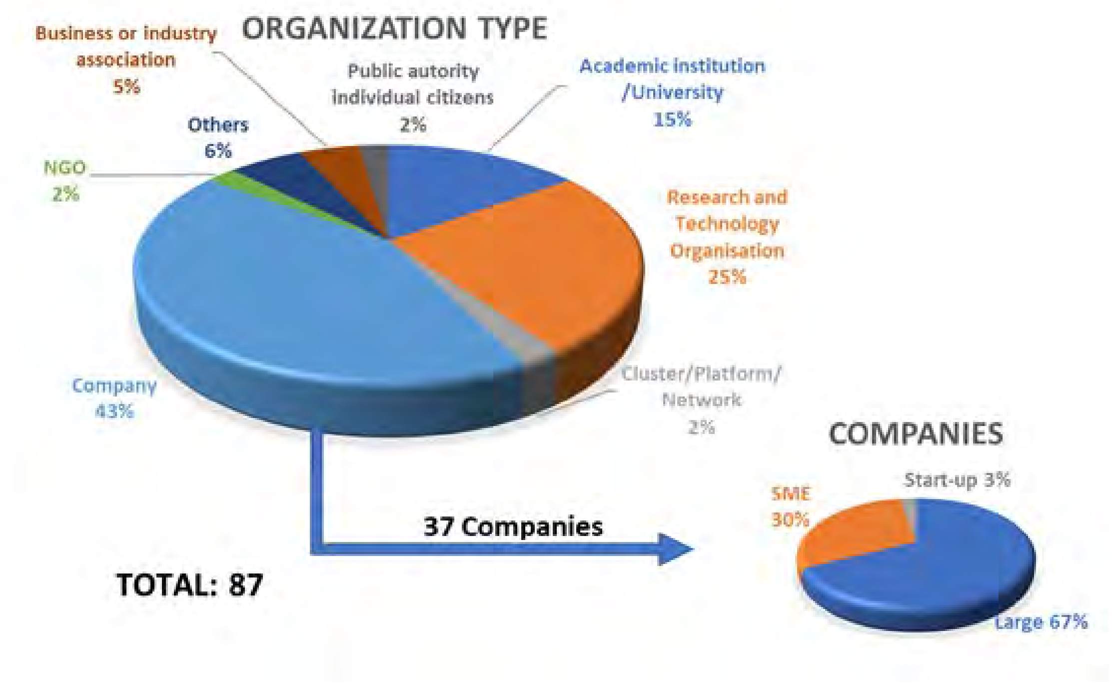


*Figure 29-Background of the respondents by organization type*

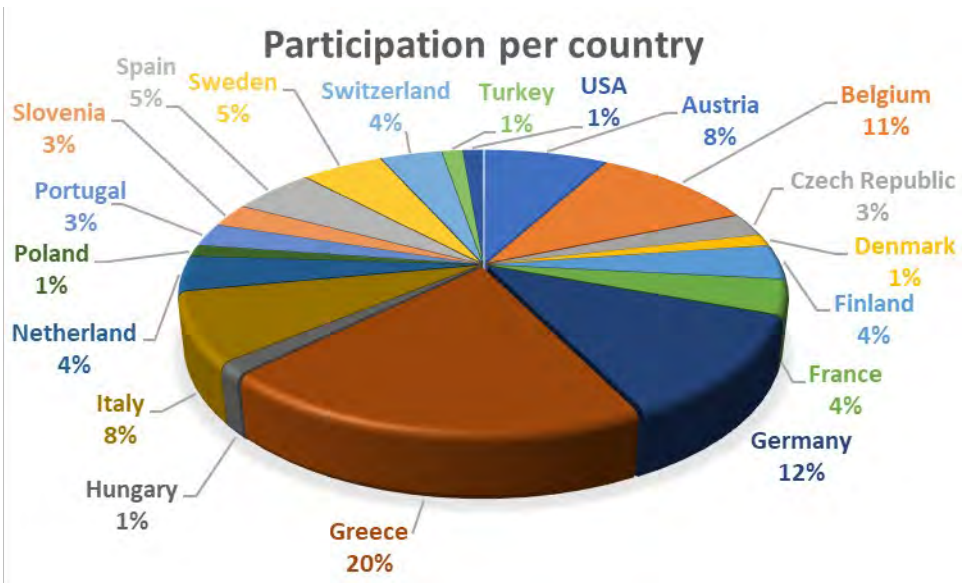


*Figure 30 - Background of the respondents - by country*

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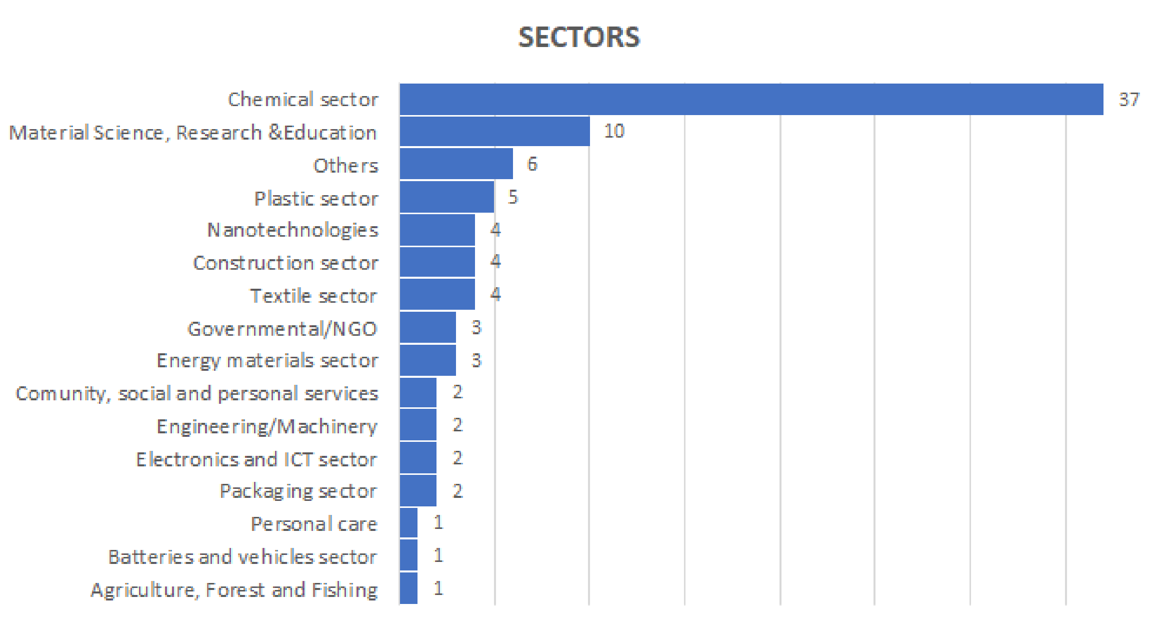


*Figure 31 - Background of the respondents bySectors*

## 4.2 Survey on the consideration of SSbD aspects

**General remarks on the survey**

The survey includes a general question (**question 9**, idem 12) regarding the consideration of safety and sustainability aspects in development of materials, products, and processes. Table 30 summarizes the results obtained. Out the total respondents, 82% (n=71) consider SSbD aspects in the development of chemicals, materials, products, or processes (Figure 32). This percentage is even higher for the companies (92%).

*Table 30 - Consideration of SSbD aspects*

| Consideration of SSbD aspects | Total respondents | | Companies | |
|---|---|---|---|---|
| | number | % | number | % |
| Not applicable | 14 | 16% | 3 | 8% |
| Yes | 71 | 82% | 34 | 92% |
| No | 2 | 2% | 0 | 0% |
| **TOTAL** | **87** | | **37** | |

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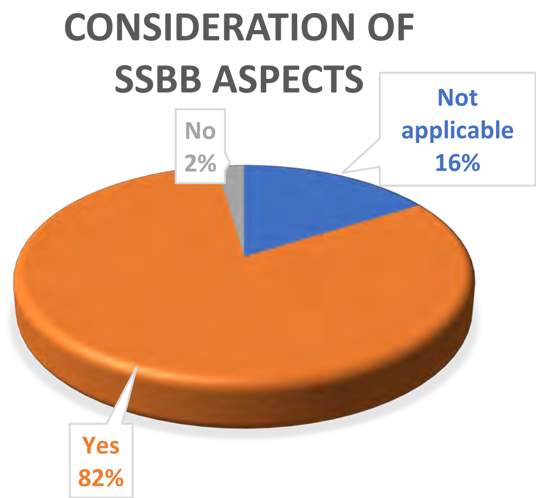


*Figure 32 - Consideration of SSbD aspects.*

Most of the "not applicable" entries come from academia, research organisations, and public authorities. Apparently, the question 9 (idem 12) was interpreted, by the participants, as targeting medium to high level of product Technology Readiness, which is clearly more company-oriented than academia-prone. So, a verdict "not applicable" does not GENERALLY refer to a lack of interest in SSbD, leaving much room for SSbD engagement in the future, or outside current product and materials generation or development. This is supported by the observation that two thirds of the "not applicable" participants contributed to at least some SSbD plans (Question 20) and/or have (and use) engineering tools for sustainability (Questions 23-26)

This shows that well over 90% of the companies in this survey are very conscious about safety and sustainability. However, we know that the survey is not representative for Europe. Just a few percent of the companies and stakeholder contacted, fulfilled the survey, who, therefore, already showed an interest in SSbD. Nevertheless, the survey gives us a unique view on the many aspects and facets of SSbD, within this slightly positively biased group of interested participants.

### What did the stakeholders say about SSbD relevance in the value chain?

**Question 10** (idem 13) invited the participants to give some details of HOW safety and sustainability in the development of materials, products, or process was anchored in the stakeholders' operations. There is a wide spread of answers; some responses were rather short – examples:

- "We support on the conceptualization of SSbD-approaches and along the implementation of them."
- "We try to make as sustainable choices as possible in development of products and processes"
- "We have a committee devoted to this matter that even regulates the ongoing research"
- "Production of sustainable materials using sustainable raw materials"

No less than 15 participants wrote a detailed elaboration of SSbD relevance and implementation, with 50 – 250 words each: (mostly from companies, but also academia, research, and associations). Here are some highlights of these detailed statements:

- "Implementing in silico methodology integrating Multiscale Modelling and Machine Learning methods and virtual screening"


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- “Company uses stage gate model for the new product development. Successful projects must demonstrate both improved sustainability and business benefits at each decision-gate”
- “Rigorous risk assessments of all materials and processing steps”
- “We have 9 corporate sustainability goals including an Innovating Safe and Sustainable by Design goal”
- “The basis for successful product stewardship is regulatory compliance to existing legislation, proactive anticipation of future requirements and a deep understanding of the impacts on our products and services of market developments to ensure service-oriented customer relations.”
- “Within our Business Development Processes, we address safety-related aspects via a comprehensive regulatory and compliance feasibility assessment and regulatory action plan: a methodology called "Design for Sustainability" (DfS) was initiated as part of the “Product Development Process”
- “Sustainability is a core element in the 2030+ Strategy of the company”
- “We have targets on products with LCA (environmental and social) to cover 100% percent of products with LCA assessment to be achieved by 2025 and Social value assessment by 2030.”
- “In trying to provide products of superior consumer value, we strive to continuously minimize risk and improve the environmental footprint of our products.”
- “We develop frameworks towards the practical application of SSbD and test these on case studies”

The following questions addressed companies only:

## Sustainability and corporate strategy

In **Question 14**, the participating companies were asked if the in-house strategic missions and visions of the enterprises contained an explicit, written Sustainability strategy and KPIs and definite goals with SSbD objectives. Fully in line with the results of the previous questions, a clear majority of 20 companies gave high ratings (7 -10 points on a scale of 10) to this question, signaling that these enterprises accept their responsibility for people and planet, and have integrated the ethics of sustainability into their corporate strategy. It might be useful to conduct further, broad-based studies into the commonality of corporate strategy guidelines for SSbD.

## Clients and customers

**Question 15** puts the focus on sustainability elements in the business process, as demanded **by clients and customers**. Are sustainability indicators or LCA data included in the product specifications by the customer? Given the limited number of companies in the survey, the clear answer from the participating enterprises is: Yes, our customers require SSbD product data; with a majority of more than 60% of respondents giving a score of 7 to 10 points (on a scale of 10) for this question. Only a very small number of respondents says, “no customer requirements”.

The survey results support the general view that demand for safe and sustainable by design (SSbD) products has increased significantly in recent years among both private and commercial customers, and these latter customers increasingly demand sustainability data with specifications and targets. The survey results are an indicator that the increased awareness of the importance of sustainability and the need to protect our environment is being translated into business processes and value chains.

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**Alternative business models**

Alternative business models supporting SSbD in a circular economy (**Question 16 and 17**) are being explored only by a small, diverse group of seven companies – in specific small market segments; partly service oriented.

**Take-home message from company-specific questions:**

Summarising the company-specific questions of the inquiry, it can be stated that the concept of safe and sustainable by design (SSbD) is becoming an integral part of corporate day-to-day business- at least for most of the participating enterprises. This topic is also becoming increasingly prevalent within corporate strategies and targets, as businesses AND THEIR CUSTOMERS are becoming more socially and environmentally conscious.

## 4.3 Survey on the safe-and-Sustainable by Design (SSbD) principles to be applied in the design

The survey included three questions regarding the application of SSbD guiding design principles in practice (Table 31).

*Table 31 - Summary of questions related to the application of SSbD design principles.*

| SURVEY SECTION – SSbD Principles | | | |
|---|---|---|---|
| Question number | Question | Number of respondents | |
| | | Total | Companies |
| 20 | Does your company/institution/R&I project consider or intend to consider any of these SSbD principles during the design phase of a material, product, or process? | 77 | 35 |
| 21 | Other sustainable principles considered by your company/institution during the design phase of the development of a material, product, or process. | 34 | 13 |
| 22 | For principles that you are not considering at the moment: Why are you not considering these principles? (e.g., missing data/information for certain materials; missing know-how, experience, or lack of education) | 43 | 20 |

Question 20 was a multiple-choice question listing all eight SSbD design principles as proposed by the JRC framework as well as four 'subprinciples' (Table 32). This addition was made to get more information on specific design aspects (i.e., critical raw materials, used volumes of solvents and water, durability, and recyclability).

The aspects of critical raw materials (SSbD1.1) and solvent amount (SSbD1.2) are related to the design principle of 'material efficiency' and are therefore listed as subprinciples to SSbD1. The principle 'design to last' (SSbD8.1) is connected to the durability of the chemical/material and therefore relates to the design principles 'design for end-of-life' and 'consider the whole life cycle'.

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It was listed as a subprinciple of SSbD8. The aspect of recyclability (SSbD8.2) also related to both design principles ‘design for end-of-life’ and ‘consider the whole life cycle’ and was listed as a subprinciple of SSbD8 as well.

*Table 32 - SSbD Principles considered in the survey (JRC framework proposed principles +sub-principles*)*

| |
|---|
| **SSBD1-Material efficiency** (*Pursuing the incorporation of all the chemicals/materials used in a process into the final product or full recovery inside the process, thereby reducing the use of raw materials and the generation of waste*) |
| ***SSBD1.1-** *Identify occurrence of use of critical raw material, towards minimizing or substituting them* |
| ***SSBD1.1-** Minimize the volume of solvents and water in the processes of manufacturing, production or use |
| **SSBD2-**Minimize the use of hazardous chemicals/materials |
| **SSBD3-**Design for energy efficiency (minimise the energy used during the chemical material production and along the supply chain) |
| **SSBD4-**Use renewable sources |
| **SSBD5-**Prevent and avoid hazardous emissions |
| **SSBD6-**Reduce exposure to hazardous substances |
| **SSBD7-**Design for end of life (*Design chemicals/materials in a way that, once they have fulfilled their function, they break down into products that do not pose any risk to the environment/humans.*<br>*Design for preventing the hindrance of reuse, waste collection, sorting and recycling/upcycling*) |
| **SSBD8-**Consider the whole Life Cycle (apply the other design principles thinking through the entire life cycle, from supply chain to the end-of-life in the final product) |
| ***SSBD8.1**--Durability-by-design (predict materials durability at the design phase of the product) |
| ***SSBD8.2**-Efficient recyclability of (raw) materials and/or products |

The application of the SSbD design principles in practice is shown in Figure 33. The highest and lowest application rates are shown for the SSbD design principles SSbD2 (n = 64; 83%) and SSbD8.1 (n = 39; 51%), respectively. It should be noted that SSbD8.1 ‘Design to last’ is highly VC specific and can (and should not!) be applied to open application products such as fragrances, pesticides, personal care products, cleaning products, or pharmaceuticals. Therefore, the lowest application rate is comprehensible.

Both human safety related design principles SSbD2 and SSbD6 as well as the environmental safety related principle SSbD5 show high application rates (n = 60 to 64; 78% to 83%). This shows that safety considerations related to the use of SVHC and the reduction of emission to the environment are widely applied in the design phase.

The other safety related design principle SSbD5 is more environmentally related (reduce/avoid emissions to the environment) and ranks fourth. SSbD1 is the most applied sustainability related design principle. The last ranked principles are SSbD7 and SSbD8.1. Both concern end-of-life considerations which seem to be much less applied in practice, compared to e.g., safety considerations.

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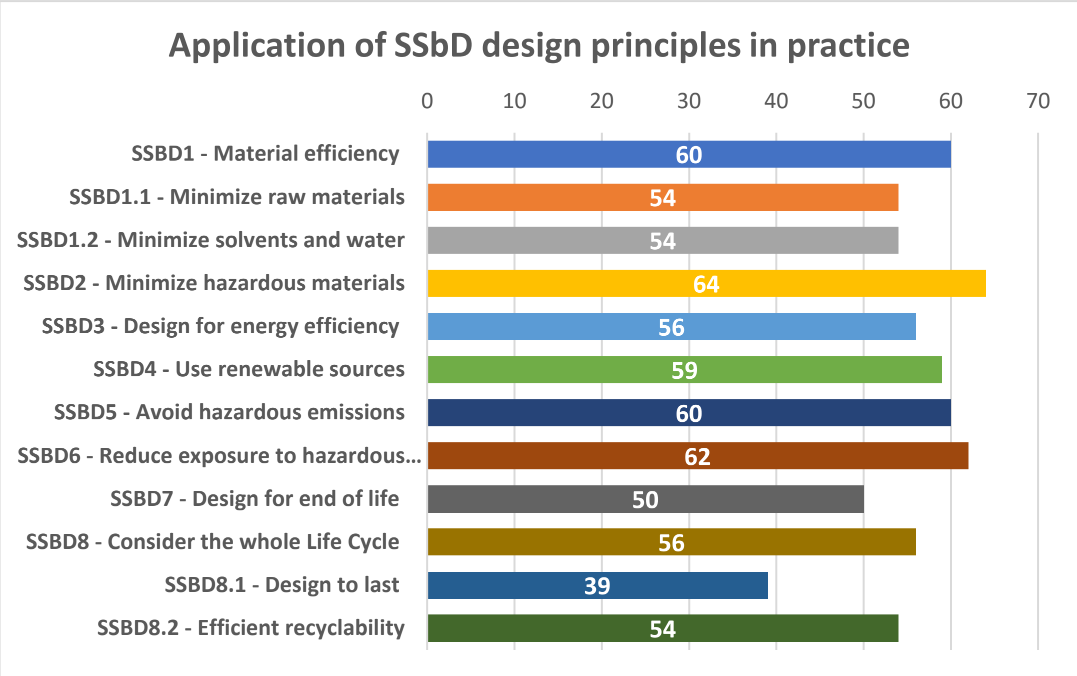


*Figure 33 - Application of SSbD design principles in practice*

The sustainability related design principles show marginally lower application rates (n = 50 to 60; 65% to 87% [excluding SSbD8.1]). It must be noted that although SSbD7 'design for end of life' is ranked second lowest, the recyclability aspect (SSbD8.2) is ranked higher (even though recyclability is an end-of-life option). It could be observed that not all respondents who selected SSbD8.1 or 8.2 also selected SSbD7 and SSbD8 – so the latter two are somewhat underrated.

In PR1.5 there is additional information about other sustainable principles and aspects considered by the respondents and the reasons for not applying all SSbD principles.

## 4.4 Survey on social dimension

This section is dedicated to analyse the **social environmental dimension** of survey on the mapping of Safe and Sustainable by design (SSbD) initiatives. Table 33 summarizes the questions of this survey section and the number of respondents obtained per question.

*Table 33 - Summary of responses in the survey section- sustainability Social Dimension: S-LCA*

| SURVEY SECTION -Sustainability Social Dimension | | | |
|---|---|---|---|
| Question number | Question | Number of respondents | |
| | | Total | Companies |
| 53 | Does your company/institution/R&I project consider or intend to consider social aspects during the design or development phase of a material, product, process, or R&D activity? | 84 | 37 |
| 54 | If yes, please indicate the aspects you consider in the social assessment. | 48 | 26 |

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| | | | |
|---|---|---|---|
| 55 | Do you use any specific database to support the social assessment? | 50 | 27 |
| 56 | If yes, please indicate | 10 | 4 |

According to the survey results the **62%** (n=54), of the responding organizations (n=87) perform or intend to perform a Social Life Cycle Assessment (S-LCA) during the design or development phase of a material, product, process (Table 34). If we focus on companies, this value is higher 76% (n=28), and this may be due to the sustainability consciousness of the companies that responded the survey as mentioned in section 4.2.

*Table 34 - Consideration of Social aspects*

| Consideration of SSbD aspects | Total respondents | | Companies | |
|---|---|---|---|---|
| | number | % | number | % |
| Yes | 54 | 62% | 28 | 76% |
| No | 33 | 38% | 9 | 24% |
| **TOTAL** | **87** | | **37** | |

From now on in this section, all the data will be referred to the **54 entities** that use or intend to use S-LCA. Figure 34 shows the percentage of respondents that consider social aspects during the design or development phase broken down into the different organization types.

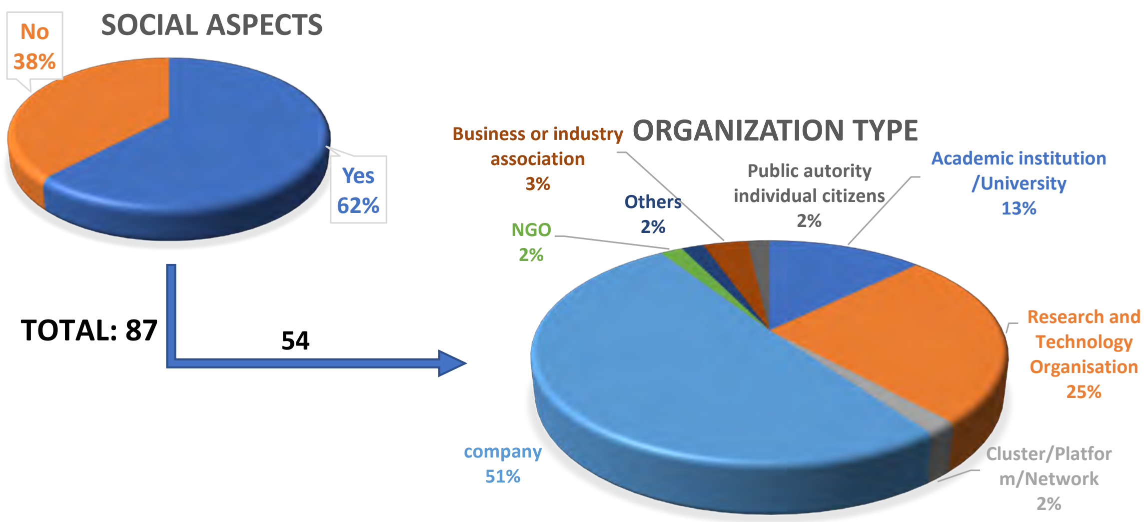


*Figure 34 - Entities that consider Social Aspects*

**Social databases**

Table 35 summaries the number of the respondents that use specialized social databases and the name of the database that they use. Only 22% of the 54 entities that consider social aspects use specialized social databases. The SHDB is used by three Research and technology organizations and

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the PSILCA by two Research and technology organization and one public authority representing Individual citizens. Three companies used their own databases (Internal database, Exiobase in combination with Stepwise method, ISO 45001).

*Table 35 - Social Databases used by the Entities interviewed*

| SOCIAL DATABASE | Number of respondents (total) | Number of companies |
|---|---|---|
| Use social database | 10 | 3 |
| SHDB | 3 | 0 |
| PSILCA | 2 | 0 |
| Others | 5 | 3 |

**Social Impact indicators**

Table 36 shows the different social impact assessment indicators, workers´ "**Health and safety" is the most popular** social indicator followed by the "equal opportunities" and consumers´ "health and safety", the other social impact indicators are considered in a percentage range between 35%-52% (these values are graphically summarised in Figure 35)

*Table 36 - Social Impact assessment indicators used by the entities interviewed*

| Impact Assessment Indicators | | Total respondents | | Companies | |
|---|---|---|---|---|---|
| | | number | % | number | % |
| Workers | Child labour | 24 | 50% | 17 | 65% |
| | Fair salary | 25 | 52% | 15 | 58% |
| | Forced labour | 21 | 44% | 16 | 62% |
| | **Health and Safety** | **42** | 88% | 21 | 81% |
| | Freedom of association and collective bargaining | 17 | 35% | 13 | 50% |
| | Working hours | 27 | 56% | 15 | 58% |
| | **Equal opportunities / discriminate** | **33** | 69% | 18 | 69% |
| Local community | Community engagement | 24 | 50% | 14 | 54% |
| | Local employment | 22 | 46% | 15 | 58% |
| Consumers | **Health and safety** | **32** | 67% | 18 | 69% |
| | Responsible communication | 23 | 48% | 16 | 62% |
| | **Total Entities** | **48** | | **26** | |

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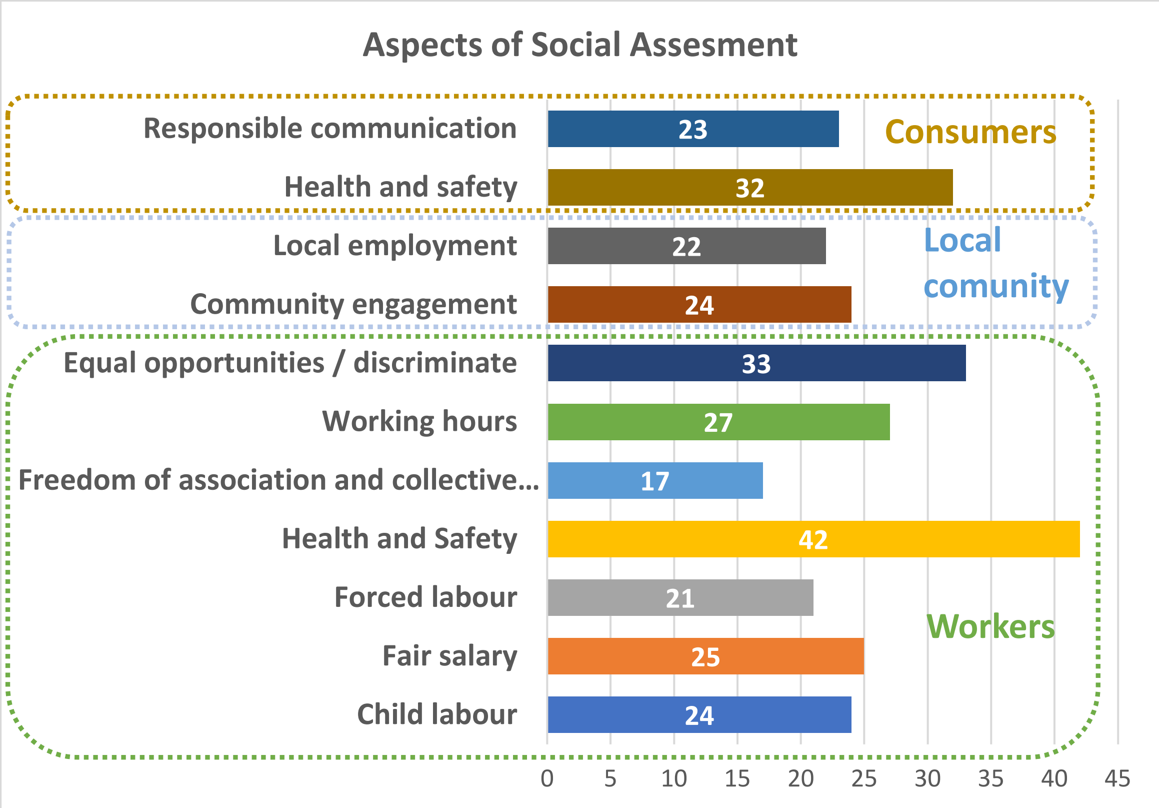


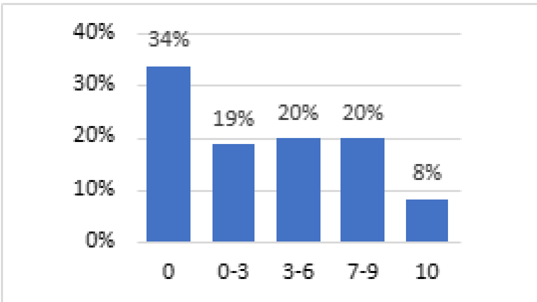

*Figure 35- Social Impact assessment indicators used by the entities interviewed*

## 4.5 Survey on sustainable engineering tools

**Original questions from the questionnaire**:

The participants were asked to give 0 to 10 points per question (10 points being the highest).

Q23. Do your modelling and simulation tools (eg CAD, FEM and others) allow for sustainability assessments and optimisation of products and components AT DESIGN STAGE?

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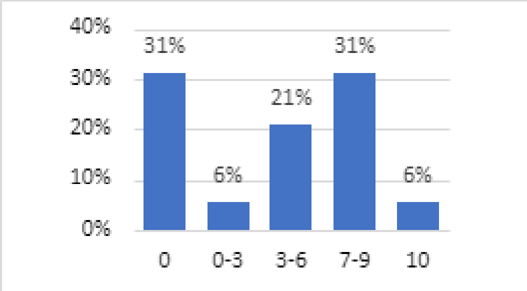
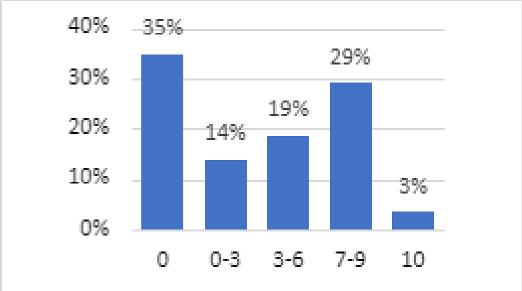
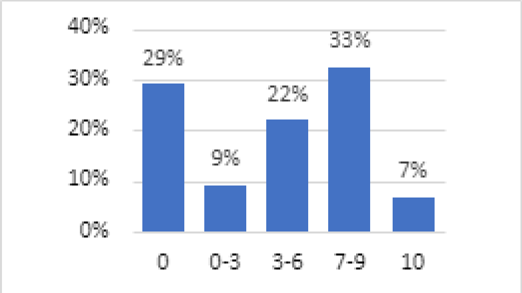
Q24. Do your design tools support Materials selection according to sustainability principles? (Non-toxic, low carbon footprint, durability, energy efficiency during processing and use, low embedded energy, low level of water or air resources, recyclability, etc.?




Q26. Do your product development tools and processes support the design of components with circular economy, elements like easy dismantling; end-of-life concept; recollection; components designed for refurbishing for second life or extended useful lifetime?




Q28. Do you apply AT DESIGN STAGE predictive design tools and accelerated experiments for predicting and optimizing the product's durability, performance, and energy consumption at maximum useful lifetime?




Questions No. 23, 24 and 28 concern SW tools, CAE and simulation functionalities extended by SSbD functionality, each highlighting a different aspect, but all looking at the implementation of technical (modelling) solutions to SSbD product design tasks.

- Q23 – sustainability assessment available?
- Q24 – supporting materials selection?
- Q28 – the aspect of predictive tools and accelerated test.

Question 26 looks at a slightly different aspect, i.e., focus on circularity:

- Q26 - Tools and processes for CE and end-of-life concepts.

**Results for all respondents**:

Within the full group of participants, the pattern of answers (with some differences) is consistent:

- About 3 – 8 % of the participants consider "SSbD in product design" fully in force
- Additional (roughly) 30% "rather use the tools", 7-9 points
- About 60% of the participants have given 0-6 points, meaning they have medium to low capacity, knowledge, or need to apply SSbD evaluations in product design.

**Evaluation more in detail: Industry**

Focusing on industry and universities: 37 companies participated (mostly large); also 13 universities participating. The subgroup of companies answers is shown in table 37:

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*Table 37-Consideration of sustainable engineering tools by the companies*

| Question | % gave Score 10 = full | % of Score 7-8-9 | Sum, % |
|---|---|---|---|
| Q23 CAE + sustain. factors | 3 | 22 | 25 |
| Q24 materials selection | 5 | 27 | 32 |
| Q26 CE and end-of-life | 5 | 27 | 32 |
| Q28 predictive tools | 8 | 41 | 49 |

- Only 3-8% gave the full score (10 points) for fully anchored and integrated SSBD evaluation in the product design process.
- While 50% of the participating companies apply predictive tools in the development workflow, only 1/4 to 1/3 use dedicated SW tools for sustainability evaluation and materials selection.

**Academia**

The participating universities / Academia, with 13 participants, draw a different picture. The total number of academic institutions / universities participating is too small to compute reliable percentage values. The results of this group can be summarised as follows:

- More than 50% (up to 70%) gave "7-10 points" when asked for simulation and modelling tools, for computer-aided SSbD and supporting tools (Q23, Q24, Q28, thus 3 out of 4 questions).
- This rating is far higher than the results of the whole survey. Model-based design tools for sustainability by design are broadly available in the universities.
- Unexpectedly, Q28 "Design for circularity, including dismantling, re-use, end-of-life concept" was marked down significantly (less than 1/3 chose "7 and better"). The relevance is not clear: Has academia not yet broadly taken up **circular economy (CE) design**, are the software tools insufficient, or is this due to the high-TRL aspects of CE product design in the value chain?

**Another recent survey of industry sustainability "uptake"**

Interesting co-incidence: The non-profit organisation, Bertelsmann Stiftung, Gütersloh, Germany, has conducted a survey of German businesses, "Sustainability Management Monitor", 2023, with 268 stakeholders from companies of the "real economy"[153] .

- Only 9% of the respondents indicated that sustainability is "fully anchored" in their organisation
- "Partially well anchored" was chosen by 35%

**Gaps and shortcomings in today's product design SSbD scene**

- As explained above, **SSbD is not yet a standard element of engineering education**.
- Today's SSbD software tools support some of the needs. But **not all parameters of eco design and circular economy are supported.**


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- **Defined criteria,** Tools and user-friendly guidance, Helpdesks **are needed**
- **Threshold values for SSbD criteria**: e.g. "which $CO_2$ footprint is good or bad?" **Needs to be determined.**
- **Practical guidelines and tools to translate the SSbD framework into manageable processes/tasks for companies and other material researchers/developers**
- How to integrate intermediates and complex chemical processes in SSbD
- **Recommendation**: set up **development teams** of **1-2 sustainability experts**

# 5. Sustainability in ongoing EU projects

## 5.1 Introduction to the projects analysed

In addition to the WP1 survey, information from other EU-funded projects related to SSbD was collected. For this purpose, the project coordinators of the most relevant identified H2020 projects and HE projects related to SSbD aspects were contacted and asked to complete the template presented in Annex B of PR1.5. The projects were contacted in January and February 2023. Efforts were focused on H2020 projects, as the HE projects have only recently started. The analysis of HE projects will be continued in WP2.

This chapter maps project information in terms of **sustainability aspects** considered in on-going EU projects. Fifteen projects completed the project template and two additional EU projects responded to the WP1 survey (Survey Chapter) and were analysed in this chapter as well, resulting in **seventeen projects** in total (Table ).

*Table 38 - List of projects that provided information*

| Project Acronym and Logo | Project Title and Description |
|---|---|
| **Horizon 2020 SSbD projects** | |
| ASINA | ***Title*:** Antimicrobial and self-depolluting nano-structured coatings in clean technologies.<br>***Brief description***: Variations of Silver Nanomaterials (AgNPs) for coated antimicrobial functional textiles. Variations of active Titanium Dioxide Nanomaterials ($TiO_2$) for coated photocatalytic functional textiles. At the basis of NMs selection there are criteria of safety and sustainability, combined with efficiency, regulatory and cost requirements, that are designed or will be re-designed to maximise the safety and sustainability profile with respect to the traditional NMs considered as benchmark NMs within the project. |
| BreadCell | ***Title*:** Upgrading of cellulose fibers into porous materials<br>***Brief description***: BreadCell develops radically new technologies to produce porous lightweight low-density materials based on natural resources. Our main material is wood pulp fibers that are commonly used for paper manufacturing. BreadCell develops foaming processes that use wood fibers and wood macromolecules. We convert renewable raw materials to high value, lightweight, energy-absorbing and load-transferring composites such as those used in sports and safety components of cars. |

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| Project Acronym and Logo | Project Title and Description |
|---|---|
| DIAGONAL | ***Title***: Development and scaled Implementation of sAfe by design tools and Guidelines for multicOmponent aNd hArn nanomateriaLs<br>***Brief description***: DIAGONAL aims to bring new methodologies to guarantee long-term nanosafety along the multicomponent nanomaterials and High Aspect Ratio Nanoparticles life cycle: from design and production to their application into nano-enabled products, the product use and end of life phases.<br>To be able to do so, DIAGONAL will analyse the materials' physicochemical properties, toxicology, behaviour, and environmental exposure, as well as human safety along their life cycle. For that, the project will develop and validate multi-scale modelling tools able to predict and characterise nano-specific properties.<br>Additionally, DIAGONAL will build on seven industrial cases facilitating the re-design of nanomaterials, nano-enabled products design and manufacturing processes. The project will also approach the standardisation of risk management, assessment and governance facilitating their use by industry. |
| Gov4Nano | ***Title:*** Implementation of Risk Governance: meeting the needs of nanotechnology<br>***Brief description:*** Nanotechnology is an increasingly growing field of scientific innovation offering societal benefits. However, nanotechnology poses significant challenges to risk governance structures and processes. The EU-funded Gov4Nano project will design and create a self-sustained Nano Risk Governance Council (NRGC) to implement the Risk Governance Framework for managing nanotechnology risks relevant to social, environmental, and economic benefits. The team will develop an operational transdisciplinary Nano Risk Governance Model for nanotechnologies lying on a framework developed by the International Risk Governance Council. The NRGC will engage and coordinate stakeholders to overcome the fragmentation of existing knowledge and information, prepare its transfer, and establish a self-sustainable Nanosafety Governance Portal for dialogues between stakeholders. |
| HARMLESS | ***Title:*** Advanced High Aspect Ratio and Multicomponent materials: towards comprehensive intelLigent tEsting and Safe by design Strategies<br>***Brief description:*** HARMLESS develops a novel, multifaceted Safe Innovation Approach to complex multi-component, hybrid nanomaterials and High Aspect Ratio Nanoparticles (MCNM & HARNs) by integrating a toolbox of New Approach Methodologies, which can test key data according to latest scientific insights into MCNM & HARNs. To ensure that industries operating at differing scale, including SMEs, pick up our approach, we create a user-friendly decision support system and validate it iteratively at scale in different case studies.<br>To be viable for industry, Safe-by-Design approaches have to predict how the multidimensional design space may affect the functionality for the intended use. Conventional characterisation and testing methods are inefficient in this regard and not flexible enough for different innovation stages and industry sectors. In particular outside large industries, potential users of Safe-by-Design suffer from the complexity and variety of testing methods. To better guide them through intelligent decision choices throughout their entire design cycles and production, we develop a user-friendly Safe-by-Design decision support tool. The tool includes machine/deep learning algorithms that support: i) automatic and intelligent selection of methods/models, ii) fusion of heterogeneous model outputs to predict the single outcome for risk assessment, and iii) knowledge integration for assessing the risk of new materials. |

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| Project Acronym and Logo | Project Title and Description |
|---|---|
| i-TRIBOMAT | ***Title***: Intelligent Open Test Bed for Materials Tribological Characterisation Services<br>***Brief description***: i-TRIBOMAT aims to establish a Sustainable Open Innovation Test Bed for intelligent Tribological Materials Characterisation, paving the way for new collaborative approaches in sharing infrastructure, competence, and data for the benefit of the European industry to support industrial innovation, to improve materials up-scaling efficiency and to bring new materials into world-wide competitive products. i-TRIBOMAT services combine conventional laboratory level tribotests and experimental surface characterization techniques with Artificial Intelligence tools, such as database searches, computer simulation and modelling, which allow up-scaling laboratory test results to infer friction and wear behaviour of real components. |
| NanoHarmony | ***Title***: Towards harmonised test methods for nanomaterials<br>***Brief description***: The NanoHarmony project, funded through Horizon 2020, has the mission to support the development of Test Guidelines and Guidance Documents for eight endpoints where nanomaterial-adapted test methods have been identified as a regulatory priority. NanoHarmony coordinates the collection and use of available data and information to support the finalisation of the test method development and to organise a sustainable network for the needed exchange, also for future regulatory development needs. |
| NanoMECommons | ***Title:*** Harmonisation of EU-wide nanomechanics protocols and relevant data exchange procedures, across representative cases; standardisation, interoperability, data workflow<br>***Brief description:*** EU-funded NanoMECommons will form an EU-wide research and innovation network aiming to develop harmonised and widely accepted characterisation protocols, utilising high-speed nanoindentation (including multi-technique protocols) and focused ion beam. These protocols will be integrated into real industrial environments to boost material, process, and product reliability with reduced measurement discrepancy, improved data interoperability and traceability (TRL 6). NanoMECommons aims to provide a unique and interoperable metadata structure (iCHADA) to enhance data quality and information management. iCHADA will support the establishment of data-driven structure-properties relations to assist the quality assurance and material design procedures in the industry. The goal is the standardisation of testing to contribute directly to Industry Commons and facilitate reusability and transferability of characterisation data across multiple manufacturing sectors. |
| ReSOLUTE | ***Title***: Research empowerment on solute carriers<br>***Brief description***: The ReSolute project will scale a unique process to create an entirely new value chain. It will use cellulosic biomass to produce the platform molecule levoglucosenone (LGO) and its derivative Cyrene™, a safe and high performing biosolvent, and convert waste by-products for beneficial utilisation.<br><br>The main technological objectives of ReSOLUTE project:<br>• To build and successfully operate a first operate a first of its kind Flagship Plant sustainably producing a bio-based building block – levoglugosenone (LGO) – and the high performing solvent Cyrene™ with a capacity of 1,000 metric tons per year.<br>• To cover the whole value chain from feedstock supply to the production of high value-added products. |

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| Project Acronym and Logo | Project Title and Description |
|---|---|
| | • To valorise Cyrene™ production residues – bio-char – by converting them into activated carbons instead of burning them. |
| RiskGONE | ***Title***: Science-based Risk Governance of Nano-Technology<br>***Brief description***: RiskGONE is a H2020 project (NMBP-13), which aimed to provide solid procedures for science-based inter-disciplinary risk governance for engineered nanomaterials, based on a clear understanding of risks, risk management practices and societal risk perception, by all stakeholders. The risk governance framework, tools and guidance documents developed within RiskGONE can be considered applicable also for advanced materials, thus ensuring that innovation progresses in a sustainable manner. The topics that have been at the core of RiskGONE's activities include: governance of nano- and advanced materials, development of a risk governance framework, safe and sustainable by design (SSbD) tools, standardization and harmonization towards test guidelines and guidance documents (TG/GDs), Cloud platform and digital IT solutions. |
| SAbyNA | ***Title***: Simple, robust and cost-effective approaches to guide industry in the development of safer nanomaterials and nano-enabled products (SAbyNA)<br>***Brief description***: The main objective of SAbyNA is to develop an overarching integrative and interactive web-based guideline "The SAbyNA SbD Guidance Platform" to support the development of safer nano-enabled products and safer processes along the product life cycle, with advanced functionalities tailored to different industrial sectors (Paints and Additive Manufacturing). A panel of safe-by-design strategies and risk mitigation measures will be incorporated in the Guidance workflows with hierarchies and decision trees to facilitate the identification of most suitable approaches for each case. |
| SbD4Nano | ***Title***: Computing infrastructure for the definition, performance testing and implementation of safe-by-design approaches in nanotechnology supply chains<br>***Brief description***: The final aim of SbD4Nano project is to develop a user-friendly e-infrastructure to promote, assist and guide industry, regulator, and civil society in the definition of well-balanced SSbD approaches. To this end, the platform will be developed as a modular infrastructure implementing interfaces for data storage, searching and sharing, toxicity and exposure modelling, cost analysis, and product performance "function" evaluation, creating an innovative framework to accelerate the collaboration between scientist and industry, and closely aligning the SbD4Nano infrastructure with user needs to promote the implementation of SSbD approaches by the industry.<br>The e-infrastructure will be designed to be interoperable with resources already existing, maximizing crosstalk and interaction with available databases and modelling approaches. This will include graphical user interfaces (GUIs) adapted to the capabilities and knowledge of end users. |
| **Horizon Europe SSbD projects** | |
| greenSME | ***Title:*** Driving manufacturing SME transformation towards green, digital and social sustainability.<br>***Brief description:*** The European manufacturing sector is facing the challenge of achieving Green Deal goals while remaining competitive. The EU-funded GreenSME project will support manufacturing small and medium-sized enterprises (SMEs) towards green, digital and social sustainability by strengthening their capacity to adopt advanced technologies (AT) and become competitive and climate neutral. The project will establish a green SME hub with a SME sustainable pathway. The hub will provide sustainability awareness and industry engagement activities, ecosystem |


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| Project Acronym and Logo | Project Title and Description |
|---|---|
| | networking opportunities and tailored advisory services to SMEs. Moreover, GreenSME project will deliver a sustainability assessment tool, an advanced sustainability action plan (ASAP) definition methodology, and finally, an AT implementation practices white book. |
| RELIANCE<br>RELIANCE | ***Title***: Smart response self-disinfected biobased nanocoated surfaces for healthier environments<br>***Brief description***: RELIANCE project aims to design and develop smart response self-disinfectant antimicrobial nanocoatings based on a new range of smart antimicrobial nanoparticles. They will consist of mesoporous silica nanoparticles with metallic copper in their structure, modified with biobased bioactive compounds: Antimicrobial peptides (AMP's) based on protein containing waste streams, and essential oils (EOs) coming from non-edible plants. The antibacterial action of these additives will be adjusted to the specific application, according to the dosages and durability requirements.<br>Applications:<br>• Antimicrobial coatings for interior part for automotive sector<br>• Antimicrobial and water repellent protective clothing coatings for pharmaceutical and medical sector.<br>• Antimicrobial and water repellent coatings for home appliance surfaces. |
| SUSAAN<br>SUSAAN SUStainable Antimicrobial and Antiviral Nanocoating | ***Title:*** SUStainable Antimicrobial and Antiviral Nanocoating<br>***Brief description:*** SUSAAN project aims at developing sustainable antiviral and antimicrobial nanocoatings, from active biobased and Inorganic nanoparticles, applied to different high traffic objects (plastic and metallic) and textiles. The products will be validated in real products, by covering three different applications: sockets & switches, bathrooms elements, and textile manufacture industries. SUSAAN project will work from the beginning in the production of sustainable by design nanocoatings with a holistic approach, considering main challenging aspects such as fast response and durable effects, low toxicity and environmental impact, scalability, and regulatory requirements. |
| TransPharm<br>TRANS PHARM | ***Title:*** Transforming into a sustainable European pharmaceutical sector ***Brief description:*** TransPharm two-track approach focusses on the one hand on the compounds itself by identifying greener and more sustainable-by-design Active Pharmaceutical Ingredients (APIs) and on the other hand on reducing the environmental impact and resilience of the manufacturing process by optimizing the synthesis route of new APIs in continuous flow and by proposing greener alternative solvents. The aim of the project is to (i) analyse and predict flow behaviour and environmental biodegradability of APIs and their synthesis pathways; (ii) identify greener and more sustainable alternatives to pharmaceutical products / APIs of concern; (iii) reduce the footprint and create important shortcuts in synthetic schemes of APIs; and (iv) assess the sustainability of pharmaceuticals over their entire life cycle. To reach the envisaged aims, the project will deliver four toolboxes (consisting of digital tools and guidelines) for the development of greener pharmaceutical products and APIs. These toolboxes will be used to (v) assess the potential to move towards the transition to greener, more agile pharmaceutical production. In addition, TransPharm will elaborate on the business case for sustainable pharmaceutical products or APIs and what is needed to bring them to the market. The project will also make sure that (vi) key project results and knowledge are properly transferred towards targeted stakeholders. TransPharm's outcome contribute to a Europe, that is self-sufficient by reducing dependence on |


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| Project Acronym and Logo | Project Title and Description |
|---|---|
| | API production in third countries; making the EU healthcare industry more competitive, sustainable, and reliable, ensuring timely supply of essential medicines from particularly complex or critical supply and distribution chains and positioning EU as a leader in innovative technologies. |
| **Other SSbD projects** | |
| DaNa4.0 | ***Title***: Data on new, innovative, and safe application related materials<br>***Brief description***: The main mission of the project DaNa is to extract relevant information on material safety related to humans and the environment from scientific literature and compile comprehensive profiles for materials/material classes; this information provides the scientific basis for a SSBD process highlighting potential issues related to a material hazard, exposure routes and the current state of the art derived from literature. |

## 5.2 SSBD aspects

The contacted projects were asked to select which of the design principles, proposed in the JRC framework[6], they consider during the design phase of a material, product, or process. The results are shown in Figure 36.

Figure 36. In the project activities, SSbD8 '**Consider the whole life cycle'** is the most considered aspect (n = 14, 82%), while SSbD4 'Use renewable sources' is the least considered one (n = 7; 41%). This shows that a life cycle thinking is strongly implemented in current EU-funded research projects.

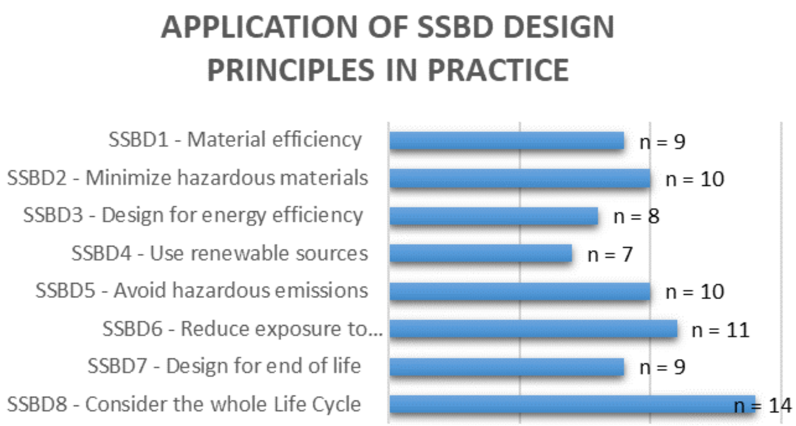


*Figure 36 - Application of SSbD design principles in the projects*

## 5.3 Application of LCA on projects

65% of the analysed projects perform or intend to perform and Environmental Life Cycle Assessment during the design or development phase of a material, product, process, or R&D activity. **SimaPro** is the most frequently used software to conduct LCAs within the analysed projects (n=6); Open LCA is used in one project, as well as Hotspon Scan. Only 5 projects identified the

[6] See Figure 6 and Table 32

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**impact assessment method** they use, and the **EF** was the most popular (n=3) followed by USETOX (n=2). See more detailed explanation in the preliminary report PR1.3.

## 5.4 Social dimension on EU projects

59% (n=10) of the analysed projects perform or intend to perform a Social Life Cycle Assessment during the design or development phase of a material, product, process, or R&D activity. Four of the analysed projects use the specialised **software database SHDB** to perform S-LCA. Figure 37 shows the different social indicators, only four projects give information related social indicators proposed in the template.

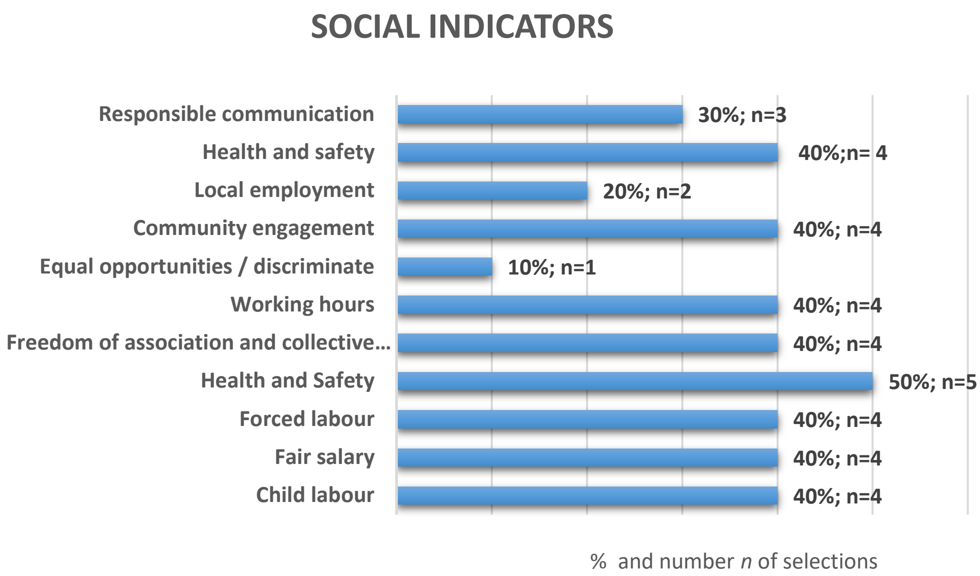


*Figure 37 - Social aspects considered by the analysed projects that perform S-LCA*

Eight of the projects interviewed provide some additional information on the social issues within their projects, summarised in Table 38.

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*Table 38 - Additional information about social considerations of the projects*

| | |
|---|---|
| **Breadcell** | Sourcing of nanocellulose (e.g., the original source of the nanocellulose). Currently for the project industrial nanocellulose is being used, but this needs to be considered for the final product production. |
| **i-Tribomat** | Tools developed in i-TRIBOMAT to predict the behaviour in use and expected lifetime of mechanical components, using laboratory testing of new materials, data-driven analysis and computer simulation lab-to-field models can contribute to reduce trial-and-error based experimental developments, which sometimes imply large energy consumption, waste generation, and health and safety risks for workers. |
| **NanoMeCommons** | Accelerate the product time to market by offering faster assessment methods, as well as offer digitalized workflows to accelerate the integration of modelling and characterization tools via an Open Innovation Environment, to share knowledge and democratise access of society to goods. Also, by providing more durable products, the society will benefit by prolong the use of those products, thus minimizing the waste generation and energy use. |
| **Resolute** | Social is at the heart of what ReSOLUTE is doing and considers all the social aspects mentioned in Table 36 . They are choosing to build on a Brownfiel site where a coal power plant is being closed, with the idea that bioeconomy, the green economy can revitalize this area. They are repurposing a petrochemical site and will hire local coal power plant employees who will become unemployed with the closing of the coal plant. |
| **SbD4Nano** | The HotSpot Scan provides an intermediate assessment focusing on the strongest human health and environmental impacts based on establishing all the material flows. The HotSpot Scan considers aspects such as industry, life-cycle stage, production scale, vapour pressure, etc. |
| **SUSANN** | Social-LCA follows the ISO 14040 framework and will be applied, assessing two types of social repercussions (i) by stakeholder categories: worker, consumer, local community, society, and value chain actors and (ii) by impact categories: human rights, working conditions, health & safety, governance & socio-economic repercussions. |
| **TransPharm** | The transition towards sustainability requires the adaptation of current production and consumption processes in such a way that these no longer threaten our health and well-being, the environment, and our common future. Greening of production and consumption is a challenging task since it involves a wide range of interrelated processes, actors, and dimensions. |
| **RiskGONE** | RiskGONE developed guidance documents for social, ethical, economical, and legal aspects of engineering nanomaterials (ENMs). A guideline for Multicriteria Decision Analysis (MCDA) framework that supports decision-makers by synthesizing multidimensional risk and benefits into a single measure of preference was also developed. |

The projects analysed consider social aspects in different ways, and there is a lack of common methodology. Some of them consider the social issues related to origin of the raw material, others focused on the adaptation of production and consumption to avoid threatens to human health and environment. Two of them focused on characterization methods to support the development of more durable and energy efficient products, minimizing the waste generation and energy use.

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## 5.5 Techno economical dimension on EU projects

Nine of the projects interviewed provide some information on the techno-economic aspects within their projects, summarised in Table 39

*Table 39 – Techno economical dimension on the analysed EU projects*

| | |
|---|---|
| **ASINA** | Life Cycle Costing will be performed by analysing the nanomaterials (NMs) and related synthesis processes to obtain them. The analysis will consider the lab and pilot scale units to synthesize the NMs with an estimation of the major synthesis costs (such as: raw materials, equipment, and energy costs). The cost effectiveness will be carried out through the Life Cycle Costing (LCC) analysis to qualify the cost economic performance of the ASINA identified NMs solutions. |
| **DIAGONAL** | Together with the LCA and S-LCA, an LCC analysis will be performed for three of the industrial cases, providing an integrated LCSA perspective. Through a “cradle-to-gate” scope, the cost of producing the novel NM products will be quantified, and the hotspots identified. This allows the tracking of the most critical manufacturing steps in terms of potential for cost reduction and provides an economic criterion to be included in the broader sustainability assessment. |
| **i-Tribomat** | This project supports the study of the tribological performance of materials and components. This allows to incorporate predictions on their behaviour in use already in the design phase, with a clear economic impact. |
| **RELIANCE** | An economic analysis is performed to compare the existing nanomaterials and associated economics with the novel additives, nanocoatings and application technologies to the different demonstrators. The economic impact assessment is performed by using the PESTLE analysis, aimed at investigating macro-environmental factors such as political, economic, social technological, environmental, legal, and ethical aspects able to have a critical impact on the market uptake of the proposed solutions. |
| **SAbyNA** | SAbyNA SbD Guidance Platform will include Cost considerations for the implementation of SbD strategies towards safer nano-enabled products and safer associated processes, some relative costs will be provided for sector specific considerations and then a Cost calculator will be integrated in the guidance platform for the user to calculate the additional costs needed for the implementations suggested by the Platform. |
| **SbD4Nano** | The contribution of the project to the safety of products will improve the acceptance of the nanotechnology into the society as well as a better image of the new technologies, ensuring the commercialization soon. In addition, the application of the outcomes of the project related to the design of safer ENMs at the source will promote the sustainable growth of the nanotechnology industry, being able to generate new jobs that will directly or indirectly support the further development of the European economy. |
| **SUSANN** | Regarding the economic dimension, a Life Cycle Cost analysis will be conducted in parallel to the LCA, to determine the total ownership costs (capital expenditures (CAPEX), operational expenditures (OPEX), among others) associated to the whole project life cycle, development of Antiviral Nanomaterials, nanocoatings and final products. |
| **TransPharm** | Application of socio-economic analysis and assessment tools to the two case studies. The concepts from the economic and societal evaluation, and integrated assessment tools will be applied to two case studies |
| **RiskGONE** | RiskGONE developed draft guidelines regarding the quantification of macro-economic benefits |

For the evaluation of the techno-economic dimension, the Life Cycle Costing (LCC) methodology is the most widely used among EU projects analysed. There is one project that will perform the economic impact assessment using a PESTLE analysis and another that will develop and integrate a cost calculator into its guidance platform to allow the user to calculate the costs.


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# 6. CONCLUSIONS

The Safe-and-sustainable-by-design (SSbD) is central in the EC Chemical Strategy for Sustainability, but a common understanding of the SSbD concept and what it means in practice, is still needed. Five main SSbD frameworks on how to operationalise SSbD have been published, considering: a) a policy and regulatory perspective (JRC, EEA, OEC) and b) an industrial perspective (CEFIC and ChemSec). The dimensions and the different SSbD approaches / recommendations are summarised in Table 4. Safety and environmental sustainability dimensions are covered in all regarded SSbD approaches, while all three sustainability pillars (environmental, social, and economic) are only covered by JRC, OECD and Cefic. The social and economic aspects show a low level of implementation and methodological maturity. Regarding environmental assessment, some SSbD approaches recommend using the Product Environmental Footprint (PEF) assessment method. There is a need for a harmonised and practical SSbD framework with clear procedures and incentives to support the industrial sector, especially SMEs.

Starting from the results of the 2021 review of Caldeira et al. [1], new, extended Scopus research was conducted. The 55 new documents analysed cover the three sustainability dimensions “economic”, “social” and “environmental”. Compared to the results obtained in the literature review performed by Caldeira et al., the number of studies considering the social dimension has significantly increased in the last two years. The most frequently identified areas where SSbD is considered are “Construction” and “Energy” (materials, supply systems and batteries)”.

When focusing on the **environmental dimension**, according to bibliographical analysis, **Ecoinvent** is the database mostly applied in LCA studies. Within software tools, **SimaPro** is the most frequent database with twice the number of results obtained in comparison to **Gabi**. **OpenLCA** is also often used. The most popular **Lifecycle environmental impact** assessment methods are **ReCiPE** and **CML. ECOTOX** and **PEF** are also used in some studies. This is consistent with the review performed by Caldeira, et al. where the most cited models for addressing the indicators they considered, were Recipe 2016, USEtox and CML (from largest to smallest use). They also showed that the **PEF** method is gaining attention for sustainability metrics (see more detailed review in the preliminary report PR1.3).

**Social dimension:** There has been an increasing interest from the chemical and materials stakeholders to implement **Social LCA (S-LCA)** in the sustainability studies, but still the number of case studies are very limited. The most used databases are (Product Social Impact Life Cycle Assessment database (**PSILCA**) and the **Social Hotspots Database** (**SHDB**). However, according to the survey results, just some entities use these specialized databases when performing S-LCA studies.

The number of studies considering social indicators is increasing significantly, with “**Health and Safety of workers**” being the most used indicator according to the bibliographical review, the survey results, and the EU projects analysis. In the report by Caldeira et al., the indicator most often used was **“No child labour”** with 11 out of 119 frameworks. Harmonization between the current approaches, such as the UNEP and the Social Value initiatives, would be required to select the impact categories.

The analysed EU projects consider social aspects in different ways, but there is a lack of a common methodology. For instance, some address social issues related to the **origin of the raw material,** while others are focused on the adaptation of production and consumption **to avoid threats to human health and environment.**

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Concerning the **Techno economical dimension**, in life cycle sustainability assessment, the economic pillar is usually addressed through the Life Cycle Costing (LCC) methodology. Three different types of **life cycle cost** analysis need to be considered: conventional **LCC** (cLCC), environmental LCC (eLCC) and social LCC (sLCC). Regarding the economic approaches mapped in the literature review, Life cycle cost is by far the predominant term reported in the studies, only two studies explicitly mention the cLCC, sLCC and the eLCC, but several studies consider environmental externalities (eLCC), as an additional cost.

Looking into the EU projects analysis, for the evaluation of techno-economical dimension, the **Life Cycle Costing (LCC)** methodology is the most widely used. The Project **RELIANCE** will perform the economic impact assessment using a PESTLE analysis and another Project **SABYNA** will develop and integrate a **cost calculator in their guidance platform** for the user to calculate the costs.

It will be critical to establish how **economic metrics** should complement **the social and environmental results.** To do so, a first step consists in defining the economic indicators of interest to policymakers and then, ensuring that these do not overlap with metrics provided in LCA or S-LCA when calculating aggregated scores. While single scores can facilitate a decision-making process to prioritize choices, they come with some limitations in terms of transparency and interpretation (by experts).

The relevance of SSbD is widely and fully recognized by all relevant groups, by academia and industry that answer the questionnaire. It can be stated that the concept of safe and sustainable by design (SSbD) is becoming an integral part of corporate day-to-day business- and is increasingly prevalent within corporate strategies and targets, as businesses AND THEIR CUSTOMERS move towards the great societal challenges. This conclusion should be taken with precaution, since the number of survey responses were not large (87).

Concerning the type of SSbD principles to be applied, the highest application rates are shown for safety related design principles. **Safety considerations** are widely applied in the design phase; followed by **material efficiency, environmental related considerations** (reduce/avoid emission to the environment), and finally by End-of-life considerations. It can be concluded that there is a need to overcome the lack of engineering tools for “design for end-of-life" to certainly boost the appropriate CE design capabilities. IRISS should consider dedicated actions on this topic.

**Modelling and characterisation tools**: Models and advanced characterization play an important role in the design of chemicals, materials, and products.

- The use **of CAE, simulation,** and predictive tools for “materials selection and product design for the CE” is limited to a small percentage of “piloting” enterprises and academic institutions. While the tools for material and process selection in the product design cycle are principally available (for sustainability by design), the holistic approaches to End-of-life concepts, design for re-use or repair, etc. including circular economy aspects is lacking dedicated engineering tools, yet. Positive trend: Academia, R&D&I Institutions, and industry develop handbooks, guidelines, best practices, and reports on success and failures. These documents ought to be collected and distributed or made available within the SSbD product design ecosystem. In conclusion, IRISS could assume a role in the driver seat in the sub-topic of product design.

- **Tribology** is a tool that helps in the design of sustainable materials, products and processes ensuring the functionality of a material/product for the selected application(s), controlling the friction, and consequently increasing the energy efficiency during processing and use


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and taking also into account the wear resistance, durability and repairability. Frequently, lab-scale tests are conducted in accelerated mode and small-scale which could have the risk of overlooking time or scale effects. To overcome these limitations, it is necessary to reproduce the failure mechanism at the laboratory, and to combine experiments with computer-based simulations to properly link “field to lab” and “lab to field”. Tribologists should combine the resources of experimental, simulation, and LCA towards the growth and implementation of sustainable tribology not only for research purposes, but also from commercial applications point of view.

This prelimnary report **PR1.2** has analysed the existing situation of SSbD (materials, products, processes) in academia and industry. Environmental, social, and economic dimensions of existing SSbD frameworks, literature trends, and LCA methodologies were summarized. The survey of actual SSbD relevance, practice, and application has identified several barriers and shortcomings on the road to broad and comprehensive future for Safe and Sustainable Designs. Despite some SSbD tools and software solutions for sustainability assessment (including LCA) during the product design stage are available; widespread application is not yet established, and design for “end-of-life" and CE-oriented design are still underdeveloped. Future IRISS workshops will hopefully improve the situation. The question of access to materials and process data needs to be addressed, especially for advanced materials. Through the IRISS consortium and with help from AMI2030, and involvement of SSbD EU Financed project stakeholders, progress can be achieved. Engineers need more SSbD skills, and development teams need eco-design capacities. IRISS can support training and education in this field.

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# 8. ANNEX I-Complementary information to literature review

Search strings in the bibliometric analysis

*Table 40 - SCOPUS search string proposed for the IRISS sustainability mapping process, considering only the economic dimension.*

| |
|---|
| ( TITLE-ABS-KEY ( "alternatives assessment" OR "chemicals alternative assessments" OR "alternatives analysis" OR "substitution assessment" OR "chemicals assessment" OR "solvent selection" OR "solvents selection" OR "solvent design" OR "safe and sustainable" OR "social LCA" OR "life cycle costing" OR "life cycle cost" ) AND TITLE-ABS-KEY ( "durability" OR "extend* lifespan" OR "extend* life span" OR "recycl*" OR "circular*" OR "safe and sustainable by design" OR "SSbD" OR "sustainab*" OR "LCSA" OR "Life Cycle Sustainability Assessment" OR "sustainability assessment*" ) AND TITLE-ABS-KEY ( "chemical*" OR "solvent*" OR "material*" OR "biomaterial*" OR "biobased*" OR "bio-based*" ) OR "packag*" OR "electronic*" OR "metal*" OR "building*" OR "construction" OR "plastic*" OR "fibre*" OR "automotive" OR "transport" OR "vehicle*" OR "batterie*" OR "food" OR "agricultur*" OR "agro*" OR "energy" ) AND TITLE-ABS-KEY ( "framework*" OR "guide*" OR "methodolog*" OR "tool*" OR "measurement*" OR "model*" OR "indicator*" OR "software" OR "app*" OR "method*" OR "technique*" ) AND TITLE-ABS-KEY ( "LCC" OR "life cycle cost*" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) |

*Table 41 - SCOPUS search string proposed for the IRISS sustainability mapping process, considering only the environmental dimension.*

| |
|---|
| ( TITLE-ABS-KEY ( "alternatives assessment" OR "chemicals alternative assessments" OR "alternatives analysis" OR "substitution assessment" OR "chemicals assessment" OR "solvent selection" OR "solvents selection" OR "solvent design" OR "safe and sustainable" OR "social LCA" OR "life cycle costing" OR "life cycle cost" ) AND TITLE-ABS-KEY ( "durability" OR "extend* lifespan" OR "extend* life span" OR "recycl*" OR "circular*" OR "safe and sustainable by design" OR "SSbD" OR "sustainab*" OR "LCSA" OR "Life Cycle Sustainability Assessment" OR "sustainability assessment*" ) AND TITLE-ABS-KEY ( "chemical*" OR "solvent*" OR "material*" OR "biomaterial*" OR "biobased*" OR "bio-based*" ) OR "packag*" OR "electronic*" OR "metal*" OR "building*" OR "construction" OR "plastic*" OR "fibre*" OR "automotive" OR "transport" OR "vehicle*" OR "batterie*" OR "food" OR "agricultur*" OR "agro*" OR "energy" ) AND TITLE-ABS-KEY ( "framework*" OR "guide*" OR "methodolog*" OR "tool*" OR "measurement*" OR "model*" OR "indicator*" OR "software" OR "app*" OR "method*" OR "technique*" ) AND TITLE-ABS-KEY ( "environment*" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) |

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***Table 42- SCOPUS search string proposed for the IRISS sustainability mapping process, considering only the social dimension***

| |
|---|
| ( TITLE-ABS-KEY ( "alternatives assessment" OR "chemicals alternative assessments" OR "alternatives analysis" OR "substitution assessment" OR "chemicals assessment" OR "solvent selection" OR "solvents selection" OR "solvent design" OR "safe and sustainable" OR "social LCA" OR "life cycle costing" OR "life cycle cost" ) AND TITLE-ABS-KEY ( "durability" OR "extend* lifespan" OR "extend* life span" OR "recycl*" OR "circular*" OR "safe and sustainable by design" OR "SSbD" OR "sustainab*" OR "LCSA" OR "Life Cycle Sustainability Assessment" OR "sustainability assessment*" ) AND TITLE-ABS-KEY ( "chemical*" OR "solvent*" OR "material*" OR "biomaterial*" OR "biobased*" OR "bio-based*" ) OR "packag*" OR "electronic*" OR "metal*" OR "building*" OR "construction" OR "plastic*" OR "fibre*" OR "automotive" OR "transport" OR "vehicle*" OR "batterie*" OR "food" OR "agricultur*" OR "agro*" OR "energy" ) AND TITLE-ABS-KEY ( "framework*" OR "guide*" OR "methodolog*" OR "tool*" OR "measurement*" OR "model*" OR "indicator*" OR "software" OR "app*" OR "method*" OR "technique*" ) AND TITLE-ABS-KEY ( "social*" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) |

For more details about the see the literature analysis result, see the excel file with the complementary information.

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| ID | Study | Title | Year | Source title | DOI |
|---|---|---|---|---|---|
| 1 | Allotey D.K., Kwofie E.M., Adewale P., Lam E., Ngadi M., | Life cycle sustainability assessment outlook of plant-based protein processing and product formulations | 2023 | Sustainable Production and Consumption | 10.1016/j.spc.2022.12.021 |
| 2 | Amini Toosi H., Lavagna M., Leonforte F., Del Pero C., Aste N., | A novel LCSA-Machine learning based optimization model for sustainable building design-A case study of energy storage systems | 2022 | Building and Environment | 10.1016/j.buildenv.2021.108656 |
| 3 | Barahmand Z., Eikeland M.S., | A Scoping Review on Environmental, Economic, and Social Impacts of the Gasification Processes | 2022 | Environments - MDPI | 10.3390/environments9070092 |
| 4 | Caraman D., Roșeanu S., Constantin I., Dâmboianu C., | Innovative Public Procurement Processes to Implement Sustainable Mobility Policies | 2023 | Smart Innovation, Systems and Technologies | 10.1007/978-981-19-6962-1_13 |
| 5 | Collotta M., Tomasoni G., Champagne P., Mabee W., | Life cycle approach for the sustainability assessment of intensified biorefineries | 2022 | Biofuels and Biorefining: Volume 2: Intensification Processes and Biorefineries | 10.1016/B978-0-12-824117-2.00013-2 |
| 6 | Corona B., Hoefnagels R., Vural Gürsel I., Moretti C., van Veen M., Junginger M., | Metrics for minimising environmental impacts while maximising circularity in biobased products: The case of lignin-based asphalt | 2022 | Journal of Cleaner Production | 10.1016/j.jclepro.2022.134829 |
| 7 | Daniela-Abigail H.-L., Tariq R., Mekaoui A.E., Bassam A., Vega De Lille M., J Ricalde L., Riech I., | Does recycling solar panels make this renewable resource sustainable? Evidence supported by environmental, economic, and social dimensions | 2022 | Sustainable Cities and Society | 10.1016/j.scs.2021.103539 |
| 8 | Degieter M., Gellynck X., Goyal S., Ott D., De Steur H., | Life cycle cost analysis of agri-food products: A systematic review | 2022 | Science of the Total Environment | 10.1016/j.scitotenv.2022.158012 |
| 9 | Di Ruocco G., Melella R., Marino V., | An integrated assessment method for the sustainability of the opaque building envelope in residential buildings with Italian GBC-HOME certification | 2022 | Architectural Engineering and Design Management | 10.1080/17452007.2021.2001307 |
| 10 | Ding Y., | New Technological Measures of Sustainable Buildings in Triple Bottom-Line Analysis | 2022 | Mathematical Problems in Engineering | 10.1155/2022/7750056 |
| 11 | Ferreira A., Pinheiro M.D., Brito J.D., Mateus R., | A critical analysis of LEED, BREEAM and DGNB as sustainability assessment methods for retail buildings | 2023 | Journal of Building Engineering | 10.1016/j.jobe.2023.105825 |
| 12 | Gulcimen S., Qadri S., Donmez R.O., Uzal N., | A holistic sustainability assessment of a university campus using life cycle approach | 2022 | International Journal of Environmental Science and Technology | 10.1007/s13762-022-04214-8 |



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| ID | Study | Title | Year | Source title | DOI |
|---|---|---|---|---|---|
| 13 | Haase M., Wulf C., Baumann M., Rösch C., Weil M., Zapp P., Naegler T., | Prospective assessment of energy technologies: a comprehensive approach for sustainability assessment | 2022 | Energy, Sustainability and Society | 10.1186/s13705-022-00344-6 |
| 14 | Jayawardane H., Davies I.J., Gamage J.R., John M., Biswas W.K., | Investigating the 'techno-eco-efficiency' performance of pump impellers: metal 3D printing vs. CNC machining | 2022 | International Journal of Advanced Manufacturing Technology | 10.1007/s00170-022-09748-2 |
| 15 | Kazemi F., Hossein pour N., Mahdizadeh H., | Sustainable low-input urban park design based on some decision-making methods | 2022 | Land Use Policy | 10.1016/j.landusepol.2022.106092 |
| 16 | Larsen V.G., Tollin N., Antoniucci V., Birkved M., Sattrup P.A., Holmboe T., Marella G., | Filling the gaps Circular transition of affordable housing in Denmark | 2022 | IOP Conference Series: Earth and Environmental Science | 10.1088/1755-1315/1078/1/012078 |
| 17 | Larsen V.G., Tollin N., Sattrup P.A., Birkved M., Holmboe T., | What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA | 2022 | Journal of Building Engineering | 10.1016/j.jobe.2022.104203 |
| 18 | Li J., Tarpani R.R.Z., Stamford L., Gallego-Schmid A., | Life cycle sustainability assessment and circularity of geothermal power plants | 2023 | Sustainable Production and Consumption | 10.1016/j.spc.2022.10.027 |
| 19 | Maffia A., Palese A.M., Pergola M., Altieri G., Celano G., | The Olive-Oil Chain of Salerno Province (Southern Italy): A Life Cycle Sustainability Framework | 2022 | Horticulturae | 10.3390/horticulturae8111054 |
| 20 | Mahmoud S., Hussein M., Zayed T., Fahmy M., | Multiobjective Optimization Model for the Life Cycle Cost-Sustainability Trade-Off Problem of Building Upgrading Using a Generic Sustainability Assessment Tool | 2022 | Journal of Construction Engineering and Management | 10.1061/(ASCE)CO.1943-7862.0002281 |
| 21 | Mele M., Campana G., | Advancing towards sustainability in liquid crystal display 3D printing via adaptive slicing | 2022 | Sustainable Production and Consumption | 10.1016/j.spc.2021.12.024 |
| 22 | Mohamed A.S., Xiao F., Hettiarachchi C., | Project Level Management Decisions in Construction and Rehabilitation of Flexible Pavements | 2022 | Automation in Construction | 10.1016/j.autcon.2021.104035 |
| 23 | Nubi O., Morse S., Murphy R.J., | Life Cycle Sustainability Assessment of Electricity Generation from Municipal Solid Waste in Nigeria: A Prospective Study | 2022 | Energies | 10.3390/en15239173 |
| 24 | Olsthoorn, M., Schleich, J., Guetlein, M.-C., Durand, A., Faure, C., | Electronics and ICT | 2023 | Energy Policy | 10.1016/j.enpol.2023.113430 |
| 25 | Papo M., Corona B., | Life cycle sustainability assessment of non-beverage bottles made of recycled High Density Polyethylene | 2022 | Journal of Cleaner Production | 10.1016/j.jclepro.2022.134442 |

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| ID | Study | Title | Year | Source title | DOI |
|---|---|---|---|---|---|
| 26 | Peña A., Rovira-Val M.R., Mendoza J.M.F., | Life cycle cost analysis of tomato production in innovative urban agriculture systems | 2022 | Journal of Cleaner Production | 10.1016/j.jclepro.2022.133037 |
| 27 | Qiao Y., Wang Z., Meng F., Parry T., Cullen J., Liu S., | Evaluating the economic and environmental impacts of road pavement using an integrated local sensitivity model | 2022 | Journal of Cleaner Production | 10.1016/j.jclepro.2022.133615 |
| 28 | Ramos A., Rouboa A., | Life cycle thinking of plasma gasification as a waste-to-energy tool: Review on environmental, economic and social aspects | 2022 | Renewable and Sustainable Energy Reviews | 10.1016/j.rser.2021.111762 |
| 29 | Rezazadeh Kalehbasti P., Lepech M.D., Criddle C.S., | Integrated Design and Optimization of Water-Energy Nexus: Combining Wastewater Treatment and Energy System | 2022 | Frontiers in Sustainable Cities | 10.3389/frsc.2022.856996 |
| 30 | Rizan C., Brophy T., Lillywhite R., Reed M., Bhutta M.F., | Life cycle assessment and life cycle cost of repairing surgical scissors | 2022 | International Journal of Life Cycle Assessment | 10.1007/s11367-022-02064-7 |
| 31 | Roci M., Salehi N., Amir S., Shoaib-ul-Hasan S., Asif F.M.A., Mihelič A., Rashid A., | Towards circular manufacturing systems implementation: A complex adaptive systems perspective using modelling and simulation as a quantitative analysis tool | 2022 | Sustainable Production and Consumption | 10.1016/j.spc.2022.01.033 |
| 32 | Salim K.M.A., Maelah R., Hishamuddin H., Amir A.M., Ab Rahman M.N., | Two Decades of Life Cycle Sustainability Assessment of Solid Oxide Fuel Cells (SOFCs): A Review | 2022 | Sustainability (Switzerland) | 10.3390/su141912380 |
| 33 | Sánchez-Garrido A.J., Navarro I.J., Yepes V., | Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction | 2022 | Journal of Cleaner Production | 10.1016/j.jclepro.2021.129724 |
| 34 | Sarkar, D., Sheth, A., Ranganath, N., | Social Benefit-Cost Analysis for Electric BRTS in Ahmedabad | 2023 | International Journal of Technology | 10.14716/ijtech.v14i1.3028 |
| 35 | Sauve G., Esguerra J.L., Laner D., Johansson J., Svensson N., Van Passel S., Van Acker K., | Integrated early-stage environmental and economic assessment of emerging technologies and its applicability to the case of plasma gasification | 2023 | Journal of Cleaner Production | 10.1016/j.jclepro.2022.134684 |
| 36 | Scolaro T.P., Ghisi E., | Life cycle assessment of green roofs: A literature review of layers materials and purposes | 2022 | Science of the Total Environment | 10.1016/j.scitotenv.2022.154650 |
| - | ~~Serra A., Gandini S., Colantoni S., Buia G., Fantaccione L., Bartocci P., Fantozzi F.,~~ | ~~Additive Manufacturing versus Investment Casting for a Gas Turbine Component: a Social Life Cycle comparison~~ | ~~2022~~ | ~~Proceedings of the ASME Turbo Expo~~ | ~~10.1115/GT2022-77981~~ |
| 37 | Sevindik S., Spataru C., | An Integrated Methodology for Scenarios Analysis of Low Carbon Technologies Uptake towards a Circular Economy: The Case of Orkney | 2023 | Energies | 10.3390/en16010419 |
| 38 | Singh P.K., Sarkar P., | An artificial neural network tool to support the decision making of designers for environmentally conscious product development | 2023 | Expert Systems with Applications | 10.1016/j.eswa.2022.118679 |

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| ID | Study | Title | Year | Source title | DOI |
|---|---|---|---|---|---|
| 39 | Soust-Verdaguer B., Bernardino Galeana I., Llatas C., Montes M.V., Hoxha E., Passer A., | How to conduct consistent environmental, economic, and social assessment during the building design process. A BIM-based Life Cycle Sustainability Assessment method | 2022 | Journal of Building Engineering | 10.1016/j.jobe.2021.103516 |
| 40 | Stefanini R., Vignali G., | Environmental and economic sustainability assessment of an industry 4.0 application: the AGV implementation in a food industry | 2022 | International Journal of Advanced Manufacturing Technology | 10.1007/s00170-022-08950-6 |
| 41 | Stefanini R., Vignali G., | The Environmental, Economic and Social Impact of Industry 4.0 in the Food Sector: a Descriptive Literature Review | 2022 | IFAC-PapersOnLine | 10.1016/j.ifacol.2022.09.602 |
| 42 | Stillitano T., Falcone G., Iofrida N., Spada E., Gulisano G., De Luca A.I., | A customized multi-cycle model for measuring the sustainability of circular pathways in agri-food supply chains | 2022 | Science of the Total Environment | 10.1016/j.scitotenv.2022.157229 |
| 43 | Sutantio A., Anwar N., Wiguna I.P.A., Suryani E., | A System Dynamics Model of Sustainable Construction for High rise Residential Projects in Developing Countries: Case of Indonesia | 2022 | Open Civil Engineering Journal | 10.2174/18741495-v16-e2205300 |
| 44 | Sutantio A., Anwar N., Wiguna I.P.A., Suryani E., | DEVELOPING A MODEL OF SUSTAINABLE CONSTRUCTION FOR CONDOMINIUM PROJECTS IN DEVELOPING COUNTRIES | 2022 | International Journal of GEOMATE | 10.21660/2022.96.3319 |
| 45 | Tempa K., Chettri N., Thapa G., Phurba, Gyeltshen C., Norbu D., Gurung D., Wangchuk U., | An experimental study and sustainability assessment of plastic waste as a binding material for producing economical cement-less paver blocks | 2022 | Engineering Science and Technology, an International Journal | 10.1016/j.jestch.2021.05.012 |
| 46 | Tushar Q., Bhuiyan M.A., Zhang G., | Energy simulation and modeling for window system: A comparative study of life cycle assessment and life cycle costing | 2022 | Journal of Cleaner Production | 10.1016/j.jclepro.2021.129936 |
| 47 | Van Cauteren D., Ramon D., Stroeckx J., Allacker K., Schevenels M., | Design optimization of hybrid steel/timber structures for minimal environmental impact and financial cost: A case study | 2022 | Energy and Buildings | 10.1016/j.enbuild.2021.111600 |
| 48 | Wijayasekera S.C., Hewage K., Hettiaratchi P., Siddiqui O., Razi F., Pokhrel D., Sadiq R., | Sustainability of waste-to-hydrogen conversion pathways: A life cycle thinking-based assessment | 2022 | Energy Conversion and Management | 10.1016/j.enconman.2022.116218 |
| 49 | Xiao H., Zhang D., Tang Z., Li K., Guo H., Niu X., Yi L., | Comparative environmental and economic life cycle assessment of dry and wet anaerobic digestion for treating food waste and biogas digestate | 2022 | Journal of Cleaner Production | 10.1016/j.jclepro.2022.130674 |
| 50 | Yang J., Weil M., Gu F., | Environmental-economic analysis of the secondary use of electric vehicle batteries in the load shifting of communication base stations: A case study in China | 2022 | Journal of Energy Storage | 10.1016/j.est.2022.105823 |
| 51 | Yuliatti M.M.E., Husin A.E., Sutikno, | Improved Performance of Toll Road Projects Based on System Dynamics Integrated Life Cycle Cost Analysis Green Retrofitting | 2022 | Civil Engineering and Architecture | 10.13189/cea.2022.100635 |

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| ID | Study | Title | Year | Source title | DOI |
|---|---|---|---|---|---|
| 52 | Zhang N., Zhang D., Zuo J., Miller T.R., Duan H., Schiller G., | Potential for CO2 mitigation and economic benefits from accelerated carbonation of construction and demolition waste | 2022 | Renewable and Sustainable Energy Reviews | 10.1016/j.rser.2022.112920 |
| 53 | Zhang R., Tang N., Zhu H., Zeng J., Bi Y., Xi Y., | Environmental and economic comparison of semi-rigid and flexible base asphalt pavement during construction period | 2022 | Journal of Cleaner Production | 10.1016/j.jclepro.2022.130791 |
| 54 | Zhao J., Li S., | Life cycle cost assessment and multi-criteria decision analysis of environment-friendly building insulation materials - A review | 2022 | Energy and Buildings | 10.1016/j.enbuild.2021.111582 |
| 55 | Zhou Z., Alcalá J., Yepes V., | Research on Sustainable Development of the Regional Construction Industry Based on Entropy Theory | 2022 | Sustainability (Switzerland) | 10.3390/su142416645 |

Strikethrough text corresponds to studies that were not available for downloading to the IRISS consortium members.

| ID | LINK | Environmental dimension | Social dimension | Economic dimension | Area of application |
|---|---|---|---|---|---|
| 1 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85146335024&doi=10.1016%2fj.spc.2022.12.021&partnerID=40&md5=d6408c5aac768dd081874a36dc98649f | Yes | Yes | Yes | Bio-based products |
| 2 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85121624702&doi=10.1016%2fj.buildenv.2021.108656&partnerID=40&md5=4e9c1a7235a62592e6cd6f0d5dde45c7 | Yes | Yes | Yes | Construction |
| 3 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85135490293&doi=10.3390%2fenvironments9070092&partnerID=40&md5=e09e4bd1c5bb3d2e5f54ce7da3dc8f49 | Yes | Yes | Yes | Energy (materials, supply systems and batteries) |
| 4 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85145654724&doi=10.1007%2f978-981-19-6962-1_13&partnerID=40&md5=d5d330ca79a11a508428ba36ffbfda2f | Yes | Yes | Yes | Automotive and Transport |

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| ID | LINK | Environmental dimension | Social dimension | Economic dimension | Area of application |
|---|---|---|---|---|---|
| 5 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85137563400&doi=10.1016%2fB978-0-12-824117-2.00013-2&partnerID=40&md5=52472863b87cb6bf1dd8ee711360791f | Yes | Yes | Yes | Bio-based products |
| 6 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85140808394&doi=10.1016%2fj.jclepro.2022.134829&partnerID=40&md5=5afb3d81532c53dadeb3d8ee8a8dd9f8 | Yes | | Yes | Construction |
| 7 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85119604433&doi=10.1016%2fj.scs.2021.103539&partnerID=40&md5=1bc9467f20f5c23bb90d234f3dca69c0 | Yes | Yes | Yes | Waste management |
| 8 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85136099955&doi=10.1016%2fj.scitotenv.2022.158012&partnerID=40&md5=2b99bed9875daaafbc40444b62a89822 | Yes | | Yes | Food systems |
| 9 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85121027209&doi=10.1080%2f17452007.2021.2001307&partnerID=40&md5=31bfb88330c9f9584576d4becf63d0c9 | Yes | Yes | Yes | Construction |
| 10 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85136145598&doi=10.1155%2f2022%2f7750056&partnerID=40&md5=631f712d56f6194281ff0c424562be65 | Yes | Yes | Yes | Construction |
| 11 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85146418718&doi=10.1016%2fj.jobe.2023.105825&partnerID=40&md5=99995d410456cb33b72d17de7ceda78b | Yes | Yes | Yes | Construction |
| 12 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85129733293&doi=10.1007%2fs13762-022-04214-8&partnerID=40&md5=26d23c7e6d2bd2053fa55a542b856a46 | Yes | Yes | Yes | Community, Social and Personal services |
| 13 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85130631154&doi=10.1186%2fs13705-022-00344-6&partnerID=40&md5=578f8d5ffe5b48b76c4e01d26e589658 | Yes | Yes | Yes | Energy (materials, supply systems and batteries) |
| 14 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85135117473&doi=10.1007%2fs00170-022-09748-2&partnerID=40&md5=0af6fd7b2857b58b8559deb42766750c | Yes | | Yes | Metals |
| 15 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85126690474&doi=10.1016%2fj.landusepol.2022.106092&partnerID=40&md5=dd4a52d580ca2e340c636f88ed9f2a4c | Yes | Yes | Yes | Community, Social and Personal services |
| 16 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85139121752&doi=10.1088%2f1755-1315%2f1078%2f1%2f012078&partnerID=40&md5=1bb1a4ab8f75f55411dd93f7af2b49dd | Yes | Yes | Yes | Construction |

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| ID | LINK | Environmental dimension | Social dimension | Economic dimension | Area of application |
|---|---|---|---|---|---|
| 17 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85125522171&doi=10.1016%2fj.jobe.2022.104203&partnerID=40&md5=bb234fcd3274a823b352088961b797d9 | Yes | Yes | Yes | Construction |
| 18 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85141700390&doi=10.1016%2fj.spc.2022.10.027&partnerID=40&md5=498c5570f1a7fcc6aee7b4ca0d69df31 | Yes | Yes | Yes | Energy (materials, supply systems and batteries) |
| 19 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85141679702&doi=10.3390%2fhorticulturae8111054&partnerID=40&md5=e8520c01cf329ea3b1c3f0ff64bbd52d | Yes | Yes | Yes | Agriculture, Forestry and Fishing |
| 20 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85129573113&doi=10.1061%2f%28ASCE%29CO.1943-7862.0002281&partnerID=40&md5=44ee9db76bc5e76421c0da8bc3b6a44f | Yes | | Yes | Construction |
| 21 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85123244252&doi=10.1016%2fj.spc.2021.12.024&partnerID=40&md5=e12f1130fda7e575e8c24cc323f11a34 | Yes | Yes | Yes | Electronics and ICT |
| 22 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85118894709&doi=10.1016%2fj.autcon.2021.104035&partnerID=40&md5=7b862db6048a98f0604ebb05da290dc8 | Yes | Yes | Yes | Construction |
| 23 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85143792468&doi=10.3390%2fen15239173&partnerID=40&md5=53a61d49bd5a829c7bfe4efe4f959417 | Yes | Yes | Yes | Energy (materials, supply systems and batteries) |
| 24 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85146710580&doi=10.1016%2fj.enpol.2023.113430&partnerID=40&md5=f9393f8f0057b9297daf8c3a43986eb2 | Yes | Yes | Yes | Electronics and ICT |
| 25 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85139868744&doi=10.1016%2fj.jclepro.2022.134442&partnerID=40&md5=a8ab5605c49cbb781891bd102d65bf16 | Yes | Yes | Yes | Packaging |
| 26 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85134263894&doi=10.1016%2fj.jclepro.2022.133037&partnerID=40&md5=5e5e810449b8ee225cf0a201e08e0b4c | Yes | Yes | Yes | Food systems |
| 27 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85136582521&doi=10.1016%2fj.jclepro.2022.133615&partnerID=40&md5=67f4ed4dcca139387c000b50db378854 | Yes | | Yes | Construction |



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| ID | LINK | Environmental dimension | Social dimension | Economic dimension | Area of application |
|---|---|---|---|---|---|
| 28 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85117567471&doi=10.1016%2fj.rser.2021.111762&partnerID=40&md5=fe0cb1d9cb2802d70d7db4461f9a3f00 | Yes | Yes | Yes | Energy (materials, supply systems and batteries) |
| 29 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85128461254&doi=10.3389%2ffrsc.2022.856996&partnerID=40&md5=f204358b9c833771394846749f357580 | Yes | Yes | Yes | Energy (materials, supply systems and batteries) |
| 30 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85131295836&doi=10.1007%2fs11367-022-02064-7&partnerID=40&md5=13337cfb9502fca51668a855e0e9d779 | Yes | | Yes | Personal care |
| 31 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85124533935&doi=10.1016%2fj.spc.2022.01.033&partnerID=40&md5=cde997b237cc4dfa1438c0346789c4af | Yes | | Yes | Electronics and ICT |
| 32 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85139757422&doi=10.3390%2fsu141912380&partnerID=40&md5=5ce110e57f88b9bf3473a5d688eda9b5 | Yes | Yes | Yes | Energy (materials, supply systems and batteries) |
| 33 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85120860289&doi=10.1016%2fj.jclepro.2021.129724&partnerID=40&md5=52c13330958e719a28252b0e3deb3e13 | Yes | Yes | Yes | Construction |
| 34 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85146890931&doi=10.14716%2fijtech.v14i1.3028&partnerID=40&md5=fafab8bd872f65b54f8357b734d2160c",Article,"Final","All Open Access, Gold",Scopus,2-s2.0-85146890931 | Yes | Yes | Yes | Automotive and Transport |
| 35 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85143706047&doi=10.1016%2fj.jclepro.2022.134684&partnerID=40&md5=13ed8e6e96c36acdc5f4f28d0bc278c3 | Yes | | Yes | Waste management |
| 36 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85126698625&doi=10.1016%2fj.scitotenv.2022.154650&partnerID=40&md5=fc9b275146dcdc3ac9764436a82259f9 | Yes | Yes | Yes | Construction |
| 37 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85145654006&doi=10.3390%2fen16010419&partnerID=40&md5=28303e9dd6c0e6484b67effdf0c60076 | Yes | | Yes | Energy (materials, supply systems and batteries) |
| 38 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85137718278&doi=10.1016%2fj.eswa.2022.118679&partnerID=40&md5=8c8836d904c657d1e88c0a52fb6fa78a | Yes | | Yes | Products (not specified) |

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| ID | LINK | Environmental dimension | Social dimension | Economic dimension | Area of application |
|---|---|---|---|---|---|
| 39 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85119280077&doi=10.1016%2fj.jobe.2021.103516&partnerID=40&md5=6866713c1e4f421250f29a01bb63b287 | Yes | Yes | Yes | Construction |
| 40 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85127531329&doi=10.1007%2fs00170-022-08950-6&partnerID=40&md5=c1c213a805eeaf43043169e297cc67c0 | Yes | Yes | Yes | Automotive and Transport |
| 41 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85144539772&doi=10.1016%2fj.ifacol.2022.09.602&partnerID=40&md5=8a43c69380f415aef82a14771a8ac6e3 | Yes | Yes | Yes | Food systems |
| 42 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85133765732&doi=10.1016%2fj.scitotenv.2022.157229&partnerID=40&md5=af2643377e2079f47ff351f9278bf421 | Yes | Yes | Yes | Agriculture, Forestry and Fishing |
| 43 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85139459376&doi=10.2174%2f18741495-v16-e2205300&partnerID=40&md5=c6b673bfe7a680583d279633097c8d15 | Yes | Yes | Yes | Construction |
| 44 | https://geomatejournal.com/geomate/article/view/3319 | Yes | Yes | Yes | Construction |
| 45 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85108515044&doi=10.1016%2fj.jestch.2021.05.012&partnerID=40&md5=26691a91128eb8c11c5982c076d19591 | Yes | Yes | Yes | Construction |
| 46 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85120633411&doi=10.1016%2fj.jclepro.2021.129936&partnerID=40&md5=ff2ee5bcc45e6c534bf2541a3b1f071b | Yes | | Yes | Energy (materials, supply systems and batteries) |
| 47 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85118350376&doi=10.1016%2fj.enbuild.2021.111600&partnerID=40&md5=cee547023a82a234660a3038d276588c | Yes | | Yes | Construction |
| 48 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85138050565&doi=10.1016%2fj.enconman.2022.116218&partnerID=40&md5=adf842728fc3258251eb90f61fe93472 | Yes | | Yes | Energy (materials, supply systems and batteries) |
| 49 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85123633983&doi=10.1016%2fj.jclepro.2022.130674&partnerID=40&md5=8d2cc53a2bfbd9aba81c16a279854b80 | Yes | | Yes | Waste management |
| 50 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85139877745&doi=10.1016%2fj.est.2022.105823&partnerID=40&md5=10062f6d84110f4e3666b224275af72a | Yes | | Yes | Energy (materials, supply systems and batteries) |

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| ID | LINK | Environmental dimension | Social dimension | Economic dimension | Area of application |
|---|---|---|---|---|---|
| 51 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85139440827&doi=10.13189%2fcea.2022.100635&partnerID=40&md5=5572c8ef2a721fd514e89e4580bb82f3 | Yes | | Yes | Construction |
| 52 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85138505445&doi=10.1016%2fj.rser.2022.112920&partnerID=40&md5=c0e7bd2bf15cdbc2266c5a183ad25c8e | Yes | | Yes | Waste management |
| 53 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85124213717&doi=10.1016%2fj.jclepro.2022.130791&partnerID=40&md5=157b41a0e05f2c57478b3675d2729a4e | Yes | | Yes | Construction |
| 54 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85118572599&doi=10.1016%2fj.enbuild.2021.111582&partnerID=40&md5=69ec0c0701b7b1f7bb8d5ea033d33e03 | Yes | | Yes | Construction |
| 55 | https://www.scopus.com/inward/record.uri?eid=2-s2.0-85144899453&doi=10.3390%2fsu142416645&partnerID=40&md5=53ac4a501ba1c94954603cf40d5dfcbd | Yes | Yes | Yes | Construction |

Note: The Scopus search were screened regarding the sustainability dimensions (environmental, social, and economic). However, safety was also considered by two of the studies (ID 18 and ID44)

| | Database | | | | | Impact assessment method | | | | | Software | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | ECOINVENT | USLCI | ELCD | PSILCA | SHDB | PEF (Product Environmental Footprint) | ReCiPe | CML | Impact World+ | USEtox | SimaPro | Gabi | OpenLCA | UMBERTO |
| 1 | X | | | | | X | X | | | | X | | X | |
| 2 | X | | | | | | | | | | | | | |
| 3 | X | | X | | | | X | X | | | X | X | X | |
| 4 | | | | | | | | | | | | | | |
| 5 | X | | | | | | X | | | | X | X | X | X |

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| | Database | | | | | Impact assessment method | | | | | Software | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | ECOINVENT | USLCI | ELCD | PSILCA | SHDB | PEF (Product Environmental Footprint) | ReCiPe | CML | Impact World+ | USEtox | SimaPro | Gabi | OpenLCA | UMBERTO |
| **6** | | | | | | X | | X | | | X | | | |
| **7** | | | | | | | | | | | X | | | |
| **8** | X | | | | | | | | | | | | | |
| **9** | | | | | | | | | | | | | | |
| **10** | | | | | | | | | | | | | | |
| **11** | | | | | | | | | | | | | | |
| **12** | X | | | | | | | | | | X | | | |
| **13** | X | | | | | | X | X | | | | X | X | X |
| **14** | | | | | | | | X | | | X | | | |
| **15** | | | | | | | | | | | | | | |
| **16** | | | | | | | | | | | | | | |
| **17** | | | | | X | | | | | | | | | |
| **18** | X | | | | X | | X | X | | X | X | X | X | |
| **19** | | | | | | X | | X | | | X | | | |
| **20** | | | | | | | | | | | | | | |
| **21** | X | | | | | | X | | | | | | | |
| **22** | X | X | | | | | | | | | | | | |
| **23** | X | | | | | | | X | | | X | | | |
| **24** | | | | | | | | | | | | | | |
| **25** | X | | | X | X | X | X | | | | X | | | |

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| | Database | | | | | Impact assessment method | | | | | Software | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | ECOINVENT | USLCI | ELCD | PSILCA | SHDB | PEF (Product Environmental Footprint) | ReCiPe | CML | Impact World+ | USEtox | SimaPro | Gabi | OpenLCA | UMBERTO |
| 26 | | | | | | | | | | | | | | |
| 27 | | | | | | | | X | | | X | | | |
| 28 | | | | | | | X | X | | X | X | X | X | X |
| 29 | | | | | | | | | | | | | | |
| 30 | X | | | | | | X | | | | | | | |
| 31 | X | | | | | | | | | | | | | |
| 32 | | | | | | | X | X | | | | | | |
| 33 | X | | | | | | X | | | | | | | |
| 34 | | | | | | | | | | | | | | |
| 35 | X | | | | | | | | | | | | | |
| 36 | X | | | | | | X | X | X | | X | X | | |
| 37 | | | | | | | X | | | | X | | | |
| 38 | X | | | | | | | | | | X | X | | |
| 39 | | | | | | | | | | | | | | |
| 40 | | | | | | | X | | | | X | | | |
| 41 | | | | | | | | | | | | | | |
| 42 | X | | | X | X | | X | | | | X | | | |
| 43 | | | | | | | | | | | | | | |
| 44 | | | | | | | | | | | | | | |
| 45 | | | | | | | | | | | | | | |

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| | Database | | | | | Impact assessment method | | | | | Software | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | ECOINVENT | USLCI | ELCD | PSILCA | SHDB | PEF (Product Environmental Footprint) | ReCiPe | CML | Impact World+ | USEtox | SimaPro | Gabi | OpenLCA | UMBERTO |
| 46 | | | | | | | | | | | | X | | |
| 47 | X | | | | | | | | | X | | | | |
| 48 | X | | | | | | X | | | | X | | | |
| 49 | X | | | | | | | X | | | X | X | | |
| 50 | X | | | | | | X | X | | | | | | |
| 51 | | | | | | | | | | | | | | |
| 52 | | | | | | | | | | | | X | | |
| 53 | | | | | | | | | | | | | | |
| 54 | | | | | | | | | | | | | | |
| 55 | X | | | X | | | | | | | | | X | |

| | Circular economy considerations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | Durability | Reusability | Repairability | Renewable | Recycled content | Lifespan | Recycling | Recovery | Valorization | MCI |
| 1 | | X | | | | | | X | X | |
| 2 | | | | X | | X | | | | |
| 3 | | | | X | | | X | | | |
| 4 | | | | | | | | | | |
| 5 | | | | | | | | X | | |

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| | Circular economy considerations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Durability | Reusability | Repairability | Renewable | Recycled content | Lifespan | Recycling | Recovery | Valorization | MCI |
| **6** | | X | | X | X | | X | X | | X |
| **7** | | | | X | | | X | X | | |
| **8** | | | | | | | | | X | |
| **9** | X | X | | | X | | X | X | | |
| **10** | | X | | | | | X | X | | |
| **11** | X | | | X | | | X | X | | |
| **12** | | | | X | | | | | | |
| **13** | | | X | X | | | X | | | |
| **14** | X | | | | | | X | X | | |
| **15** | | | | X | | X | X | | | |
| **16** | | | | | | | X | | | |
| **17** | X | X | | X | | | X | X | | |
| **18** | | X | X | X | | X | X | X | | |
| **19** | | | | | | | X | | | |
| **20** | | | | X | | | | | | |
| **21** | | | | | | X | | | | |
| **22** | X | | | | | | X | | | |
| **23** | | X | | | | | | X | | |
| **24** | X | | X | | | | X | | | |
| **25** | X | X | | | X | | X | X | | X |
| **26** | | | | X | | X | X | X | | |

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| | Circular economy considerations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | Durability | Reusability | Repairability | Renewable | Recycled content | Lifespan | Recycling | Recovery | Valorization | MCI |
| 27 | | | | | | | X | | | |
| 28 | X | X | X | X | | | X | X | X | |
| 29 | | X | | X | | | | X | | |
| 30 | | X | X | X | X | X | X | | | |
| 31 | | X | X | | | | X | X | | |
| 32 | | | | X | | X | X | X | | |
| 33 | X | | | | | | X | X | | |
| 34 | | | | X | | | | | | |
| 35 | | | | X | | | | X | X | |
| 36 | X | X | | | | X | X | X | | |
| 37 | | X | | X | | | X | X | | |
| 38 | | | | | | | X | | | |
| 39 | | | | | | | | | | |
| 40 | | X | | X | | | X | X | | |
| 41 | | | | | | | | | | |
| 42 | | X | | X | | X | X | X | X | X |
| 43 | X | X | | | | | X | | | |
| 44 | X | X | | X | | | X | | | |
| 45 | X | X | | | | | X | | | |
| 46 | | | X | X | | X | X | X | | |
| 47 | | X | | | | | | | | |

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| | Circular economy considerations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Durability | Reusability | Repairability | Renewable | Recycled content | Lifespan | Recycling | Recovery | Valorization | MCI |
| **48** | | X | | X | | | | X | | |
| **49** | | | | X | | X | | X | | |
| **50** | | X | | X | | | X | X | | |
| **51** | | X | X | X | | | X | | | |
| **52** | | X | | X | | | X | | | |
| **53** | | | | | | | X | | | |
| **54** | X | | | X | | | X | X | X | |
| **55** | | | | | | | | | | |

| | **Environmental indicators** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Ecotoxicity | Acidification | Eutrophication | Climate change | Global warming | GHG emissions | Ozone depletion | Human toxicity | Fossil resources | Mineral resources | Land resources | Water resources | Land use | Resource use |
| **1** | X | X | X | X | X | X | | X | | | | | X | X |
| **2** | | X | X | | X | | X | | | | | | X | X |
| **3** | X | X | X | X | X | X | X | X | | | | | | |
| **4** | | | | | | X | | | | | | | | |

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| | Environmental indicators | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Ecotoxicity | Acidification | Eutrophication | Climate change | Global warming | GHG emissions | Ozone depletion | Human toxicity | Fossil resources | Mineral resources | Land resources | Water resources | Land use | Resource use |
| **5** | X | X | X | X | | X | X | X | | | | | X | |
| **6** | | | | X | | X | | | X | | | | X | X |
| **7** | X | X | X | X | | | X | X | | | | | X | |
| **8** | | X | X | X | X | | | | | | | | X | |
| **9** | | | | | | | | | | | | | | |
| **10** | | | | | | X | | | | | X | | | |
| **11** | | | | X | X | X | | | | | | | X | |
| **12** | | | | X | X | X | | | | | | | | |
| **13** | | | | X | X | | X | X | | | | | X | |
| **14** | X | | | | X | X | | X | | | | | X | |
| **15** | | | | | | | | | | | | X | X | |
| **16** | | | | | | | | | | | | | | |
| **17** | | | | X | | X | | | | | | | | X |
| **18** | X | X | X | X | X | X | X | X | | | | | X | |
| **19** | X | X | X | X | X | X | X | X | | | | | | |
| **20** | | | | X | X | | | | | | | | X | |
| **21** | | | | | | | | | | | | | | |
| **22** | | X | X | X | | X | | X | | | | | | |
| **23** | | X | X | X | X | X | | X | | | | | | X |

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| | Environmental indicators | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Ecotoxicity | Acidification | Eutrophication | Climate change | Global warming | GHG emissions | Ozone depletion | Human toxicity | Fossil resources | Mineral resources | Land resources | Water resources | Land use | Resource use |
| **24** | | | | | | X | | | | | | | | X |
| **25** | X | X | X | X | | | | X | | | | | | |
| **26** | | | | X | | X | | | | | | | | |
| **27** | X | X | X | X | X | | | X | | | | | | |
| **28** | X | X | X | X | X | X | X | X | X | | | | | |
| **29** | | | | X | | X | | | | | | | | |
| **30** | | | | | | | | | | | | | | |
| **31** | | | | | | | | | | | | | | |
| **32** | X | X | X | X | X | X | X | X | | | | | | |
| **33** | | | X | X | | | X | | | X | | | X | |
| **34** | | | | | | | | | | | | | | |
| **35** | X | X | | X | | | | X | | | | | | |
| **36** | X | | X | | X | | X | | | | | | | |
| **37** | X | X | X | X | | X | X | X | | | | | | |
| **38** | | | | | | | | | | | | | | X |
| **39** | | | | | | | | | | | | | | |
| **40** | | | | X | X | X | X | X | X | | | | X | |
| **41** | | | | | | | | | | | | | | |
| **42** | | | X | | | | | | | | | | | X |

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| ID | Environmental indicators | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ecotoxicity | Acidification | Eutrophication | Climate change | Global warming | GHG emissions | Ozone depletion | Human toxicity | Fossil resources | Mineral resources | Land resources | Water resources | Land use | Resource use |
| **43** | | | | | X | | | | | | | | | |
| **44** | | | | | | X | | | | | | | | |
| **45** | | | | | | | | | | | | | | |
| **46** | | X | X | | X | | X | | | | | | | |
| **47** | X | X | X | | X | | X | X | | | | | X | |
| **48** | X | X | X | X | X | X | X | X | | | | | X | |
| **49** | X | X | X | X | X | X | X | X | | | | | | |
| **50** | | | X | | X | | | | | | | | | |
| **51** | | | | X | X | X | | | | | | | | |
| **52** | | | | | | | | | | | | X | | |
| **53** | | | | X | X | X | | | | | | | | |
| **54** | | | | | | | | X | | | X | | | |
| **55** | X | X | X | X | X | X | X | X | | | | | X | |

| ID | LCA stages/phases | | | | | | |
|---|---|---|---|---|---|---|---|
| | Raw material extraction | Production/Processing/Manufacturing Stage/Phase | Use/Consume Stage/Phase | End of life | Disposal | Recycling | Reuse |
| **1** | | X | X | X | X | | X |
| **2** | | | | | X | | |

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| | LCA stages/phases | | | | | | |
|---|---|---|---|---|---|---|---|
| **ID** | Raw material extraction | Production/Processing/Manufacturing Stage/Phase | Use/Consume Stage/Phase | End of life | Disposal | Recycling | Reuse |
| **3** | | X | | | X | X | |
| **4** | | | | | X | | |
| **5** | X | | | | X | | |
| **6** | X | | | X | X | X | X |
| **7** | | | | X | X | X | |
| **8** | | X | X | X | | | |
| **9** | | X | | X | X | X | X |
| **10** | | X | | | X | X | X |
| **11** | | | | | X | X | |
| **12** | | | X | X | X | | |
| **13** | X | | X | X | X | X | |
| **14** | | X | X | X | X | X | |
| **15** | | | | | | X | |
| **16** | | | | | | X | |
| **17** | X | | X | X | X | X | X |
| **18** | | | | X | X | X | X |
| **19** | X | | | X | X | X | |
| **20** | | | | | | | |
| **21** | | | | X | X | | |
| **22** | | | X | X | | X | |
| **23** | | | | X | X | | X |

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| ID | LCA stages/phases | | | | | | |
|---|---|---|---|---|---|---|---|
| | Raw material extraction | Production/Processing/Manufacturing Stage/Phase | Use/Consume Stage/Phase | End of life | Disposal | Recycling | Reuse |
| 24 | | X | X | | | X | |
| 25 | X | X | X | X | X | X | X |
| 26 | | X | | | | X | |
| 27 | | X | | X | X | X | |
| 28 | X | | X | X | X | X | X |
| 29 | | | | | X | | X |
| 30 | | | | | | X | X |
| 31 | | | X | X | X | X | X |
| 32 | X | X | | X | X | X | |
| 33 | | | X | X | X | X | |
| 34 | | | | | | | |
| 35 | | | X | | | | |
| 36 | X | X | X | X | X | X | X |
| 37 | | X | X | X | X | X | X |
| 38 | | | | | X | X | |
| 39 | | | | X | | | |
| 40 | X | | | X | X | X | X |
| 41 | | | | | | | |
| 42 | X | X | X | X | X | X | X |
| 43 | | | | | | X | X |
| 44 | | | | | | X | X |

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| ID | LCA stages/phases | | | | | | |
|---|---|---|---|---|---|---|---|
| | Raw material extraction | Production/Processing/Manufacturing Stage/Phase | Use/Consume Stage/Phase | End of life | Disposal | Recycling | Reuse |
| 45 | | | | | X | X | X |
| 46 | X | X | | X | X | X | |
| 47 | | X | | X | X | | X |
| 48 | | | | | X | | X |
| 49 | X | | | | X | | |
| 50 | | | X | X | X | X | X |
| 51 | | | X | | X | X | X |
| 52 | | | | X | X | X | X |
| 53 | X | | | | | X | |
| 54 | | | | | X | X | |
| 55 | X | | | | | | |

| ID | Social indicators | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Poverty | Corruption | Child labor | Forced labor | Fair salary/wage | Working hours | Local employment | Health and Safety (workers) | Health and Safety (consumers) | Freedom of association | Collective bargaining | Equal opportunities | Discrimination | Community engagement |
| 1 | | | | | | | | | | | | | | X |
| 2 | | | | | | | | | | | | | | |
| 3 | | | | | | | | X | X | | | | | |
| 4 | X | | | | | | | | | | | | | |
| 5 | | | X | X | | | | X | X | X | X | | | X |

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| | Social indicators | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Poverty | Corruption | Child labor | Forced labor | Fair salary/wage | Working hours | Local employment | Health and Safety (workers) | Health and Safety (consumers) | Freedom of association | Collective bargaining | Equal opportunities | Discrimination | Community engagement |
| **6** | | | | | | | | | | | | | | |
| **7** | X | | | | | | | | | | | | | |
| **8** | X | | | | | | | | | | | | | |
| **9** | | | | | | | | | | | | | | |
| **10** | | | | | | | | | | | | | | |
| **11** | | | | | | | | | | | | | | |
| **12** | | | X | | | | | X | X | | | X | X | |
| **13** | | | | | | | | X | X | | | | | |
| **14** | | | | | | | | | | | | | | |
| **15** | | | | | | | | | | | | | | |
| **16** | | | | | | | | | | | | | | |
| **17** | | | | | | | | | | | | | | |
| **18** | | | | | | | X | X | X | | | | | X |
| **19** | | X | X | | X | X | X | | | | | X | X | |
| **20** | | | | | | | | | | | | | | |
| **21** | | | | | | | | | | | | | | |
| **22** | | | | | | | | | | | | | | |
| **23** | | | | | | X | | X | X | | | X | | |
| **24** | | | | | | | | | | | | | | |

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| | Social indicators | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Poverty | Corruption | Child labor | Forced labor | Fair salary/wage | Working hours | Local employment | Health and Safety (workers) | Health and Safety (consumers) | Freedom of association | Collective bargaining | Equal opportunities | Discrimination | Community engagement |
| 25 | | | | | | | X | X | | X | | | X | |
| 26 | | | | | | | | | | | | | | |
| 27 | | | | | | | | | | | | | | |
| 28 | | | | | | | X | | | | | | | |
| 29 | | | | | | | | | | | | | | |
| 30 | | | | | | | | | | | | | | |
| 31 | | | | | | | | | | | | | | |
| 32 | | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 33 | | | | | X | X | X | X | X | | | | | |
| 34 | | | | | | | | | | | | | | |
| 35 | | | | | | | | | | | | | | |
| 36 | | | | | | | | | | | | | | |
| 37 | | | | | | | | | | | | | | |
| 38 | | | | | | | | | | | | | | |
| 39 | | | | | | X | | | | | | | | |
| 40 | | | | | | | | | | | | | | |
| 41 | | | | | | | | | | | | | | |
| 42 | X | X | X | | X | | | | | | | | | |
| 43 | | | | | | | | X | X | | | | | |

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| | Social indicators | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Poverty | Corruption | Child labor | Forced labor | Fair salary/wage | Working hours | Local employment | Health and Safety (workers) | Health and Safety (consumers) | Freedom of association | Collective bargaining | Equal opportunities | Discrimination | Community engagement |
| 44 | | | | | | | | X | | | | | | |
| 45 | | | | | | | | | | | | | | |
| 46 | | | | | | | | | | | | | | |
| 47 | | | | | | | | | | | | | | |
| 48 | | | | | | | | | | | | | | |
| 49 | | | | | | | | | | | | | | |
| 50 | | | | | | | | | | | | | | |
| 51 | | | | | | | | | | | | | | |
| 52 | | | | | | | | | | | | | | |
| 53 | | | | | | | | | | | | | | |
| 54 | | | | | | | | | | | | | | |
| 55 | X | | | | | | | | | | | | | |

| | LCC indicators (I) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Purchase cost | Production cost | Minimum selling price | Profitability | Net present value | Added value | Payback period | LCC | Waste cost | Recycling cost | Willingness to pay | cLCC | eLCC | sLCC | Financial incentives |
| 1 | | X | X | X | X | | X | X | | | | | | | |
| 2 | | | | | X | | X | X | | | | | | | |
| 3 | | | | | | | | X | | | | | | | |
| 4 | | | | | | | | X | | | | | | | |

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| | LCC indicators (I) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Purchase cost | Production cost | Minimum selling price | Profitability | Net present value | Added value | Payback period | LCC | Waste cost | Recycling cost | Willingness to pay | cLCC | eLCC | sLCC | Financial incentives |
| 5 | | | | | | | | X | | | | | | | |
| 6 | | | | | | X | | X | | | | | | | |
| 7 | | | | | | | X | X | | X | | | | | |
| 8 | | X | | X | X | X | X | X | | | X | X | X | X | |
| 9 | | | | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | | | | |
| 11 | | | | | | | | X | | | | | | | |
| 12 | | | | | | | | X | X | | | | | | |
| 13 | X | X | | | X | X | X | X | | | | | | | |
| 14 | | X | | | X | | | X | | | | | | | |
| 15 | | | | | | | | X | | | | | | | |
| 16 | | | | | | | | | | | | | | | |
| 17 | | | | X | | | | X | | | | | | | |
| 18 | | | | | X | | | X | | | | | | | |
| 19 | | X | | | | | | X | | | | | | | |
| 20 | | | | | X | | X | X | | | | | | | |
| 21 | X | X | | | | | | X | | | | | | | |
| 22 | | | | | X | | | X | | | | | | | |
| 23 | | | | | | | | X | | | | | | | |
| 24 | | | | | | | | | | | X | | | | |

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| | LCC indicators (I) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Purchase cost | Production cost | Minimum selling price | Profitability | Net present value | Added value | Payback period | LCC | Waste cost | Recycling cost | Willingness to pay | cLCC | eLCC | sLCC | Financial incentives |
| **25** | X | X | | | | | | X | | | | | | | |
| **26** | | X | | X | | | | X | X | | X | | | | |
| **27** | | | | | X | | | X | | | | | | | |
| **28** | | | X | X | X | X | X | X | | | | | | | |
| **29** | | | | | | | | X | | | | | | | |
| **30** | | | | | | | | | | | | | | | |
| **31** | | | | | | | | X | | | | | | | |
| **32** | | | | X | X | | X | X | | X | | | | | |
| **33** | | | | | | | | X | | | | | | | |
| **34** | | | | X | | | | | | | | | | | |
| **35** | | | | | X | X | | X | | | | | | | |
| **36** | | | | | X | | | X | | | | | | | |
| **37** | | | | | | | | X | | | | | | | |
| **38** | | | | | | | | X | | | | | | | |
| **39** | | | | | | | | X | | | | | | | |
| **40** | | | | X | | X | | X | | | | | | | |
| **41** | | | | | | | | X | | | | | | | |
| **42** | | | | X | X | | X | X | | | | X | X | X | |
| **43** | | | | X | | | | X | | | | | | | |
| **44** | | | | | | | | | | | | | | | |

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| | LCC indicators (I) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Purchase cost | Production cost | Minimum selling price | Profitability | Net present value | Added value | Payback period | LCC | Waste cost | Recycling cost | Willingness to pay | cLCC | eLCC | sLCC | Financial incentives |
| **45** | | X | | | X | | | X | | | | | | | |
| **46** | | | | | X | | | X | | | | | | | |
| **47** | | X | | | | | | | | | | | | | |
| **48** | X | X | X | | X | | | X | | | | | | | |
| **49** | | | | | X | | | X | | | | | | | |
| **50** | X | X | | X | X | | X | X | | | | | | | X |
| **51** | | | | | | | | | | | | | | | |
| **52** | | | | X | | | | X | | | | | | | |
| **53** | | | | | | | | X | | | X | | | | |
| **54** | | X | | | X | | X | X | | X | | | | | |
| **55** | X | | | | | | | X | | | | | | | |

| | LCC indicators (II) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Internal rate of return (IRR) | Investment cost | Revenues | Electricity cost | Operating and maintenance costs | Capital cost | Raw material cost | Labour cost | External cost | Gross Domestic Product (GDP) | Monetization |
| **1** | X | | | | | X | | | | | |
| **2** | X | | | | | | | | | | |
| **3** | | | | | | | | | | | |
| **4** | | | | | X | | | X | X | X | |

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| | **LCC indicators (II)** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Internal rate of return (IRR) | Investment cost | Revenues | Electricity cost | Operating and maintenance costs | Capital cost | Raw material cost | Labour cost | External cost | Gross Domestic Product (GDP) | Monetization |
| **5** | | | | | | | | | | | |
| **6** | | | | | | | | | | | |
| **7** | | | | | | X | | | | | |
| **8** | X | X | X | | | | | | X | | X |
| **9** | | | | | | | | | | | |
| **10** | | X | | | | | | | X | X | |
| **11** | | | | | | | | | | | |
| **12** | | | | | | | | | | | |
| **13** | | X | X | | | X | X | | | X | |
| **14** | | | | | | X | X | X | | X | |
| **15** | | | X | | | | | | | | |
| **16** | | | | | | | | | | | |
| **17** | | X | | | | | | | | | |
| **18** | | X | X | | | X | | | | | |
| **19** | | X | | | | | | X | | | |
| **20** | | | | | | X | | | | | |
| **21** | | | | | | | | X | | | |
| **22** | | | | | | | | | | | |
| **23** | | | X | X | X | X | | | | | |
| **24** | | | | X | | | | | | | |

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| | LCC indicators (II) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Internal rate of return (IRR) | Investment cost | Revenues | Electricity cost | Operating and maintenance costs | Capital cost | Raw material cost | Labour cost | External cost | Gross Domestic Product (GDP) | Monetization |
| **25** | | | | | | | | | | | |
| **26** | | X | X | | | | X | X | X | | X |
| **27** | | | | | | | | X | | | |
| **28** | X | | X | | | | | | | | |
| **29** | | | | | | X | | | | | |
| **30** | | | | | | | | | | | |
| **31** | | | X | | | | | X | | | |
| **32** | | X | | | | | | | | | |
| **33** | | | | | | | | | | | |
| **34** | X | | | | | X | | | | | X |
| **35** | X | X | X | | | | | | | | |
| **36** | | | | | | | | | | | |
| **37** | | X | | X | | | | X | | | |
| **38** | | | | | | | | | | | |
| **39** | | | | | | | | | | | |
| **40** | | | | | X | | | X | | | |
| **41** | | | | | | | | | | | |
| **42** | X | X | X | | | | | X | X | | X |
| **43** | | X | | | | | | | | X | |
| **44** | | X | | | | | | | | X | |

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| | LCC indicators (II) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | Internal rate of return (IRR) | Investment cost | Revenues | Electricity cost | Operating and maintenance costs | Capital cost | Raw material cost | Labour cost | External cost | Gross Domestic Product (GDP) | Monetization |
| **45** | X | | | | | | | | | | |
| **46** | | X | | | | | | | | | |
| **47** | | X | | | | | | | X | | X |
| **48** | | | X | | | X | | | | | |
| **49** | | | X | | | X | | X | | | |
| **50** | | X | X | X | | X | | | | | |
| **51** | | | | | X | | | | | | |
| **52** | | | | | | | | X | | X | |
| **53** | | | | | | | | X | | | |
| **54** | | X | | X | | | | | | | |
| **55** | | | | | | | | X | | X | |

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