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

Preliminary report

Lifecycle analysis mapping

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Table of contents

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Abbreviations and Acronyms

Abbreviation	Definition
CFF	Circular Footprint Formula
CFP	Carbon Footprint of Product
C2C	Cradle to Cradle
EF	Environmental Footprint
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
GWP	Global warming potential
ICT	Information and Communication Technologies
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Analysis
LCT	Life Cycle Thinking
NGO	Non Governamental Organization
OEF	Organization Environmental Footprint
OEFSRs	Organization Environmental Footprint Sector Rules
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PR	Preliminary report
RP	Representative product
SETAC	Society of Environmental Toxicology and Chemistry
SSbD	Safe and Sustainable by design
UNEP	United Nations Environment Program
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

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1. Executive Summary

This preliminary report PR1.3 “Lifecycle assessment mapping” is the main outcome of the task 1.3 “Lifecycle methods and criteria” and is part of the mapping activity conducted within Work Package 1 (WP1) “Complete overview of Safe and Sustainable by design (SSbD) methods and criteria” of the IRISS project. PR1.3 is focussed on analysing one of the core elements of the SSbD concept, the assessment of environment sustainability aspects of a material throughout its entire value chain, from raw material extraction to waste management. Life Cycle Assessment (LCA) provides a scientific basis for decision-making in SSbD in terms of environmental performance. By comparing the environmental impacts of different supply chain configurations, materials, or technologies during the design phase, LCA enables the selection of the most sustainable option, reduction of environmental impacts, and the contribution to a greener future.

A literature review was carried out to elaborate the mapping. Literature sources were public documents (policy documents and papers), public reports, and scientific publications in open databases. The literature review covered the 3 main pillars of sustainability (environmental, social, and techno-economical dimensions). The detailed methodology used for the literature review is described in the preliminary report “PR1.2- Sustainable by design methods and criteria mapping”. This preliminary report PR1.3 is focused on the **Life cycle environmental assessment dimension.** Within the report, the **standards, methodologies, and tools** (databases, software impact assessment methods, and environmental indicators) have been analysed. This information has been complemented with the results obtained from the survey that was conducted within the IRISS network and the identified stakeholders, to understand the status of SSbD application and competencies in both academia and industries.

The work is divided into 6 main sections starting with a description of the objectives of this preliminary report and the introduction to the Life Cycle Assessment (LCA) concept (chapter 2). Chapter 3 maps the main standards and methodologies related to LCA. Apart from the two primary standards widely recognized and followed in LCA (ISO 14040 and ISO 14044), several standards and guidelines have been identified and briefly described. Special attention has been paid to EPD (Environmental Product Declaration) and PEF (Product Environmental Footprint) that have been analysed in more detail. The PEF is the LCA methodology recommended by the European Commission to be used in the recently published SSbD framework developed by the Joint Research Centre (JRC) [1].

Chapter 4 describes the main LCA software, database and impact assessment methods identified in the literature review. Availability of data (of good quality) is one key aspects for Life Cycle modelling. Ecoinvent, has been identified as the database with the higher number datasets and it is the most widely used according to the bibliographical search, survey results and the EU project analysis. Concerning the LCA software, a variety of tools can be found in the market, encompassing both commercial options that require purchase and freely available alternatives. Based on the literature review, survey, and EU project analysis, SimaPro has emerged as the most frequently utilized software, closely followed by GaBi and OpenLCA. In terms of Impact assessment methods, the survey results and ongoing Horizon Europe projects suggest that the EF (Environmental Footprint) methodology is the most employed impact assessment methodology. This aligns with the methodology proposed by the JRC SSbD framework.

Chapter 5 analyses one of the most challenging issues of LCA in the context of SSbD, how to perform a LCA study at the design phase of a new material, when the maturity level of the technology is low and there is no industrial data available. To overcome this gap, in the last years there has been a growing interest in the ex-ante LCA also known as prospective LCA. Since SSbD involves cutting-

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edge technologies and processes, there are inherent uncertainties regarding their performance, scalability, and environmental impact. Ex-ante LCA helps in quantifying and managing these uncertainties by utilizing process simulations, lab-scale data, and modelling techniques. This allows for a more comprehensive understanding of potential environmental impacts and the identification of critical areas for further research and improvement.

The analysis regarding environmental dimension outputs from the survey is summarized in chapter 6. The results obtained align with the findings of the literature review. Besides, an analysis on how the relevant identified SSbD related EU projects implement LCA during the design phase has been performed in chapter 7, showing a similar trend to the survey results.

The report ends with the main **conclusions of the study** (chapter 8). With the introduction of the Joint Research Center (JRC) and the European Commission's Safe and Sustainable-by-Design (SSbD) framework, the interest in ensuring the safety and sustainability of materials at the early stages of innovation is increasing rapidly.

In essence, LCA plays a crucial role in SSbD as it helps to identify environmental hotspots, quantify impacts, aid in decision-making during the design process, and enhance transparency and accountability. By integrating LCA into the design and management of supply chains, companies can make more sustainable choices, reduce environmental impacts, and contribute to a sustainable future. Nevertheless, there are still several methodological challenges that needs to be addressed and will be further analysed within IRISS WP2-“gap analysis”.

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2. Introduction

This preliminary report PR1.3 is part of the IRISS Project "IRISS – International ecosystem for accelerating the transition to Safe-and-Sustainable-by-Design materials, products and processes" and includes the results from the activities carried out within task 1.3 of the work package 1 (WP1) of the IRISS project. WP 1 aims to obtain a complete overview of the SSbD methods and criteria.

Elements for the definition of SSbD criteria are depicted in Figure 1, they 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 (Life Cycle Assessment), LCC (Life Cycle Costing), S-LCA (Social Life Cycle Assessment), etc.
- **Methods**: measurement methods, models, software tools and databases to get the numerical value of the different indicators.
- **Indicators:** magnitudes for impact assessment (e.g., ecotoxicity, children labour...)
- **Tools**: Software, applications, databases supporting the analysis done by adopting specific methods.

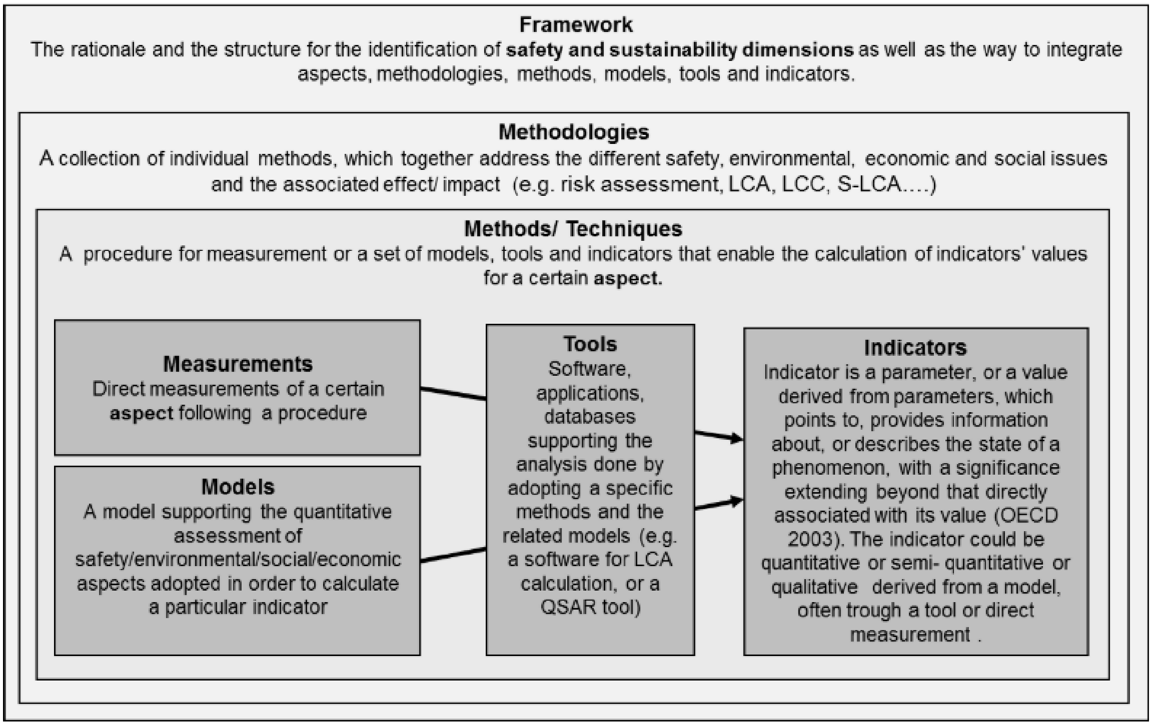

Figure 1 – Conceptual representation of the elements to be considered in the development of a framework for the definition of criteria for SSbD chemicals and materials taken from [2]

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 included in WP1:

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

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

This preliminary report PR1.3 includes the results from the activities carried out within task 1.3 and the main objective is to map the available life cycle assessment methodologies, indicators, and tools.

The design of the material is focused to provide a function (or service) while reducing harmful impacts to human, health and environment for better public engagement, consumer acceptance, adapting regulations to speed up market uptake. The SSbD approach requires to consider all stages of the material and product development lifecycle, to design sustainable products and processes. This includes the production process, transport, and use (including durability, reparability), recycling, and end of life. Available databases and methodologies (e.g., UseTox, Ecoindicator, PEF, ReCiPe, PSA) has been mapped.

2.1 Introduction to Life Cycle Assessment

The second half of the twentieth century was characterised by a greater awareness of the importance of the protection of the environment and the possible negative impacts associated with products and processes. Several organizations increased their interest in the application of methodologies aimed at a better understanding of the interactions that their products or activities had with the environment. In the last years, Life Cycle Assessment (LCA) became one of the most important tools for environmental management. According to this, every product, process, or activity must be seen from the perspective of its life cycle. This means that if there is the necessity of evaluating the environmental impacts of a product, its manufacturing is not enough, but its entire life cycle with all life cycle stages must be considered, from the extraction of the raw materials to its disposal or recycling. In other words, LCA is a method to assess the environmental impacts of goods and processes from **"cradle to grave**" quantitatively [4], which covers:

1. Raw Material Extraction, also called the "cradle"
2. Manufacturing & Processing
3. Transportation
4. Usage & Retail
5. Waste handling also called the "grave"

However, historically there has been a tendency to perform simplified LCA studies using a **Cradle-to-gate approach.** Cradle-to-gate only assesses a product until it leaves the factory gates before it is transported to the consumer (stages 1 &2). This can be advantageous when the use phase and end-of-life considerations have limited relevance or are outside the scope of the assessment. By narrowing the scope, the assessment can prioritize and target specific areas for environmental improvement. An example of a cradle-to-gate product might be an aluminium can of a soft drink. company focuses on measuring the environmental impact of the materials needed to produce the drink itself as well as the aluminium packaging, plus the impact of the transportation required to deliver the cans to nearby stores. However, the company assumes that consumers will handle the

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product's use and end-of-life stages, including recycling the cans, making it unnecessary for the company to measure the final destination of their product.

The other main reason to select the cradle to gate approach is the resource and time constraints. Conducting a cradle to grave LCA requires more extensive data collection, analysis, and modelling efforts, which can significantly increase the complexity and resource requirements of the assessment.

Since 2010, the "**circular economy**" received increasing international attention. Its main purpose is to revolutionize how materials are used in our economy. This is where **"cradle-to-cradle"** emerged as the ideal for products' life cycles. Cradle-to-cradle is usually associated with the design principle and methodology created in 2001 by Professor Michael Braungart and William McDonough [5]. Its's abbreviation C2C. This design approach is accompanied by a sustainability label for products that are C2C designed and certified [6] . However, cradle-to-cradle is also applied in the scientific method Life Cycle Assessment (LCA).

Cradle-to-cradle is a variation of cradle-to-grave but exchanges the waste stage with a recycling/upcycling process that makes it reusable for another product – essentially "closing the loop". Cradle-to-cradle is one of the several "life cycle models" that guide the scope and methodology of LCA.

A well-known definition of LCA is given by the Society of Environmental Toxicology and Chemistry (SETAC). Namely, "*LCA is a methodology to evaluate the environmental burdens associated with a product, process, or activity. It identifies and quantifies energy and materials used and waste released to the environment; it assesses the impact of energy, materials, and releases to the environment; it identifies and evaluates opportunities for environmental improvements. LCA embraces the entire life cycle of a product, process, or activity, encompassing extraction and processing of raw materials; manufacturing, transportation, and distribution; use, reuse, maintenance; recycling and final disposal*" [7]. Thus, it aims at assessing the environmental burdens through the identification and quantification of energy and materials consumed, emissions and waste produced. It also can help to identify possible environmental improvements at various points in the life cycle of products, processes, and activities. Another recognized definition was proposed by ISO, namely "*LCA is a compilation and evaluation of inputs, outputs, and potential environmental impacts of a product system throughout its life cycle*" [8].

The international regulatory reference for carrying out LCA studies is represented by the ISO standards belonging to the 14040 series, which is part of the group of ISO 14000 standards for the environmental management systems. These standards present general requirements that can be applicable to every type of product or activity. They were developed for the first time at the end of the nineties. Nowadays we rely on the following documents:

- ISO 14040:2006/AMD 1:2020 Environmental management—Life cycle assessment—Principles and framework—Amendment 1.
- ISO 14044:2006/AMD 2:2020 Environmental management—Life cycle assessment—Requirements and guidelines—Amendment 2.

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3. Standards and methodologies

The ISO 14000 family for management system standards is devoted for companies and organizations of any type that require practical tools for their environmental management and their certification (ISO 14001:2015). The ISO 14000 family of standards are developed by ISO Technical Committee ISO/TC 207 and its various subcommittees. ISO 14001 provides requirements with guidance for use that relate to environmental systems. Other standards in the family focus on specific approaches such as audits, communications, labelling and life cycle assessment analysis, as well as specific environmental challenges such as climate change.

It is important to highlight that LCA practitioners must not only comply with the ISO 14040 and ISO 14044, mentioned above, but must also take into consideration other documents depending on the motivation that led them to use this methodology and the type of product or service under study. For example, if the LCA methodology is applied with the purpose of publishing an Environmental Product Declaration (EPD), other specific standards must be considered. EPDs are LCA-based tools used to communicate the environmental performance of a product.

In Table 1, a list of recognized international standards related to LCA methodology is presented. Table 2 lists the recognized product environmental accounting methods and guidance documents useful to apply the LCA methodology properly and to develop an EDP.

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Table 1 - List of international ***standards related to LCA methodology, updated from [4]***

Document	Year of publication (revised)	Title
ISO 14040	2006 (2020)	Environmental management — Life cycle assessment — Principles and framework
ISO 14044	2006 (2020)	Environmental management — Life cycle assessment — Requirements and guidelines
ISO 14025	2010	Environmental labels and declarations—Type III environmental declarations—Principles and procedures
ISO/TS 14027	2017	Environmental labels and declarations—Development of product category rules
ISO/TR 14047	2012	Environmental management—Life cycle assessment—Illustrative examples on how to apply ISO 14044 to impact assessment situations
ISO/TS 14048	2002	Environmental management—Life cycle assessment— Data documentation format
ISO/TS 14071	2014	Environmental management—Life cycle assessment— Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044
ISO/TS 14072	2014	Environmental management—Life cycle assessment—Requirements and guidelines for organizational life cycle assessment
ISO/WD TS 14074	2022	Environmental management—Life cycle assessment— Principles, requirements and guidelines for normalization, weighting, and interpretation
ISO 14067	2018	Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification
ISO 14046	2014	Environmental management — Water footprint — Principles, requirements, and guidelines
ISO 14020	2020 (2022)	Environmental labels and declarations — General principles
ISO 14021	2016	Environmental labels and declarations — Self-declared environmental claims (Type II environmental labelling)
ISO 14050	2009	Environmental management — vocabulary

Table 2 - List of recognized product environmental accounting methods and guidance documents that can be useful to apply the LCA methodology

- PEF (Product Environmental Footprint) Guide, Annex to Commission Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organizations (April 2013) [9]
- ILCD (International Reference Life Cycle Data System) Handbook [10][11]
- Ecological Footprint Standards [12]
- Greenhouse Gas Protocol - Product Life Cycle Accounting and Reporting Standard (WRI/ WBCSD, 2011) [13]
- PAS (Publicity Available Specification) 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (BSI) [14]
- ENVIFOOD Protocol [15]

A detailed description of most of the above-mentioned methods is available in "Analysis of Existing Environmental Footprint methodologies for Products and Organizations: Recommendations, Rationale, and Alignment" [16]. Based on this document, a short description of relevant methodologies is included below, focused on environmental footprint of products applying the Life Cycle Thinking (LCT) approach.

ISO 14067: Carbon Footprint of Product (CFP)

Carbon Footprint of Product ISO 14067 was prepared by the Technical Committee ISO/TC 207, Environmental management, Subcommittee SC 7, Greenhouse gas (GHG) management and related activities. The International Standards Organization proposed ISO 14067 aimed at measuring the carbon footprint for the life cycle of products, by calculating the greenhouse gas emissions from companies and their activities. This International Standard specifies principles and requirements for studies to quantify the CFP, based on life cycle assessment specified in ISO 14040 and ISO 14044. Requirements and guidance for the assessment of a partial carbon footprint (partial CF) are also provided. ISO 14067 is applicable to CFP studies and partial CF studies with or without the intention to be publicly available.

This International Standard provides for the adoption of product category rules (PCR), where they have been developed in accordance with ISO 14025 and are consistent with ISO 14067. This International Standard addresses **the single impact category of climate change** and does not assess other potential social, economic, and environmental impacts arising from the provision of products. Product carbon footprints assessed in conformity with this International Standard do not provide an indicator of the overall environmental impact of products.

International Reference Life Cycle Data System (ILCD)

ISO 14040 and 14044 standards provide an important framework for LCA. This framework, however, leaves the individual experts, practitioners, and data developers, with a range of important choices that can be individually interpreted, leading towards differences in consistency, reliability, and comparability of the results of the assessment. Equally, the methodological assumptions behind the life cycle data can differ widely, so that data from different sources can be not interoperable.

An important effort towards the harmonization of LCA was made by the European Commission Joint Research Centre with the development of the **European International Life Cycle Data System (ILCD).** The aim of the ILCD was to provide **in depth guidelines for the application of LCA to the European context**, both from a procedural and a scientific point of view, defining specific rules for the many options left open by the ISO, to enhance scientific robustness, consistency, reproducibility, and comparability of LCA studies. ILCD publications have been established through a series of extensive public and stakeholder consultations.

This system consists primarily of the ILCD Handbook and the ILCD Data Network [9]. The Handbook is a series of technical guidance documents (first edition March 2010). It is developed through peer review and consultation and is in line with the ISO 14040 and 14044, while it provides further specified guidance for more quality-assurance than the broader ISO framework can offer. The ILCD Handbook provides detailed provisions for product (situation A and situation B) and corporate analysis (situation C). To facilitate this development, links were established with National LCA Database projects in all parts of the world, and with the World Business Council for Sustainable Development (WBCSD) and the United Nations Environment Program (UNEP). However, some problematic aspects of this Handbook have also been reported, dealing with its consistency when it is regarded as a scientific document [10].

GHG Protocol

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The World Resources Institute (WRI) and the WBCSD started to develop its corporate standard in 1998 and its Product and Supply Value Chain GHG Accounting and Reporting Standard in September 2008. The revised edition of the GHG Protocol Corporate Standard was published in 2004, a culmination of a two-year multi-stakeholder dialogue, designed to build on experience gained from using the first edition. It includes additional guidance, case studies, appendices, and a new chapter on setting a GHG target. The GHG Protocol Corporate Standard provides standards and guidance for companies and other types of organizations preparing a GHG emissions inventory. It covers the accounting and reporting of the six greenhouse gases covered by the Kyoto Protocol—carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_x), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6).

The **Corporate Value Chain** (Scope 3) and Product Life Cycle Accounting and Reporting Standards were published in October 2011, after a 3-year multistakeholder development process. These standards include requirements and guidelines on both product life cycle accounting and calculation and reporting of corporate "Scope 3" emissions – i.e., corporations' indirect emissions, other than those already counted under "Scope 2" emissions from the generation of purchased energy. These two standards are based on the life cycle approach. The Scope 3 standard is a supplement to the Corporate Standard, while the Product Standard builds upon the ISO 14040 series of standards.

PAS 2050

PAS 2050 is a **Publicly Available Specification** for the assessment of the life cycle greenhouse gas emissions of goods and services. It was first published in 2008 and then updated in 2011. It was originally developed over 18 months through a consensus building process involving technical knowledge/expertise from a wide group of international stakeholders. Over 1000 stakeholders consulted over two rounds of consultation. It was overseen by an independent Steering Group of experts, representing academia, NGO, Governments, industry, etc. It was also supported by working groups of experts, market research and pilots with companies. The PAS 2050:2011 specifies requirements for the assessment of the life cycle GHG emissions associated with the life cycle of goods and services ("products"), based on life cycle assessment techniques and principles (i.e., ISO14040/44). Requirements are specified for identifying the system boundary, the sources of GHG emissions that fall inside the system boundary, the data requirements for carrying out the analysis, and the calculation of the results. It includes the six GHGs identified under the Kyoto 16 **protocol** and covers the whole life cycle of products, including the use phase and emissions from direct land-use changes that have taken place over the past 20 years.

Ecological footprint

The **Ecological Footprint** standard is developed by Global Footprint Network. It provides measure of the extent to which human activities exceed biocapacity. Specifically, this method integrates (i) the area required to produce crops, forest products and animal products, (ii) the area required to sequester atmospheric CO_2 emissions dominantly caused by fossil fuel combustion, and (iii) the equivalent area estimated to be required by nuclear energy demand.

BP X30-323

The repository of good practices, BP X30-323, was prepared under the French law (called "Grenelle I"). It establishes the prospect of regulatory communication of environmental information relating to product. This document was developed with over 300 organizations representing all the various relevant stakeholders, sectors, and NGOs gathered in the ADEME (Agency for Environment and Energy Management) / AFNOR (French Association of Normalization) platform. BP X30-323 is in line

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with ISO 14040 and ISO 14044 and can evolve following international or European community normative evolution. BP X30-323 gives general principles for the environmental communication of products. The carbon footprint is required whatever the category of product. The environmental communication includes indicators limited in number and specific to a category of product. These indicators consider the main relevant impacts generated by the product. BP X30-323 defines main principles for drawing up methodological guides specific to product categories (PCR). These methodological guides are developed by relevant stakeholders of different sectors and are validated by the ADEME / AFNOR platform. 10 methodological guides (PCR) are already available. In parallel, ADEME has initiated the development of a public database to provide generic data that will enable the calculation of these indicators.

3.1 Environmental Product Declarations (EPDs)

The **EPD (Environmental Product Declaration**) system is used to provide transparent and standardized information about the environmental impact of a product throughout its life cycle. It allows companies to assess, compare, and communicate the environmental performance of their products.

An EPD is a communication document that offers comprehensive details regarding a product's environmental impact throughout its life cycle. It is a summarized report extracted from an in-depth LCA that complies with the ISO 14040 series. EPDs frequently contain data on a product's energy and resource consumption and its emissions and waste during production, use, and end-of-life. They also mention the product's potential to be recycled and any steps taken to lessen its environmental impact.

An EPD is a so-called type III environmental declaration that is **compliant with the ISO 14025** standard. A type III **environmental declaration** is created and registered in the framework of a programme, such as the **International EPD® System.**

EPDs registered in the International EPD System are publicly available and free to download through the EPD Library [17].

In physical terms, an EPD consists of two key documents:

- The **underlying LCA report,** a systematic and comprehensive summary of the LCA project to support the third-party verifier when verifying the EPD. This report is not part of the public communication.
- **Public EPD document** that provides the LCA results and other EPD content.

As a voluntary declaration of the life cycle environmental impact, having an EPD for a product does however not imply that the declared product is environmentally superior to alternatives [18].

The **EPD system** is based on **guidelines and PCRs published by national** program **operators**. The development of PCRs conforms to the standard ISO 21930:2017, but apart from this, the national program operators have some degree of freedom. This can be observed in the use of different templates and to some extent different content in EPDs from different national program operators. There might also be different national practices when it comes to technical issues and accepted practice, but the extent of such differences is not always completely known [19].

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Product Category Rules (PCR) provide the rules, requirements, and guidelines for developing an EPD for a specific product category. A PCR is a copyrighted document that is part of the EPD "cookbook" and contains the recipe to create a high-quality EPD for a specific product category.

Each PCR defines the specific rules and requirements for conducting life cycle assessments and comparing the environmental performance of products within their respective categories. The EPDs that are based on the same PCR, are comparable as the PCR sets the rules for the LCA that the EPD must meet, (e.g., allocation rules, data quality requirements and system boundaries). For example, following the same PCR several different types of isolation materials can be compared for an informed choice of what to select for use in a build. Another example could be the PCR for Electrical and Electronic Equipment that outlines rules for comparing the environmental impact of electronic products, including computers, smartphones, appliances, and lighting equipment. It specifies criteria such as energy efficiency, resource conservation, hazardous substance management, recyclability, and end-of-life treatment options.

PCRs expire every three-to-five years and must be updated to address relevant changes in the industry. PCR updates involve several steps: identifying the need for an update, engaging stakeholders for input, forming a Technical Working Group (TWG) to oversee the update process. Revising the PCR based on scientific knowledge and stakeholder feedback and conducting public consultation to ensure transparency and inclusiveness in the update process. The next step is the reviewing and adjusting the PCR based on feedback, obtaining official approval. Once approved, the updated PCR is implemented, and stakeholders are notified about the changes. Manufacturers and organizations can then use the updated PCR to develop EPDs for their products, reflecting the latest requirements and recommendations.

Several PCRs exist for different sectors and are developed by program operators periodically. Figure 2 illustrates the different Product categories and the number of PCRs per category registered in international EPD system library (at the time this analysis was made, March 2023).

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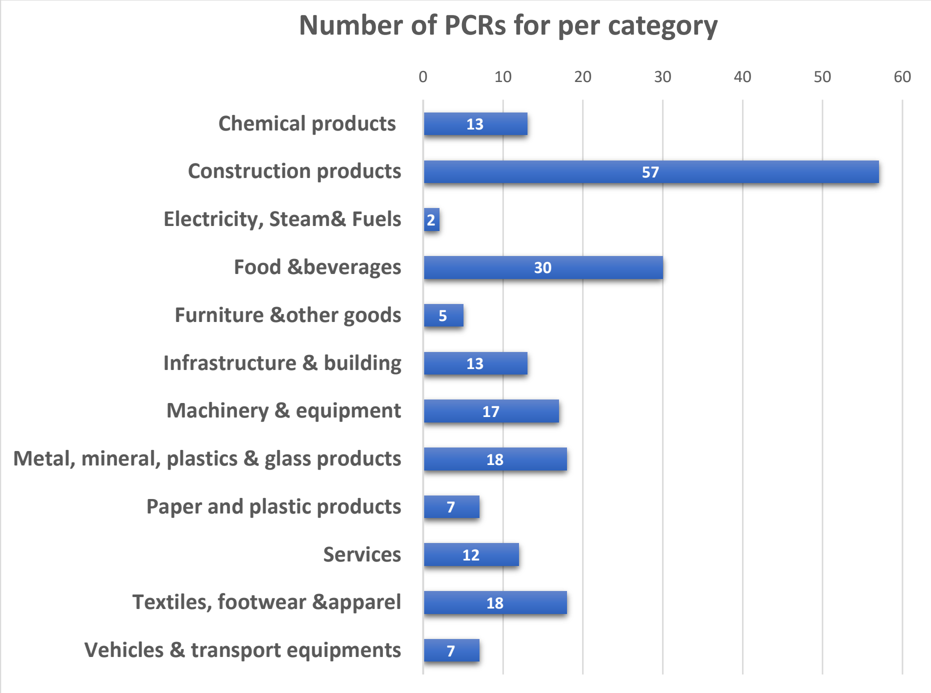

Figure 2 - EPDs categories and number of existing PCR for each category [17]

From this Figure 2 it can be seen that construction is the more active sector in the generation of EPDs, followed by the Food & beverages. However, there are some sectors where the number of PCRs is very limited or inexistent. This can be attributed to several factors as:

- **Industry focus and demand**: The availability of PCRs often aligns with the level of industry interest and demand. Sectors such as construction and food & beverages have traditionally been more proactive in adopting sustainability practices and incorporating life cycle thinking into their operations. Consequently, there is a higher demand for PCRs in these sectors, leading to the development of a larger number of rules to meet industry-specific needs.
- **Complexity and diversity of sectors:** Sectors that are inherently complex or diverse in terms of products, processes, or value chains tend to face challenges in developing standardized PCRs. These sectors may have a wide range of products with varying characteristics, making it difficult to define comprehensive and representative rules that capture the diversity of the sector. Developing PCRs for such sectors requires extensive data collection, stakeholder involvement, and technical expertise, which can be resource-intensive and time-consuming.
- **Lack of resources and expertise**: Developing PCRs requires significant resources, including technical expertise, financial investment, and coordination among stakeholders. Sectors with limited resources or fewer organizations actively engaged in sustainability initiatives may face challenges in initiating and driving the development of PCRs. This can result in a slower pace of PCR development or even a lack of PCRs in those sectors.
- **Emerging or niche sectors**: Sectors that are relatively new or considered niche may have limited PCRs available. As emerging sectors evolve and gain traction, the need for PCRs may arise, but it takes time for the industry to recognize the importance and demand the development of sector-specific PCRs. In these cases, PCRs may be under development or not yet prioritized due to the sector's nascent stage or limited market size.

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- **Regional variations and priorities**: PCRs are often developed at the regional or national level to address specific environmental and market contexts. Different regions may have varying priorities in terms of sectoral sustainability assessments, leading to differences in the number and focus of PCRs across countries or regions. Sectors that are more regionally concentrated or have varying environmental challenges may see disparities in the availability of PCRs.

In summary, the limited or nonexistent number of PCRs in certain sectors can be attributed to factors such as industry focus, complexity, resource constraints, emerging or niche status, and regional variations. Over time, as sustainability practices become more widespread and industry demand increases, efforts can be made to develop PCRs in these sectors to enhance transparency and facilitate environmental assessments.

The use of EPDs is generally voluntary, with companies choosing to develop and disclose EPDs to demonstrate their commitment to sustainability and provide useful information to consumers, businesses, and other stakeholders. However, in some cases, EPDs may be required or encouraged by regulations, certifications, or industry standards. For example, certain green building certifications, such as LEED (Leadership in Energy and Environmental Design), may require EPDs for specific building materials.

Overall, while the use of EPDs is primarily voluntary, it is becoming increasingly common as companies and consumers prioritize environmental sustainability and seek more information about the environmental impact of products.

3.1.1 Tools to generate EPDs

The use of a specialized software can play a crucial role in reducing time and costs and facilitating the process when generating an Environmental Product Declaration (EPD) by streamlining and automating various processes. EPD software often provides pre-designed templates and standardized formats, ensuring consistency and adherence to specific industry standards. This eliminates the need to start from scratch, reducing time and effort. Besides EPD software often incorporates the latest regulatory requirements and industry standards. It helps to ensure that the generated EPD meets the necessary compliance criteria, reducing the risk of non-compliance-related expenses. On the other hand, Environmental impact assessment methodologies and standards evolve over time. Software tools can automatically update and incorporate the latest changes, ensuring that EPDs remain accurate and up to date. This avoids the need to redo assessments or update documents manually.

Over the past few years, there has been a significant increase in the publication of software to generate EDPs. These software tools have, to some extent, replaced manual EPDs.

As a point of inception, the implementation of a software tool for a particular product group has had to be approved by an independent verifier, with the help of one example EPD and a background report. According to the analysis perform by Johnsen et al. [19] a practical problem in this regard is that the verifier of the tool is hired for a smaller, time-limited project, whereas potential quality issues with generated EPDs remains a continuous problem also after this verification is finished.

Currently there are 4 approved Pre-Verified EPD international systems, the **GGCA** Tool for Concrete [20], the **One Click LCA** EPD Generator and the EPD generator for **Gunnar Prefab AB** [21] for Construction Products [22], the TMF EPD-generator – Kitchen and Bathroom [23].

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A pre-verified EPD tool contains data and calculation models to simplify the LCA calculation procedure based on a reference PCR. It undergoes pre-verification to ensure the production of accurate data when provided with the correct input.

3.1.2 Environmental performance indicators

The **International EPD System** proposes a list of the default environmental impact and inventory indicators, to use in EPDs. Requirements or recommendations in a PCR may deviate from the default list if such deviations have been justified in the PCR development process. The default list is regularly updated based on developments in LCA methods, practices, and standards, while ensuring the market stability of EPDs. To obtain the most up-to-date and accurate information on default environmental impact indicators, it is recommended to consult the official documentation and resources provided by the International EPD System. [24]

The latest update of the default list was made 2022-03-29, referred to as **Version 2.0.** This version has adopted the core environmental impact indicators of **EN 15804:2012+A2:2019/AC:2021** as mandatory indicators (Table 3).

Table 3 - Core environmental impact indicators (EN 15804:2012+A2:2019/AC:2021)

Impact Category	Unit
Climate change total	kg CO_2 eq
Climate change – fossil	kg CO_2 eq
Climate change – biogenic	kg CO_2 eq
Climate change - land use and land use change	kg CO_2 eq
Ozone Depletion	kg CFC 11 eq
Acidification	mol H+ eq
Eutrophication, freshwater	kg P eq
Eutrophication, marine	kg N eq
Eutrophication, terrestrial	mol N eq/person
Photochemical ozone formation	kg NMVOC eq/person
Resource depletion, minerals, and metals	kg Sb eq
Resource depletion, fossils	MJ
Water use	m^3 water eq of deprived water/person

Concerning the **characterisation factors (CF)** for Version 2.0 of the default list, it has been updated to the list of **"EN 15804 reference package"** [25] based on EF (Environmental Footprint) released on February 2023.[26]

3.2 Product Environmental Footprint (PEF)

Over the past two decades, there has been a significant global adoption of Life Cycle Assessment (LCA) across various sectors, including businesses and governmental organizations. Regrettably, despite this widespread acceptance, there has been a lack of consensus on key methodological aspects such as scope setting, allocation rules, impact categories, characterisation methods, and the application of normalization and weighting. Therefore, even today, LCAs conducted on the same product can produce entirely different outcomes depending on the entity performing the assessment [27].

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The European Commission proposed the **Product Environmental Footprint (PEF)** and **Organisation Environmental Footprint (OEF)** methods as a common way of measuring environmental performance (EU Commission Recommendation 2021/2279 [28]). The Product Environmental Footprint (PEF) and the Organization Environmental Footprint (OEF) are the EU recommended LCA based methods to measure and communicate the potential life cycle environmental impact of products (goods or services) and organizations, respectively. Together they form the basis for the **EU Environmental Footprint (EF).**

The overarching purpose of PEF information is to enable to reduce the environmental impacts of goods and services considering the supply chain activities (from extraction of raw materials, through production and use and to final waste management). This purpose is achieved through the provision of detailed requirements for modelling the environmental impacts of the flows of material/energy and the emissions and waste streams associated with a product throughout its life cycle. The rules provided in the PEF method enable to conduct PEF studies that are more reproducible, comparable, and verifiable, compared to other existing alternative approaches. However, comparability is only possible if the results are based on the same **Product Environmental Footprint Category Rules (PEFCR).** The development of PEFCRs complements and further specifies the requirements for PEF studies [29].

PEFCRs are specific rules that complement the general PEF methods by providing further specification at the level of a specific product category or sector. These rules help to place the focus of the PEF studies on those aspects and parameters that matter the most, and hence contribute to increase relevance, reproducibility, and consistency of the results versus a study based on the general requirements of the EF methods. While the general PEF methods offer some flexibility in their application, PEFCRs are more prescriptive than the ISO standards for Life Cycle Assessment (LCA) 14040-44. To ensure fair comparison and comparative assertions, an EF (Environmental Footprint) study should be based on specific sector rules. Moreover, PEFCRs and Organization Environmental Footprint Sector Rules (OEFSRs) reduce the effort as well and the cost of performing an EF study.

The PEF is designed to measure and communicate the life cycle environmental performance of products and organizations. The PEF, along with the Organization Environmental Footprint (OEF), forms the Environmental Footprint (EF) methods, which are based on the established methodology of LCA. A calculation based on the general PEF/OEF methods gives quantitative information on the impacts of the product or organization, taking into consideration the entire value chain (from the extraction/growing of resources to the end-of-life stage), i.e., following a life cycle approach. Following the framework standardized by ISO 14040-44, the EF is structured in similar steps, yet providing further specifications necessary to achieve a higher degree of robustness, consistency, reproducibility, and comparability.

The PEF methodology is currently being used primarily within the European Union (EU) as a framework for assessing and communicating the environmental performance of products. The PEF is under development and in the period between the end of the Environmental Footprint pilot phase and the possible adoption of policies implementing the PEF and OEF methods, a transition phase is established. During this transition phase PEF has been used in several sectors, including textiles, construction, batteries and photovoltaic electricity, food and beverages (see Table 4), but still there are several sectors that needs to be addressed. Besides the methodology, the PEF also provides a database. This database was developed to support the PEF method and functions as a new standard environmental database for the EU industries.

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The EU intended to further promote the use of the PEF methodology in the future to support sustainable consumption and production. The aim is to integrate environmental performance considerations into product design, development, and decision-making processes. The PEF methodology is expected to play a role in shaping environmental policy, green public procurement, and eco-labeling schemes within the EU. PEF is the European Commission recommended method to assess life cycle environmental performance of products on the market. [30]

It is important to note that the application and regulatory requirements of the PEF methodology may vary across different jurisdictions and regions. Therefore, staying updated with the latest developments in EU legislation, policy, and guidelines related to the PEF methodology is essential for understanding its current and future use. To ensure comparability of LCA studies that are used in the SSbD context, specific guidelines should be developed. In the meanwhile, the SSbD framework recommends using the PEF method.

3.2.1 Product Environmental Footprint Category Rules (PEFCR)

A key step of the development of the PEFCR is the definition of the Representative Product (RP), i.e., the average product sold in the EU market that is representative for the considered product group. The RP may be a real or a virtual product (i.e., non-existing product calculated based on weighted average of sales in the European market and taking in consideration all the existing technologies covered by the product category). The environmental performance of the RP represents the benchmark, to which regards the environmental performance of other products of the same family is compared.

Twenty-one PEFCRs/OEFSRs have been developed in the pilot phase (see Table 4), and more are under development [31].

Table 4 - Product Environmental Footprint Category Rules (PEFCRs) [32]

- Beer
- Dairy products (liquid milk, dried whey products, cheeses, fermented milk products, butterfat products)
- Decorative paints
- Household liquid laundry detergents
- Hot and cold-water supply pipe systems
- Intermediate paper product (graphic papers, packaging papers, Tissue)
- Feed for food producing animals
- IT equipment
- Leather
- Metal sheets
- Packed water
- Pasta
- Pet Food
- Photovoltaic electricity production
- Rechargeable batteries
- T-shirt
- Thermal insulation
- Uninterrupted Power Supply
- Wine

From the list in Table 4 it is evident that the number of PEFCRs is still very limited. Despite the low number of PEFCRs, efforts are being made to increase their development, particularly in sectors of high environmental significance or where demand for environmental performance information is

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growing. Stakeholders, including industry associations, governmental bodies, and environmental organizations, continue to work towards expanding the availability of PEFCRs to cover a broader range of product categories.

3.2.2 Inventory, modelling, and circularity in EF

In inventory of all input and output, elementary (resources, emissions) and non-elementary (energy, waste, materials) flows shall be compiled for all processes included in the value chain. All flows must be modelled until the elementary flow level to calculate the associated impact on the life cycle of the product or organization in scope (e.g., from the output waste, the specific air, water, and soil emissions generated by the treatment processes are determined).

The mandatory life cycle stages included in an EF study are:

- **Raw material acquisition and pre-processing**: e.g., extraction of resources, pre-processing of all materials (including recycled materials), agriculture, forestry, packaging production, and transportation associated with these activities.
- **Manufacturing**: all processes taking place from the entry to the exit gate of the production facilities (e.g., chemical processing, manufacturing, assembly).
- **Distribution**: transport and storage of the finished product(s), including the refrigeration and warehouse activities consumptions (e.g., energy).
- **Use stage**: product(s) use for the defined function and lifetime, including all necessary inputs (e.g., energy, maintenance materials, coolant) as well as waste and emissions generated during use.
- **End of life:** all activities occurring from the moment the product(s) cease to perform its function and is disposed or recycled. This includes e.g., collection and transport, dismantling, sorting, processing into recycled material, landfill, or incineration.

For certain products (i.e., intermediate), a limited number of life cycle stages shall be considered (i.e., excluding the use and end-of-life). Intermediate products are those for which all stages of the life cycle are considered from the extraction of resources through the production process to the factory gate (**cradle-to-gate**).

One crucial aspect of an inventory analysis in LCA studies is to accurately and consistently model waste and recycled materials, and to allocate environmental burdens and credits to users and producers of such flows. The PEF and OEF methods provide an approach that has been developed through a dedicated consensus-building process for this specific purpose: the **Circular Footprint Formula (CFF)** [29]. The CFF is built up on three parts, namely a material, an energy, and a disposal formula (Table 5) and gives the overall quantity of emissions and resources that belong to the system's inventory due to recycling, disposal, and energy recovery processes.

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Table 5 - Parameters of the Circular Footprint Formula [33]

CFF formula	Parameters
Material	Proportion of recycled material entering the system (i.e., recycled content)
	Proportion of material that will be recycled in a subsequent system
	Emissions and resource use to produce virgin and recycled material
	Emissions and resource use for the recycling processes
	Quality ratio of recycled and recyclable material
	Quality of the substituted virgin material
Energy	Proportion of material used for energy recovery at the end-of-life.
	Lower heating value
	Efficiency of energy recovery
	Emissions and resource use for energy recovery
	Emissions and resource use of substituted energy sources
Disposal	Emissions and resource use of disposed material

Concerning the modelling approach, the PEF methodology primarily follows an attributional approach, but it may include elements of consequential modelling in specific cases or when assessing certain aspects of the life cycle. However, the PEF methodology is predominantly attributional, aiming to provide a standardized and comparable assessment of the environmental performance of products. [34][35].

Attributional modelling focuses on quantifying the environmental impacts associated with the life cycle stages of a product, assuming a predefined system boundary and fixed inputs and outputs. It assesses the direct environmental burdens and resource consumption throughout the life cycle, without considering indirect or systemic effects. Consequential modelling, on the other hand, considers the broader system effects and potential changes in supply and demand that result from a specific product or process. It considers the potential shifts in production, consumption, and market dynamics, considering the consequences of different choices or scenarios.

3.2.3 Impact Assessment methods

The purpose of life cycle impact assessment (LCIA) is to group and aggregate the information collected from the life cycle inventory of a product (or organization) and to assess their respective contributions to each EF impact category. Table 6 illustrates the impact categories considered in PEF/OEF and the indicators used to assess them.

The JRC proposed SSbD frameworks[1] recommends to use the 16 impact categories defined by PEF grouped in 4 groups: toxicity, climate change, pollution and resources, as presented in Table 6. Some recent works, as the research project ORIENTING [36], aimed at developing an operational methodology for product Life Cycle Sustainability Assessment, proposes to extend the EF impact assessment adding the biodiversity lost indicator

In the PEF methodology all the impact assessment phases are mandatory, classification, characterisation, normalization, and weighting (whereas in ISO 14000 series only the first two ones are mandatory). It is interesting to note that ISO 14044, mention that weighting shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public The standard emphasizes the importance of presenting and interpreting impact assessment results

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without the use of weighting factors, as it can introduce subjectivity and uncertainty. This is opposite to the recommendations of PEF.

Table 6 - Impact categories included in PEF/OEF and details of the methods and indicators used to assess them (based on [33] and grouped according to the recommendations suggested by JRC framework [1])

LEVEL	Impact category	Impact category Indicator (unit of measure)	Description
Toxicity	Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured
	Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	
	Ecotoxicity, freshwater	Comparative Toxic Unit ecosystems (CTUe)	Impact of toxic substances on freshwater ecosystems
Climate change	Climate change	Radiative forcing as global warming potential – GWP100 (kgCO2 eq)	Increase in the average global temperature resulting from greenhouse gas emissions (GHG)
Pollution	Ozone depletion	Ozone Depletion Potential – ODP(kg CFC-11 eq)	Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation
	Particulate matter	Impact on human health (diseaseincidence)	Impact on human health caused by particulate matter emissions and its precursors (e.g., sulfur and nitrogen oxides)
	Ionising radiation, humanhealth	Human exposure efficiency relative to U-235 (kBq U-235 eq)	Impact of exposure to ionising radiations on human health
	Photochemical ozone formation, human health	Tropospheric ozone concentration increase (kg NMVOC eq)	Potential of harmful tropospheric ozone formation (“summer smog”) from air emissions
	Acidification	Accumulated Exceedance – AE(mol H^+ eq)	Acidification from air, water, and soil emissions (primarily sulfur compounds)mainly due to combustion processes in electricity generation, heating, and transport.
	Eutrophication, terrestrial	Accumulated Exceedance – AE(mol N eq)	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilizers, combustion, sewage systems.
	Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (kgP eq)	
	Eutrophication, marine	Fraction of nutrients reaching marine end compartment (kg Neq)	Impact of toxic substances on freshwater ecosystems.
Resources	Land use	Soil quality index, representing the aggregated impact of land use on: Biotic production; Erosion resistance; Mechanical filtration; Groundwater replenishment (Dimensionless – pt)	Transformation and use of land for agriculture, roads, housing, mining, or other purposes. The impact can includeloss of species, organic matter, soil, filtration capacity, permeability.

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LEVEL	Impact category		Impact category Indicator (unit of measure)	Description
		Water use	Weighted user deprivationpotential (m^3 world eq)	Depletion of available water dependingon local water scarcity and water needs, for human activities and ecosystem integrity.
		Resource use, minerals, and metals	Abiotic resource depletion – ADP ultimate reserves (kg Sb eq)	Depletion of non-renewable resources and deprivation for future generation.
		Resource use, fossils	Abiotic resource depletion, fossil fuels – ADP-fossil (MJ)	

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4. Tools

4.1 Database mapping

4.1.1 Introduction

Availability of data of good quality is a crucial aspect when it comes to Life Cycle modelling. Life Cycle modelling requires data on various stages of a product's life cycle, including raw material extraction, manufacturing, transportation, use, and end-of-life scenarios. Good-quality data should cover all these stages and provide a comprehensive representation of the product's environmental impacts. Incomplete or inadequate data can lead to biased assessments and inaccurate estimations of resource consumption or emissions.

Data collection can involve primary data from surveys or measurements, or secondary data from databases, literature, or industry-specific sources. LCA databases are essential tools for conducting life cycle assessments because they provide the necessary information to calculate and analyse the environmental impacts of a particular system or product. This section is focussed on mapping the LCI (Life Cycle Inventory) database available on specialized LCA databases.

LCI databases contain detailed information about the inputs (e.g., energy, materials, water) and outputs (e.g., emissions, waste) associated with various processes and activities throughout a product's life cycle. These databases provide a comprehensive inventory of the environmental burdens and resource consumption associated with different materials and processes. LCI data can be specific to a particular region, industry, or product category. They are typically used as inputs in LCA studies to quantify and assess the environmental performance of products and systems.

Life Cycle Assessment data allows policy makers to develop sound sustainable consumption and production policies, and industries can base their innovation and strategic sustainability decisions on more robust information. Enhanced data accessibility and interoperability benefits the whole life cycle community and contribute to the mainstream adoption of LCA methodologies. The growing interest in science-based decision making has increased the need for the availability and accessibility of LCA data [37]. There are different initiatives working in this direction aiming to achieve a wide usage of LCA through better accessibility and interoperability of LCA data. (e.g Among them the **GLAD (Global LCA Data Access network)** and the **open LCA NEXUS** initiative. For this database mapping study we will focus on **open LCA NEXUS**.

Hosted by the UN Environmental Programme under the Life Cycle Initiative, the **GLAD network** [37] is comprised of independently operated LCA databases, also referred to as nodes, providing users with a common interface to find and access life cycle inventory datasets from different sources. The data providers connected to GLAD ranges from several national database initiatives, important industry/sector-specific databases, as well as the major background LCA databases.

Further development of GLAD through the “GLAD EF Mapping” project resulted in the GLAD nomenclature resource package, which is available on the GitHub repository of the UN Environment Program [38] since May 2022. The repository includes elementary flow lists, mapping files, guidance for developers of data format exchange converters, as well as documentation of common mapping issues and proposed solutions. Data users are welcome to consult and contribute to the repository

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openLCA Nexus [39] is an online repository for LCA data. It combines data offered by world leading LCA data providers such as PE International (Sphera i databases), the ecoinvent centre (ecoinvent), or the Joint Research Centre from the European Commission (ELCD, European Life Cycle Database).

Datasets provided in Nexus can be imported in LCA software. Some of them are open access while other ones can only be acquired by purchasing the license. They share a common basis of elementary flows and other reference data and have been "mildly harmonized", in coordination with the respective data providers, to overcome methodological differences. In this study, the database mapping has been performed through the openLCA Nexus tool. It provides free and for purchase databases for use in openLCA with several searching tools and filters.

The mapping of the different databases considers the following aspects:

- Impact derived from different **process families** involved during life cycle: raw material extraction, energy consumption, transport, processing (manufacturing), (re)use and recycling.
- **Sectors**: chemical, construction, textiles, plastics, electronics, batteries, agriculture/food-packaging, automotive.

The mapping has been performed analysing the number of significant datasets after the searching of specific keywords and/or keyword combinations.

4.1.2 Environmental databases

Table 7 summarizes the main characteristics of the LCA databases considered during the mapping. Database extensions and non-English language databases have been removed from the study. Additional details, use advice and documents for the different databases can be obtained from the openLCA Nexus site at the Database section [40] This searching was performed in January 2023, but as it is a live site, the figures might change through time.

Table 7 - Main characteristics of the environmental LCA databases considered in the mapping. All of them were taken from the open LCA NEXUS platform. The table includes information about licensing (free or purchase), total number of datasets and a brief description of the database content.

Database name	Free	Datasets	Description
Agribalyse	✓	15592	AGRIBALYSE 3.1 is a French LCI database for the agriculture and food sector. Provided by ADEME, the database includes LCIs for 2517 agricultural and food products produced and/or consumed in France. It combines a production-based and a consumption-based approach.
Agri-footprint	x	6342	Agri-footprint is a life cycle inventory (LCI) database for the agriculture and food sector. It covers data on agricultural products: feed, food, and biomass. The aim of the database is to facilitate transparency and a more rapid transformation to sustainable food supply chains.
ARVI	✓	23	The ARVI database contains a model of a value chain of wood-polymer composite production. It was developed within the ARVI (Material Value Chains) research programme funded by

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Database name	Free	Datasets	Description
			CLIC Innovation LTD. The database includes a wide range of global and local parameters which can be used to modify the product system according to the modelling needs.
Carbon Minds	x	14840	Carbon minds is a large-scale LCI dataset for the environmental assessment of chemicals and plastics. Backed by a consistent, 3rd party certified methodology and annual updates, cm.chemicals covers 1000 chemicals in 190 geographical regions and is a one-stop data source for ISO 14040/14044 compliant life-cycle assessment studies for chemicals and plastics.
ecoinvent	x	42212	Ecoinvent is the most famous LCA database worldwide used by more than 5000 organisations worldwide. The database contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services with more than 18000 datasets.
ELCD	✓	608	Since its first release in 2006, the ELCD (European reference Life Cycle Database) comprises Life Cycle Inventory (LCI) data from EU-level business associations and other sources for key materials, energy carriers, transport, and waste management.
EN15804 add-on	x	19565	This add-on for ecoinvent is a database for Environmental Product Declarations (EPDs) according to the EN15804 norm. Verified to be compliant with EN15804.
Environmental Footprints	✓	3185	The Environmental Footprint (EF) database is designed to support the use of PEF category rules and organisation environmental footprint sector rules.
ESU World Food	x	7694	The Worldwide LCA food database developed by ESU-services Ltd. includes over 2100 processes related to agriculture, food processing and consumption activities. Depending on the database type, the processes are available as LCIA data sets or unit processes.
EuGeos' 15804-IA	x	33010	EuGeos' 15804+A2_IA v4.1 database is a version of ecoinvent v3_6 extended to allow calculation of the indicators required in construction product EPD to meet European standard EN 15804.
exiobase	✓	17748	EXIOBASE is a global, detailed Multi-Regional (MR) Environmentally Extended (EE) Supply and Use / Input Output database (SUT/IOT). It was developed by harmonizing and detailing SUT for a large number of countries, estimating emissions and resource extractions by industry, linking the country EE SUT via trade to an MR EE SUT, and producing an MR EE IOT from this.
idea	x	3847	IDEA v2 (Inventory Database for Environmental Analysis) is a hybrid inventory database that features both statistical and process-based data. It comprehensively covers nearly all economic activities in Japan and contains about 3800 processes that are classified based on the Japan Standard Commodity

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Database name	Free	Datasets	Description
			Classification. IDEA v2 is provided as a group of interlinked unit process datasets and very transparent.
IDEMAT	x	1336	IDEMAT (short for Industrial Design & Engineering MATerials database) is a compilation of LCI data of the Sustainable Impact Metrics Foundation, SIMF, a non-profit spin-off of the Delft University of Technology. It is designed for the need of designers, engineers and architects in the manufacturing and building industry.
LCA Commons (complete)	x	9207	The LCA Commons is a database providing US representative LCA data. The 9200 datasets have been developed by the different US governmental agencies such as USDA, National Renewable Energy Laboratory (NREL), National Agricultural Library (NAL) and US Forest service and have been created with varying modelling perspectives and nomenclature frameworks.
NEEDS	✓	933	Database created by the NEEDS (New Energy Externalities Developments for Sustainability) project: Life cycle inventories of future electricity supply in Europe. It contains industrial LCI data on transport services, electricity, and material supply.
Ökobaudat	x	4561	Construction materials database, provided by the German Federal Ministry of Transport, Building and Urban Development as of October 2018.
OzLCI2019	✓	957	The Evah OzLCI2019 Free Database has been created by the Australian partner The Evah Institute. It covers Australasian regional supply including imports and has been developed by using openLCA. It can be used in combination with the latest version of the openLCA impact assessment methods (LCIA methods), which is available under downloads and free of charge.
The Evah Pigments Database	x	193	This inventory database has 55 pigments including 31 inorganic pigments of 16 different colours from 8 regions and 24 organic pigments of 10 different hues from 5 regions. Inorganic pigments defined by their colourways, properties, chemical formula, and synthesis.

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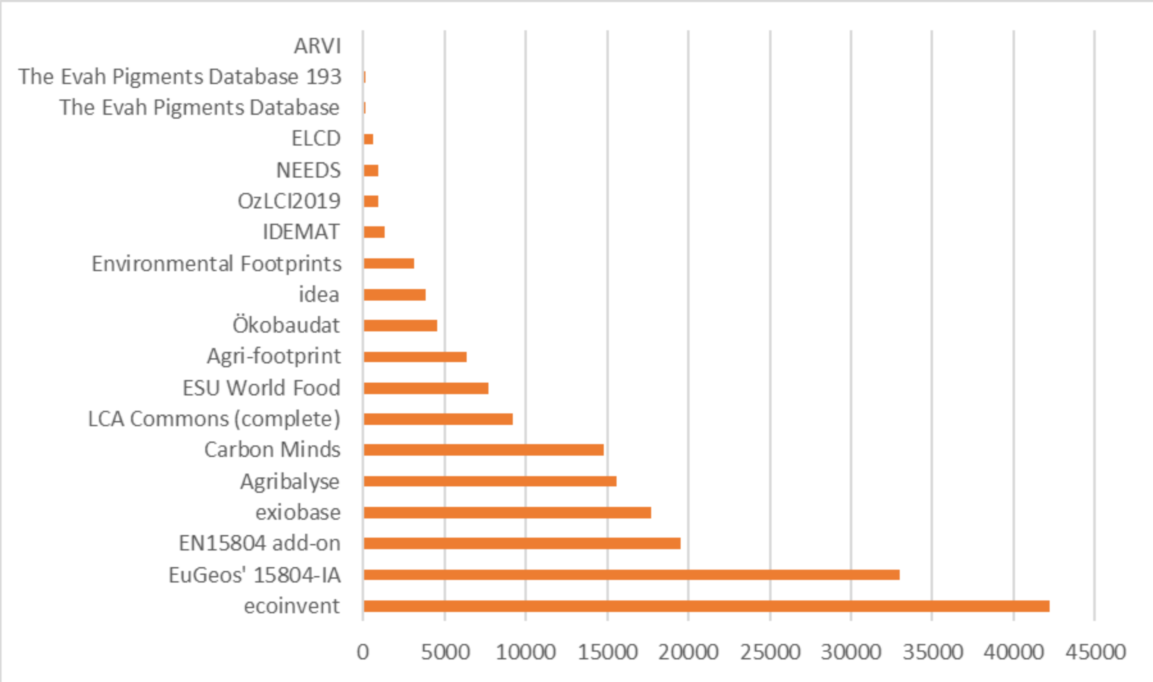

Figure 3 - Number of datasets for each database.

Table 8 *- Searching keywords for the mapping of each process, from raw material extraction to waste treatment.*

Process	keywords
Material	raw material*
Energy	energy Biomass electricity electricity mix cogeneration electricity coal fuels* diesel petrol gasoil gas heat solar renewable
Transport	transport* rail* road* aircraft* aeroplane* truck* lorry lorries car* vehicle* ship* barge freight
Process	Process* manufacturing
Use	use repair remanufacture refurbish
Waste treatment	waste scenario landfill incineration household wastewater residue* Recycling

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Table 9 - Search output. Number of datasets per process family.

	PROCESSES DURING LC					
DATABASE	Material	Energy	Transport	Process	Use	Waste treatment
Agribalyse	3518	4128	4529	13616	1407	1900
Agri-footprint	2734	6270	4950	6126	3493	689
ARVI	5	6	15	23	2	9
Carbon Minds	14840	14840	14840	14840	10454	274
ecoinvent	20614	35763	28528	28980	16607	15633
ELCD	141	501	492	573	413	461
EN15804 add-on	9985	16756	13215	19565	7552	7005
Environm. Footprints	2154	3143	3110	2948	1810	2293
ESU World Food	2465	7509	4487	7523	2223	2033
EuGeos' 15804-IA	12429	21982	17793	14710	11606	11462
exiobase	385	2509	1164	673	194	1973
idea	817	488	598	997	135	317
IDEMAT	803	427	205	115	48	338
LCA Commons	465	4742	3249	9095	5827	1921
NEEDS	2	842	188	22	6	933
Ökobaudat	3210	2335	2572	3419	2426	1755
OzLCI2019	3	85	170	26	118	295
The Evah Pigments DB	4	43	46	142	16	13
TOTAL	**78152**	**109870**	**91687**	**115358**	**55566**	**39522**

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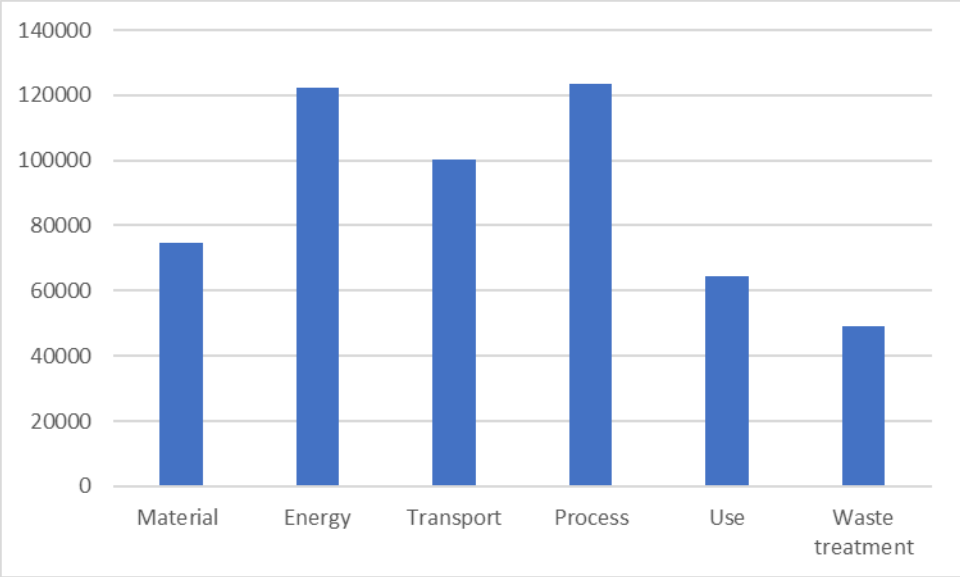

Figure 4 - Number of datasets for the different process families involved during life cycle

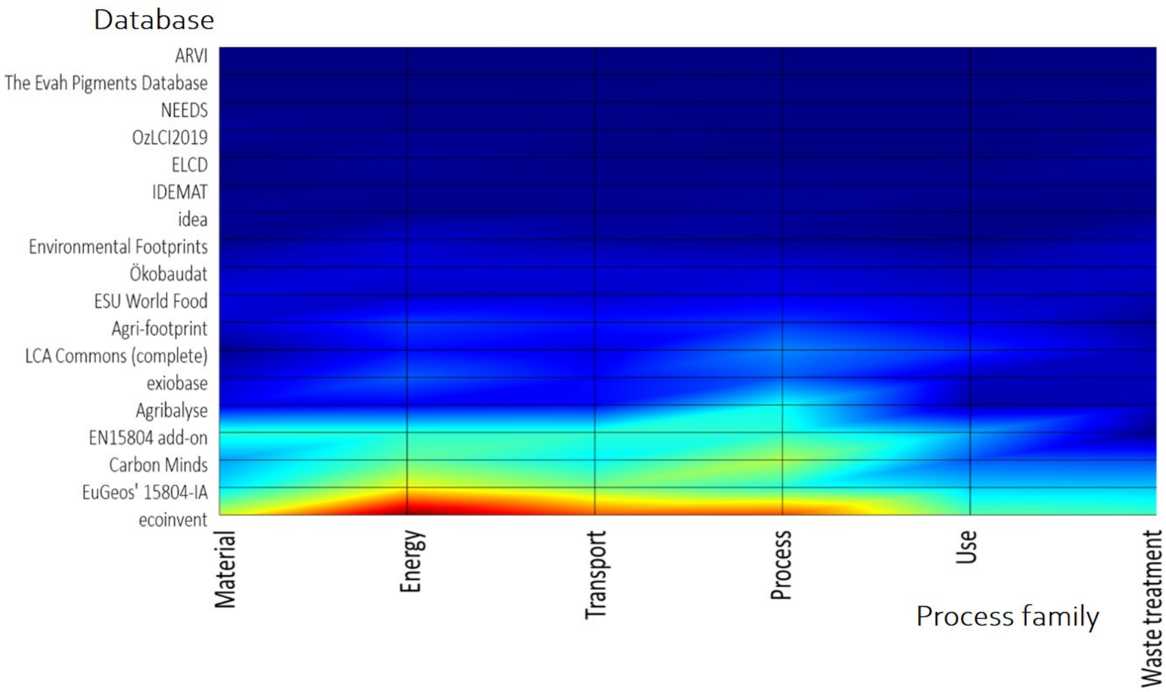

Figure 5 - Dataset colormap for each process family and database

The information volume ranking (Figure 3) and color mapping (Figure 5) indicates that two databases (ecoinvent and EuGeos) gather 41% of all the datasets studied. The available information along the life cycle indicates that the product conception step (extraction of raw materials, energy, processing, and transport) has more information than the other steps (use and end of life) (Figure 4). LCA software has been historically used for the analysis of linear processes (produce-use-disposal) and specially for their manufacturing stages. Databases are created according to users' needs and therefore, there is a lack of information about the use stage and recycling phases.

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Table 10 - Sectors: Searching keywords

Sector	keywords
Chemical	chemical substance* organic* inorganic*
Construction	construction building*
Textiles	textile* Fibre* fiber* cotton wool Polyester
Plastics	Plastic* polymer*
Electronics	electronic* semiconductor*
Batteries	batter*
Agriculture/food	Agriculture food water, vegetable* animal* forest*
Packaging	packag* cardboard paper
Automotive	automotion vehicle* car*

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Table 11 - Search output. Number of datasets per sector

	SECTORS								
DATABASE	Chem	Const	Text	Plast	Elec	Batt	Agri/food	Packag	Autom
Agribalyse	1514	913	140	242	32	19	13735	4553	2527
Agri-footprint	2261	18	152	15	0	3	4889	2255	1228
ARVI	1	0	6	10	0	0	0	2	5
Carbon Minds	14840	0	48	5781	0	0	5146	0	21872
ecoinvent	10943	4391	993	5357	1098	305	10760	1762	5234
ELCD	140	293	20	62	2	2	92	20	441
EN15804 add-o	5744	4305	955	3610	1085	284	11378	1618	4987
Environm. Foot	1523	1063	179	532	199	12	1984	653	2636
ESU World	1323	579	142	323	112	29	3611	1853	1010
EuGeos' 15804	6096	7313	1329	2831	1951	291	17936	2593	7617
exiobase	95	144	240	425	0	0	768	288	192
idea	768	110	187	195	100	9	543	121	503
IDEMAT	65	59	112	296	32	22	99	89	155
LCA Commons	74	4339	1304	99	17	1	188	68	1713
NEEDS	30	12	0	187	0	0	12	0	41
Ökobaudat	603	3298	1184	1472	136	18	2042	1522	2181
OzLCI2019	74	36	89	21	0	0	33	38	10
The Evah P.	40	2	6	27	0	0	45	15	29
TOTAL	**46134**	**26875**	**7086**	**21485**	**4764**	**995**	**73261**	**17450**	**52381**

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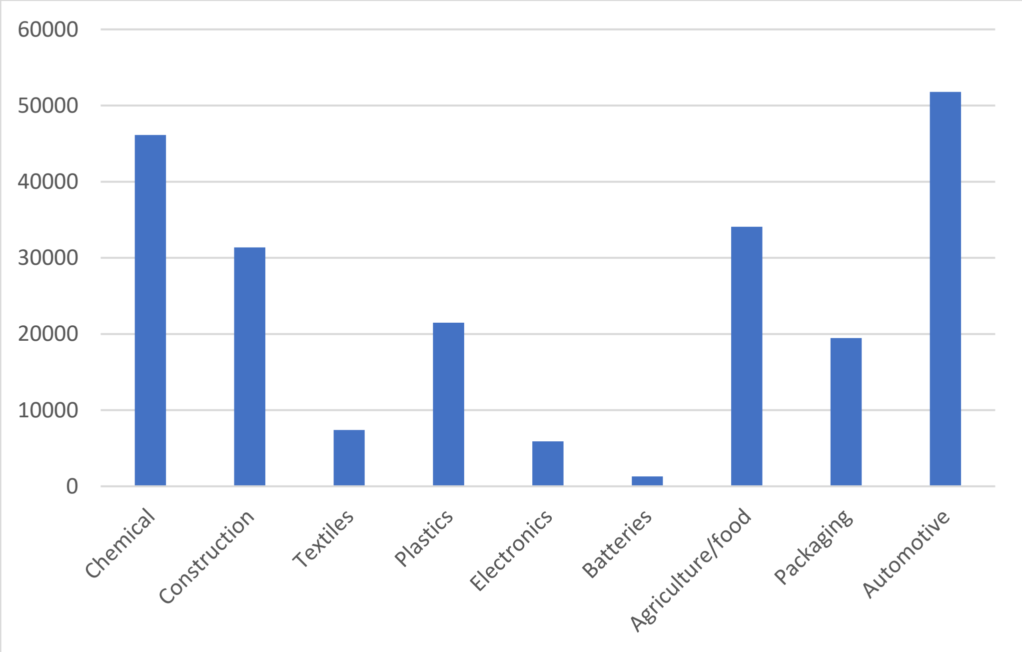

Figure 6 - Number of datasets for the different sectors

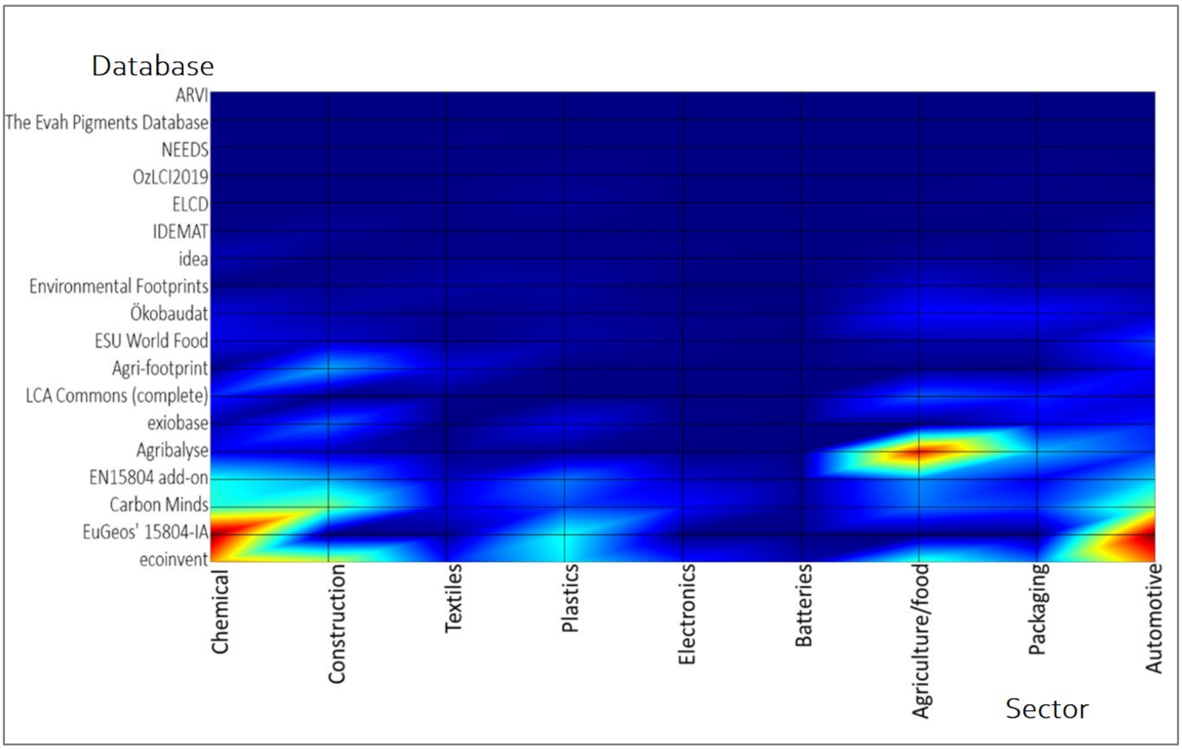

Figure 7 - Dataset colormap for each sector and database

Analysing the distribution of information by sectors, the textile, electronics, and battery sectors have the lowest LCA data information volume, while the automotive, chemical products and agriculture sectors have the most (Figure 6, Figure 7). Apart from the agriculture/food sector, where most of the datasets belong to Agribalyse, the rest of the sectors are mainly covered by ecoinvent and EuGeos databases.

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Figure 8 - European Market size by sector

Figure 8 shows the European market size by sector. As it can be observed, construction and agriculture/food are the greatest ones, followed by electronics and textiles. There is no evident relationship between the market size and the amount of LCA databases. Chemical and automotive sectors are relatively small compared to agriculture, but they have a larger amount of LCA datasets. This could be related to the fact that the environmental laws that affect to the chemical, automotive and agriculture sectors are stricter than in other sectors. [41]

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4.2 LCA Software

LCA usually requires handling a large number of data and make assumptions, since most system models are complex with many interlinkages and calculations needed. The use of specific software tools can facilitate this process, and currently, there are several LCA software tools available in the market, which can be purchased or free.

To provide meaningful LCA results, LCA software requires two key components: the LCI (Life Cycle Inventory) databases (mentioned in section 4.1.2) and LCIA (Life Cycle Impact Assessment) characterisation factors. In particularly the databases are often connected to licenses available for a fee. This is because the development and maintenance of high-quality LCI databases and LCIA factors require significant resources, expertise, and ongoing updates to reflect the latest scientific knowledge and data. Organizations or research institutions invest in creating and managing these databases and factors, and they charge a fee to cover the costs and ensure continued access to reliable and up-to-date information.

The European Platform on LCA (EPLCA) has compiled in the repository a “Tools” section an exhaustive list of LCA tools created by different developers, with more than 60 different software [42]. In this section we will briefly describe the different LCA software tools, where the ecoinvent database (the database with the higher number of datasets according to the analysis performed in section 4.1.2) is implemented [43], (see Table 12).

Table 12 - LCA software tools. Description and websites provided in the ecoinvent’s list of software tools [43]

SimaPro	**SimaPro is the world’s leading LCA software** chosen by industry, research institutes, and consultants in more than 80 countries. For more than 20 years, SimaPro offers state-of-the-art features that LCA experts would expect from a **professional LCA software package.** https://simapro.com/
sphera	Sphera combines leading Life Cycle Assessment (LCA) modeling and reporting software with reliable and consistent environmental data. With more than 20 sector-specific databases. https://sphera.com/life-cycle-assessment-lca-software/
openLCA	**openLCA is world-wide the only free**, open source LCA software that **can be used for professional ecological, social, and economic life cycle assessments**. Among other things, openLCA **can be used for LCAs, carbon & water footprints, eco-design, environmental product declarations, life cycle costing and social life cycle assessment.** http://www.openlca.org/
umberto® know the flow.	Umberto is one of the leading LCA software solutions worldwide. It has been used for more than 25 years by LCA experts from industry, consulting and research, and education. This easy-to-use software is used for **Product and Corporate Carbon Footprints, LCAs, Environmental Product Declarations, Life Cycle Costing and Resource efficiency projects.** https://www.ifu.com/umberto/lca-software/
Altermaker	Ecodesign Studio is an online tool for **LCA and ecodesign.** Through its intuitive and user-friendly interface, users can easily model the life cycle of their product, analyse the results, and deploy their eco-design strategy. Ecodesign Studio is thus a tool adapted to deploy life cycle thinking in companies, from SMEs to large corporations. https://ecodesign-studio.com/

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	3DEXPERIENCE® platform. ecoinvent is the official provider of LCA environmental data for the Dassault 3DEXPERIENCE® platform to be used for **sustainability assessments in the design phase of industrial products.** The 3DEXPERIENCE platform is provided by Dassault Systèmes, the 3DEXPERIENCE® Company, which provides businesses and people with **virtual universes to imagine sustainable innovations for today and tomorrow.** https://www.3ds.com/
	SAP Product Footprint Management integrates into your SAP S/4HANA Cloud or SAP S/4HANA system and **reuses your existing business data** to combine it with environmental factors and to **calculate the footprints** of your products periodically and at scale. https://www.sap.com/products/scm/product-footprint-management.html
	One Click LCA is the #1 easy and automated **LCA & EPD software for the construction industry**. The software is used in 130+ countries by leading businesses, including WSP, AECOM, Sweco, Saint-Gobain, ArcelorMittal. It integrates all leading standards, databases, and design software tools globally, including Autodesk Revit, Trimble Tekla, Grasshopper, Rhino, IES-VE, and Design Builder. The software can be used for buildings, infrastructure, renovations, construction products and materials, and portfolios. https://www.oneclicklca.com/
	EcoImpact is a complete cloud hosted, secure, enterprise level suite of product and packaging sustainability software to manage your corporate sustainability goals. The COMPASS module leverages quick Life Cycle Analysis (LCA) that can be ISO compliant. COMPASS was originally conceived at the SPC (Sustainable Packaging Coalition) as a pioneering tool designed for **packaging engineers.** https://trayak.com/ecoimpact-new-features/
	Air.e LCA includes all the features needed in a professional LCA tool, with a competitive price and a great learning curve. Users can create complex Life Cycles, **like Environmental Footprints,** in an easy and transparent way. Air.e LCA is designed thinking in the best user experience and includes powerful tools for the LCA expert. https://www.solidforest.com/en/index.html
	eBalance is a full-featured LCA software, developed by IKE Environmental Technology and shipped with Chinese and global high-quality databases. The eBalance package is a professional tool for LCA studies of all kinds of products. It is the **best choice for LCAs of products manufactured in China** and has been chosen by more than 1000 users from China and the world. http://www.ike-global.com/#/
	The TEAM™ 5.4 LCA software is a powerful and flexible tool allowing to build and use large databases representing the operations associated with products and processes and perform their related LCA. https://www.pwc.com/gx/en.html
	eToolLCD is an intuitive, web-based, whole building life cycle assessment (LCA) and design software developed by engineers with a passion for **sustainable buildings.** Design focused and performance based, genuinely sustainable outcomes are made easy. https://etool.app/
	Ansys Granta is a range of market-leading materials information management software solutions. It includes tools to apply a comprehensive database of materials engineering, processes, and ecological data to assess environmental impact and risks in products and **product designs.** https://www.ansys.com/
	eQopack is an ecodesign SaaS tool developed by Quantis in partnership with Kleis Technology. It was designed to equip packaging engineers with a user-friendly

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	platform to embed environmental sustainability within the **packaging innovation** process and to allow them to make more sustainable design choices and accelerate innovation toward sustainability. https://quantis.com/what-we-do/sustainability-transformation/services/our-approach/eqopack-packaging-assessment-tool/
Instant LCA Packaging™	**Instant LCA Packaging**™ is an innovative **eco-design and eco-labelling tool,** enabling non-experts to easily and instantly, evaluate the environmental impacts of their packaging. The first tool to use pre-integrated LCA models based on ISO standards and recognized LCA databases, it guarantees reliable results. https://packaging.instantlca.com/
PackageSmart	**PackageSmart LCA** helps packaging designers to evaluate the environmental impacts of their design decisions and clearly depict where and what changes could be made. For some this may bring **focus** to **durability and re-use** and for others **light weighting or biodegradability.** EarthShift Global has developed a simplified LCA software, PackageSmart. https://earthshiftglobal.com/packagesmart
eco-bat	**Eco-Bat 4.0** is an independent tool with which you can very quicky model a **building** and perform a thorough life cycle impacts assessment. https://eco-sai.com/en/index_en.html
eFootprint	Developed and launched in 2013 by IKE Environmental Technology from China, eFootprint is the first online **LCA/carbon footprint** tools as well as supply chain management system, **equipped with Chinese indigenous LCA database** (CLCD), **ecoinvent and ELCD.** eFootprint has been adopted by hundreds of companies, universities, consultancy, certification agencies and associations. Thousands of LCA/carbon footprint projects from various industries and sectors have been accomplished with eFootprint. https://www.weblca.net/home

In terms of features, some of the software tools can be more useful than others due to functionality issues, availability of database and datasets, user interface, data quality and data management, as well as the modelling principles to build product systems and unit processes.

Although there is a lack of literature on the topic, some studies have already been developed to verify the use of different software tools, such as the analysis performed in 2017 by Lopes Silva et al. [44]. They evaluated some of the leading software tools for LCA in the world (openLCA, SimaPro and Umberto) and concluded that **different LCA results can be found depending on which software tool is chosen.** The biggest differences were observed for SimaPro within the “acidification” and “photochemical ozone formation”, where impacts were up to 22,7% and 66.7% higher than the obtained using the other software, respectively.

More recently in 2022 Pongérard et al. [45] performed a study with the aim to show which LCA tools are usable in preliminary analysis performed by non-experts like students in mechanical engineering or designers. The four software tools studied as part of this research and the main conclusions of the analysis of each of them are briefly presented:

- **ArtoACV [46]:** Online software used at INSA Toulouse in Mechanical Engineering and created by ArtoGreen. ArtoACV has a very complete database which need **fewer assumptions to be made than the other software studied (except Umberto LCA** +). Nevertheless, this tool has the drawback of still being **available only in French.**

- **Bilan Produit [47]:** Developed by ADEME, this LCA software is free and therefore simplified in terms of database and modelling. It is an accessible, **fast, free software** with lots of information about the **Base IMPACTS database. [48]**

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- **Ecodesign Studio [49]:** Created by Altermaker, it is an **online platform** allowing **collaborative environmental analysis.** Pongérard et al. [45] concluded from their analysis that this is a very intuitive software and is accompanied by a website with quality content about LCA. I**ts management of collaborative work makes this tool interesting and convenient for companies**.

- **Umberto LCA+ [50]**: Compared with the other software, Umberto is not an online tool and is more **suitable for experts in LCA** according to Pongérard et al. [45] Although its high level of flexibility is convenient for making detailed analyses, it requires considerable personal investment from a non-expert in LCA.

They analysed the capacity of LCA tools to combine ease of use and consistency of results. They observed that **a "perfect" LCA tool, suitable for all studies, does not exist. Even though tools generally allow the users to reach the same conclusions, some parameters can strongly influence the result.** The software choice depends strongly on the type of study and the needs of the designer. Through the cases studied, it appears that the quality of the results is greatly **influenced by the assumptions made by the user, the available incoming flow (databases), and the calculation methods integrated in the software.**

Some sectors are especially **active** in LCA studies and have specific tools developed, which is the case of the **building sector**. Table 13 shows a non-exhaustive list of software tools that can be used for the calculation of the life cycle impacts of a building, for a single indicator such as the global warming potential (GWP), or for multiple indicators (LCA). The "Carbon Footprint" tool calculates only the GWP.

Table 13 - Non-exhaustive list of GWP and LCA tools applicable to the building sector [51]

Tool	Link	Applicability
Athena (Canada)	http://www.athenasmi.org/our-software-data/impact-estimator/	Building-specific
Arquimedes (Spain)	http://arquimedes.cype.es/	Building-specific
BEES (USA)	http://www.nist.gov/el/economics/BEESSoftware.cfm/	Building-specific
Bilan Produit ADEME (France)	http://www.base-impacts.ademe.fr/bilan-produit	Generic
Carbon Footprint (UK)	https://www.carbonfootprint.com/	Generic
COCON (France)	http://eosphere.fr/COCON-comparaison-solutions-constructives-confort.html	Building-specific
eToolLCD (Australia)	http://etoolglobal.com/	Building-specific
Eco-bat (Switzerland)	http://www.eco-bat.ch/index.php?option=com_content&task=blogcategory&id=14&Itemid=30	Building-specific
EcoCalculator (Canada)	http://www.athenasmi.org/tools/ecoCalculator/	Building-specific

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Tool	Link	Applicability
EcoEffect (Sweden)	http://www.ecoeffect.se/	Building-specific
ECOSOFT (Austria)	http://www.ibo.at/en/ecosoft.htm	Building-specific
EIME (France)	http://codde.fr/en/our-software/eime-en/eime-presentation	Generic
ELODIE (France)	http://www.elodie-cstb.f/default.aspx	Building-specific
envest 2 (UK)	http://envestv2.bre.co.uk/	Building-specific
EQUER (France)	http://www.izuba.fr/logiciel/equer	Building-specific
GaBi (Germany)	http://www.gabi-software.com	Generic
GaBi-Build-IT (Germany)	http://www.pe-international.com/sweden/services-solutions/green- building/building-lca/	Building-specific

In terms of LCA software application in the different industrial sectors, in PR1.2 [52] a literature review of Sustainable by design methods and criteria was performed to update (February 2023) the work previously performed by Caldeira et al. [2] via Scopus (October 2021). These authors compiled and reviewed the most relevant publications on safety and sustainability dimensions, aspects, methods, indicators, and tools, focusing on chemicals and solvents. The review conducted in PR1.2 included additional search terms encompassing other type of materials (e.g., materials, biomaterials, biobased materials). 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). A total of 55 documents were retrieved (full list available in PR1.2) by screening their titles and abstracts, and they were analysed in terms of (i) sustainability dimensions, (ii) methods, databases and software tools used for impact assessment, (iii) LCA stages and Circular economy considerations, and (iv) environmental, social, and economic indicators. The different sectors covered by these publications were classified as follows: Construction; Energy (materials, supply systems and batteries); Electronics and ICT; Automotive and Transport; Food systems; Agriculture, Forestry and Fishing; Packaging; Metals; Waste management; Community, Social and Personal services; Personal care; Bio-based products; Products (not specified).

From the 55 documents analysed, Table 14 shows the number of studies that used LCA specialized software. Within software tools, SimaPro was the most frequently used with twice the number of results obtained for Gabi. OpenLCA and UMBERTO were also used often to support the studies found.

Table 14 - Number of studies obtained in the LCA software analysis, performed on PR1.2 literature review [52]

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

4.3

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4.4 Life Cycle Impact Assessment methods and Environmental indicators

4.4.1 Introduction

In a **Life Cycle Assessment**, the emissions and resources consumed that can be attributed to a specific product are compiled and documented in a **Life Cycle Inventory**. An impact assessment is then performed, considering human health, the natural environment, and issues related to natural resource use. The assessment includes **different impact categories** (e.g., climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related) respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion). The emissions and resources are assigned to each impact category, and then they are converted into characterisation factors derived from the LCIA models. **The different emissions and resources** consumed, as well as the different product options, **can** then **be cross compared in terms of the impact indicators.**

According to ISO 14044 (2006), the Life Cycle Impact Assessment (LCIA) proceeds through two mandatory and two optional steps:

1. **Selection of impact categories and classification,** where the categories of environmental impacts, which are of relevance to the study, are defined by their impact pathway and impact indicator, and the elementary flows from the inventory are assigned to the impact categories according to the substances' ability to contribute to different environmental problems. (Mandatory step according to ISO).

2. **Characterisation**, where the impact from each emission is modelled quantitatively according to the underlying environmental mechanism. The impact is expressed as an impact score in a unit common to all **contributions within the impact category** (e.g., kg CO_2- equivalents for greenhouse gases contributing to the impact category climate change) **by applying characterisation factors**. A characterisation factor is a substance-specific factor calculated with a characterisation model for **expressing the impact from a particular elementary flow, in terms of the common unit of the impact score**. (Mandatory step according to ISO).

3. **Normalization**, where the different characterised **impact scores are related to a common reference**, e.g., the impacts caused by one person for one year, in order to **facilitate comparisons across impact categories**. (Optional step according to ISO).

4. **Weighting,** where a **ranking** and/or weighting of the **different environmental impact categories** is performed reflecting the relative importance of the impacts considered in the study. Weighting may be needed when trade-off situations occur in LCAs used for comparisons (optional step according to ISO). Weighting is often value based and sometimes ends up in a single value that represents an aggregated or composite measure of the environmental impacts across different impact categories. while using a single value in the weighting step of LCA may simplify the analysis, it is still subjective as it relies on subjective judgments or stakeholder preferences. Transparency, stakeholder involvement, and adherence to best practices are essential to mitigate subjectivity and enhance the credibility of the weighting process. According to ISO 14044, weighting shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public, as it can introduce subjectivity and uncertainty.

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4.4.2 LCIA methods

The first impact assessment methodologies for Life Cycle Assessment, termed **Life Cycle Impact Assessment methodologies,** can be traced back to before 1992 [53]:

- The **EPS** (**Environmental Priority Strategies**) methodology based on endpoint modelling **expressing results in monetary values.** [54][55]
- **Swiss Ecoscarcity** (or Ecopoints) based on the **distance to target principle.**[56]
- The **CML 1992** (Dutch guidelines) methodology based on **midpoint modelling.** [57]

These three methodologies formed the basis for three main schools that were further developed, and today there are many LCA practitioners that belong to one of the three schools of thought. Nowadays there are many Impact assessment methods. Table 15 lists some of the most common methods (according to the survey results section 6.2.3), indicating whether they include Normalization and Weighting steps, and a classification of the impact methods into 2 different contexts, “European” and “Global”. “European” includes comprehensive LCIA methods that are focused on the European context and, therefore, mostly useful when doing LCA studies in Europe. “Global” includes comprehensive LCIA methods with a global scope, i.e., ideal to apply in studies with a global value chain.

Table 15 - Most common Impact Assessment methods according to survey results

Method	Coverage	Normalization	Weighting
CML-IA	Europe	X	
Environmental prices	Europe		X
EF 3.0	Europe	X	X
EN 15084	Europe	X	X
EPD (2018)*	Europe		
EPS 2015	Europe	X	X
IMPACT World+	Global	X	X
ReCiPe 2016	Global	X	X
Methods with single metric or environmental impact area: • IPCC 2021 • USEtox			

**Note: The EDP system specifies a default LCIA method but requirements in a PCR may deviate from the default list.*

Below the impact assessment methods mentioned in Table 15 are briefly described.

EF Method 3.0: EF method is the impact assessment method adopted in Environmental Footprint transition phase of the European Commission. The implementation is based on EF method 3.0 published for use during the EF transition phase. It includes the normalization and weighting factors published in November 2019. **The EF method 3.0 is the one to be used by Product Environmental Footprint Category Rules (PEFCRs) and Organization Environmental Footprint Sector Rules**

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(OEFSRs), as well as PEF and OEF studies, developed during the EF Transition Phase. It is included in many of the LCA software solutions and can hence be used in LCAs that are not PEF/OEF studies.

Environmental Prices: Environmental Prices is a method developed by CE Delft for expressing **environmental impacts in monetary terms**. Environmental prices thus indicate the loss of economic welfare that occurs when one additional kilogram of the pollutant finds its way into the environment. In LCA context environmental prices are used as weighting sets, which allows calculation of single score results. **It includes characterisation and weighting.**

CML-IA: CML-IA is a LCA methodology developed by the Institute of Environmental Science (CML) of Leiden University in The Netherlands. CML-IA is a database that contains characterisation factors for life cycle impact assessment. The impact assessment method implemented as CML-IA methodology is defined for the midpoint approach. The CML Guide provides a list of impact assessment categories grouped into: Obligatory impact categories (Category indicators used in most LCAs); Additional impact categories (operational indicators exist, but are not often included in LCA studies) and other impact categories (no operational indicators available, therefore impossible to include quantitatively in LCA) [58].

EN 15804+A2: The EN 15804 standard covers **Environmental Product Declarations** (EPDs) of **Construction Products.** The 2019 EN 15804 + A2 revision of this standard has aligned their methodology with the EF 3.0 method, except for their approach on biogenic carbon. According to the EN 15804, biogenic carbon emissions cause the same amount of Climate Change as fossil carbon, but can be neutralized by removing this carbon from the atmosphere again.

EPS 2015d is a damage-oriented impact assessment method. It is a part of the EPS system (Environmental Priority Strategies in product design). In the EPS system, **willingness to pay to restore changes** in the safeguard subjects is chosen **as the monetary measurement**. **The indicator unit is ELU (Environmental Load Unit)**, which includes characterisation, normalization, and weighting.

EPD (2018): This method is the successor of EPD (2013) and is intended for the creation of **Environmental Product Declarations** (EPDs), as published on the website of the Swedish Environmental Management Council (SEMC) An EPD is always created according to a Product Category Rule. This method is especially important for everybody who is reporting a Product Category Rule (PCR) published by Environdec.

IMPACT World+ is the update and compilation of the IMPACT 2002+, LUCAS, and EDIP methods. The method has global scope and is available both as **midpoint and endpoint** (**damage level**). Most of the regional impact categories are spatially resolved and all the long-term impact categories are subdivided between **shorter-term** damages (over the 100 years after the emission) **and long-term** damages.

ReCiPe 2016 The ReCiPe 2016 method is a new version of ReCiPe 2008, created by RIVM, the Radboud University, the Norwegian University of Science and Technology, and PRé Sustainability. In ReCiPe midpoint indicators or endpoint indicators can be chosen. Like its predecessor, ReCiPe 2016 includes both **midpoint (problem oriented)** and **endpoint (damage oriented)** impact categories, available for three different perspectives (individualist (I), hierarchist (H), and egalitarian (E)). The characterisation factors are representative for the global scale.

USEtox is a scientific consensus model endorsed by the **UNEP/SETAC Life Cycle Initiative** for characterising human and ecotoxicological impacts of chemicals. It has been developed by a team of researchers from the **Task Force on Toxic Impacts** (TF LCIA 2) **under the UNEP-SETAC Life Cycle**

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Initiative [59] as the scientific consensus for toxicity-related impact categories. USEtox is designed to **describe the fate, exposure, effects of chemicals and includes both midpoint and endpoint factors**.

IPCC 2021 is the successor of the IPCC 2013 method, which was developed by the Intergovernmental Panel on Climate Change (IPCC). This method is based on the final government distribution version of the IPCC report "AR6 Climate Change 2021: The Physical Science Basis", which is still subject to copy-editing, corrigenda, and trickle backs [61]. The IPCC 2021 method provides different types of characterisation factors, which results in **six methods that quantify global warming** potential (GWP) and **two methods that quantify global temperature potential (GTP).**

As mentioned in section 4.2, in PR1.2 [52] a literature review was performed on the Sustainable by design methods and criteria, where 55 documents were analysed. Table 16 shows the number of studies that use specific impact assessment methods. Among them, **the most frequent impact assessment methods are ReCiPE and CML.**

Table 16 - Number of studies obtained in the analysis of Impact assessment methods, performed on PR1.2 literature review [52]

Impact assessment methods				
EF	ReCiPe	CML	Impact World+	USEtox
4	17	13	1	3

4.4.3 Environmental indicators

In LCA the environmental impact is normally categorised or organized into impact categories. Examples of impact categories include climate change, human toxicity, eutrophication, resource depletion, and land use. Each impact category represents a distinct aspect of environmental impact and helps organize and classify the potential effects of a product or system throughout its life cycle.

Each category has its own impact indicator which is a quantitative measure used to quantify and compare within each category the magnitude of this impact. For example, the impact indicator for climate change impact category could be greenhouse gas emissions expressed in terms of carbon dioxide equivalents (CO_2e). The impact categories considered by the PEF in relation with the corresponding environmental impact indicator is illustrated in Table 6.

Regarding the analysis of the environmental impact categories considered in the literature review performed in PR1.2 where 55 documents were analysed, the number of results obtained is shown in Table 17. Table 18 presents the impact categories considered in the most used impact assessment methodologies according to the literature review (ReCiPe and CML), the survey results (PEF and ReCiPe) and EU projects analysis (PEF).

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Table 17 - Number of studies obtained in the analysis of environmental impact categories formed on PR1.2 literature review [52]

LEVEL	Impact category	Number of studies considering the impact category
Toxicity	**Human toxicity**	22
	Ecotoxicity	18
Climate change	**Climate Change**	30
	Global Warming	26
	GHG emissions	27
Pollution	**Ozone depletion**	18
	Acidification	21
	Eutrophication	24
Resources	**Land use**	17
	Water use	2
	Resource use, minerals, metals	1
	Resource use, fossils	3

Table 18 – Impact categories considered in CML, ReCiPe and PEF methodology

LEVEL	Impact category		CML-IA	ReCiPe	PEF
Toxicity	Human toxicity	**Human toxicity,cancer**	X	X	X
		Human toxicity, non-cancer		X	X
	Ecotoxicity	**Ecotoxicity, freshwater**	X	X	X
		Terrestrial ecotoxicity	X	X	
Climate change	**(Indicators related to) Climate Change**		X	X	X
	Global Warming		X		
Pollution	**Ozone depletion**		X	X	X
	Particulate matter			X	X
	Ionising radiation, human health			X	X
	Photochemical ozone formation		X	X	X
	Photochemical Oxidation		X		
	Acidification		X	X	X
	Eutrophication	Eutrophication, terrestrial	X		X
		Eutrophication, freshwater		X	X
		Eutrophication, marine		X	X
Resources	Land use			X	X
	Water use			X	X
	Resource use, minerals, metals		X[1]	X	X
	Resource use, fossils			X	X

[1] Abiotic Depletion

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The most used impact categories in the studies analysed herein were **"Climate change", "GHG emissions" and "Global warming"**, which were covered in around half of the publications. Note that "Climate change" designated herein as an impact category, would cover indeed specific indicators related to climate change, according to those reported by Caldeira et al. [2]. 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.**

These authors 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. The **"Climate change"** indicator was found to be the most reported in the analysis described in PR1.2 (30 publications out of 55). Therefore, **more attention** is being paid to climate change issues in the last two years **for products** in general, but the number of studies addressing this category are still quite limited.

"Eutrophication", "Human toxicity" and "Acidification", applied often in the frameworks reviewed by Caldeira et al. [2], remain among the most used environmental indicators considering the results obtained in our study in PR1.2.

4.5 LCA stages and circular economy considerations

The circular economy aspects are analysed more deeply in preliminary report PR1.4 - "Design for circular Economy" [62]. This section shows the LCA stages and circular economy considerations analysed in the literature review performed in PR1.2[52]. The terms were selected in line with those most cited in the 55 publications revised. Table 19 provides the number of results found.

Table 19 - Number of studies obtained in the analysis of LCA stages and Circular economy considerations of the literature review performed in PR1.2 [52]

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

The "Disposal", "Recycling" and "Reuse" stages are indeed a part of the End-of-life stage. However, they were screened independently in the analysis to provide more accurate results. **"Disposal" and "Recycling"** were the **most frequent** stages considered by the studies analysed, **followed by "End of life".** This would be reasonable given the attention that circularity concepts are gaining in the last few years, which means that these final stages are currently being more integrated in the life cycle of products.

Caldeira et al. [2] reviewed the "Resources, processing- and product-related aspects" by organising them in four sections, addressing (i) Type and quantity of resources, and efficiency of the

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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. The recycling stage was also one of the most cited in the present study, but the "Reuse" concept was also widely considered. This is in line with the circular economy concept for products in general, where reuse is preferred to recycling**.**

In the mapping study conducted on circular economy considerations, it was found that "Recycling" was the most frequently mentioned aspect, which aligns with expectations. The terms "Renewable", "Recovery" and "Reusability" are gaining attention, together with "Durability", which was considered in 14 out of the 55 publications analysed.

5. LCA of new technologies at the design phase (Ex-ante LCA)

The environmental assessment of emerging technologies at an early phase of their development has received increasing attention over the past few years [63]. An increasing number of novel technologies are claimed to be environmentally sustainable [64], while such claims need to be proven by carrying out, for example, early on environmental assessments. Determining possible environmental impacts at an early stage of research and development (R&D) allows reorienting technology development towards improved environmental performance levels at relatively low costs. In contrast, changes are difficult to implement and will entail much higher costs when a technology is close to commercialization. However, this implies a change from ex-post to ex ante environmental assessments [65]

Life Cycle Assessment (LCA) is a powerful tool for achieving sustainability. Traditional LCAs analyse well defined and developed industrial systems (in an ex-post manner) for which industrial scale data is readily available. However, the application of such ex-post LCA to new technologies is problematic since their system specifications at the industrial scale are highly uncertain and large-scale process data is generally lacking.

To fill this gap, **ex ante LCA** has evolved in recent years, aiming to assess emerging technologies at an early stage of development by exploring, among others, possible scenarios of their future industrial scale implementation.

Ex Ante LCA, also known as prospective or forward-looking LCA, is a methodology used to assess the environmental impact of products, systems, or processes before they are fully developed or implemented. It provides valuable insights into the potential environmental consequences of various alternatives, aiding decision-making during the early stages of product development and design.

The key principle of Ex Ante LCA is to identify and analyse the potential environmental impacts of different design choices and alternatives before they are implemented. By conducting an assessment at an early stage, decision-makers can consider environmental considerations alongside economic and social factors, enabling them to make more informed and sustainable choices.

Using ex-ante in relation to ex-post data is not thoroughly researched in the LCA community. There are limited studies (e.g., [63][66][67][68][69][71][72]) which focus on the effect of using ex-ante data instead of ex-post on LCA applications because it is challenging to find comparable data for a specific technology in different technology development level.

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In the review performed by Buyle et al. [66] proposed a generic theoretical framework as a guideline for ex-ante LCA. This This framework includes the entire technology life cycle, from the formulation of its initial idea up to continuous improvements of mature technologies, including their market penetration. Three technology related subcategories are included (technology development, technological learning and technology diffusion), as well as one methodological aspect (the selection of the system model). The results of this review indicate that most of the ex-ante LCAs focus on emerging technologies that have already gone through some research cycles within narrowly defined system boundaries. There is a lack of attention given to technologies that are at a very early development stage, when all options are still open and can be explored at a low cost. It is also acknowledged that technological learning impacts the financial and environmental performance of mature production systems. Once technologies are entering the market, shifts in market composition can lead to substantial changes in environmental performance.

Tsoy et al. [67] provided an overview of upscaling methods used in ex ante LCA and introduce an up-scaling method as procedure that projects how a new technology currently available at a lower TRL may look and function at a higher TRL. Upscaling should ideally be performed in three steps: (1) projected technology scenario definition, (2) preparation of a projected LCA flowchart, and (3) projected data estimation. Since different kinds of expertise are required for upscaling in ex ante LCA, they recommend that technology experts from different fields are involved in performing ex ante LCA, e.g., technology developers, LCA practitioners, and engineers. Figure 9.

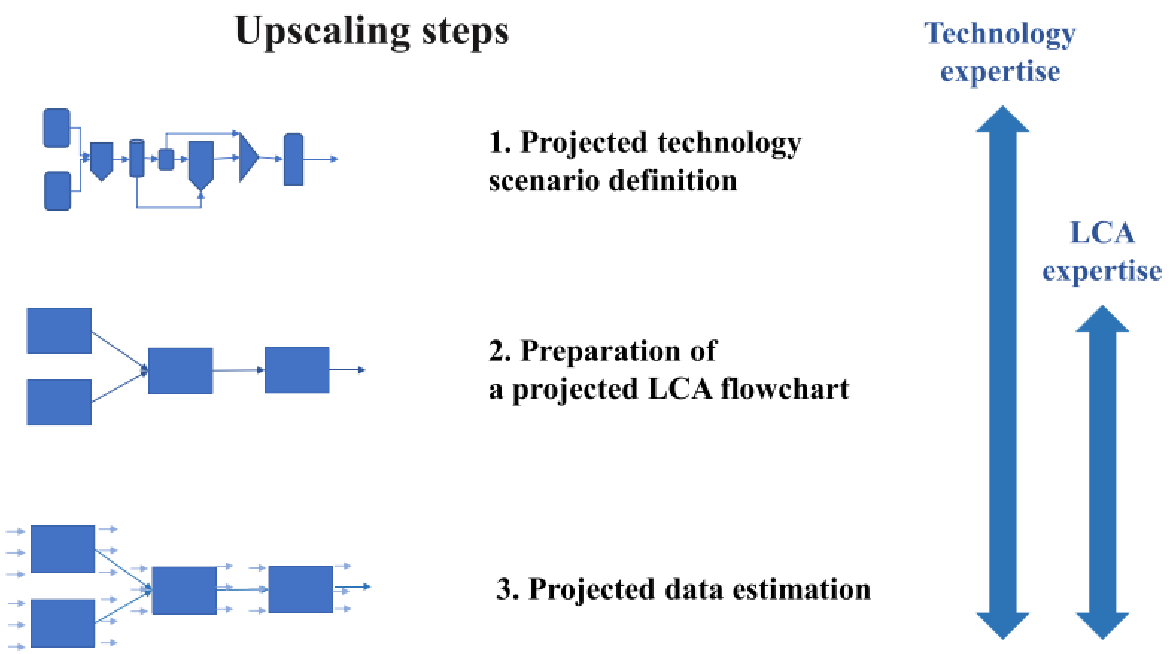

Figure 9 - The framework showing the upscaling steps in ex ante LCA proposed by Tsoy et al. [67]

Concerning data estimation, data produced from lab or bench scale apparatuses are used to perform ex-ante life cycle assessment (LCA) studies of emerging technologies. On one hand, ex-ante assessments are preliminary because they concern scales significantly smaller than commercial and this difference in scales results in large differences in process efficiencies and operating conditions. On the other hand, commercial data for emerging technologies may not exist [68].

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Traditional LCA studies analyse well defined and developed industrial systems in an ex-post manner. In this case, a classical uncertainty analysis which focuses on "known unknowns" can happen. [67] Figure 10 illustrates how the sources of LCA data result in high or low uncertainty. Recent developments in LCA literature focus on assessing emerging technologies based on lab or bench scale data. In LCA of emerging technologies a classical uncertainty analysis is not enough due to unknown future situations. Therefore, quantifying uncertainty in ex-ante LCA adds another dimension of quantifying "unknown unknowns".

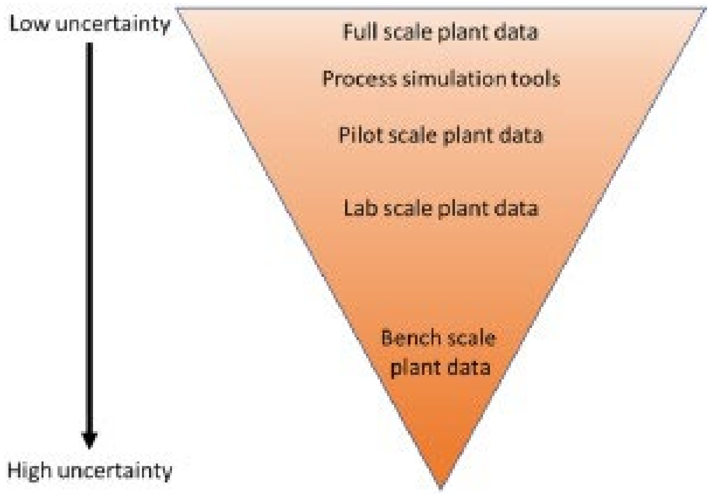

Figure 10 - Uncertainty in LCA studies, adapted from [69] by [68]

Tsalidis et al. [68] analysed the different effects of data scales on LCA in a case study of torrefaction technology and assessed based on bench scale data, lab scale data, data derived from process simulations, pilot scale data and commercial scale data. They concluded that process efficiencies improved significantly between the bench scale system and systems with higher technology readiness levels (TRLs), such as pilot, process simulations and commercial scale systems. Furthermore, process simulations resulted in scores closer to commercial scale regarding all considered environmental impacts.

Ex ante LCA, plays a crucial role in the context of SSbD due to the following reasons:

- **Early-stage assessment**: SSbD involves the development and integration of emerging technologies, which often lack sufficient data and information at the early stages of their implementation. Ex ante LCA allows for the assessment of potential environmental impacts and sustainability considerations of these technologies before they are fully developed or implemented at an industrial scale.
- **Design optimization:** By employing ex ante LCA, designers and researchers can identify and analyse the environmental implications of different design choices and alternatives. This proactive approach enables them to optimize the design and make informed decisions that minimize negative environmental impacts throughout the life cycle of the system or product being developed.
- **Future scenario evaluation**: Ex ante LCA helps in exploring various future scenarios of technology implementation and development. It allows for the assessment of the potential

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environmental benefits or drawbacks associated with different pathways and strategies, enabling stakeholders to make informed decisions regarding technology adoption and investment.

- **Mitigation of uncertainties**: Since SSbD involves cutting-edge technologies and processes, there are inherent uncertainties regarding their performance, scalability, and environmental impact. Ex ante LCA helps in quantifying and managing these uncertainties by utilizing process simulations, lab-scale data, and modeling techniques. This allows for a more comprehensive understanding of potential environmental impacts and the identification of critical areas for further research and improvement.

In summary, ex ante LCA plays a vital role in the context of SSbD by providing early-stage assessment, design optimization, scenario evaluation, and mitigation of uncertainties. It facilitates informed decision-making and ensures that sustainability considerations are integrated into the design and development of emerging technologies, leading to more sustainable and environmentally friendly solutions. However, this methodology is still under development and faces several challenges.

- **Uncertainty in data and assumptions**: Conducting ex ante LCA requires making assumptions about future technologies, their performance, and their environmental impacts. These assumptions are often based on limited data and can introduce uncertainties that affect the accuracy of the assessment. The lack of comprehensive, validated data on emerging technologies and their potential environmental effects poses a significant challenge in conducting reliable ex ante LCA.
- **Limited knowledge about system boundaries**: In the early stages of technology development, defining system boundaries for ex ante LCA can be challenging. The complexity of SSbD systems, which involve multiple interconnected components and processes, makes it difficult to establish clear boundaries and account for all potential environmental impacts. This can lead to incomplete or biased assessments.
- **Lack of standardized methodologies**: Ex ante LCA in the context of SSbD often lacks standardized methodologies due to the novelty and evolving nature of the technologies involved. The absence of consistent guidelines and frameworks can lead to variations in approaches, making it difficult to compare and interpret results across different studies. Harmonization and standardization efforts are necessary to enhance the reliability and consistency of ex ante LCA in SSbD.
- **Limited stakeholder engagement**: SSbD requires the involvement of diverse stakeholders, including researchers, policymakers, industry experts, and end-users. However, engaging these stakeholders in the ex-ante LCA process can be challenging. Their input and insights are crucial for identifying relevant environmental aspects, setting goals, and validating assumptions. Failure to involve stakeholders adequately can lead to incomplete assessments and lack of acceptance or implementation of the results.
- **Dynamic and evolving nature of SSbD**: SSbD is characterised by rapid technological advancements and evolving system configurations. This dynamic nature poses difficulties for ex ante LCA, as the assessment needs to keep pace with these changes. Updating and refining the analysis as new information becomes available is essential, but it can be resource-intensive and time-consuming.

Addressing these challenges requires ongoing research and collaboration among stakeholders to develop robust methodologies, improve data availability, enhance stakeholder engagement, and adapt the assessment process to the evolving nature of SSbD.

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6. LCA survey

6.1 Introduction

Within WP1, an online survey was designed to collect information from IRISS partners and stakeholders, who were asked to participate via email to support the analysis of the application of the SSbD principles in the organizations. Specifically, the survey aimed to provide input to map SSbD activities, to define the gaps and to develop a Roadmap to operationalise at EU Level, the SSbD for materials, products, and processes. A special focus was placed on the initiatives that implement sustainability aspects in material and product R&D. A transcript of the survey is included in Annex B of PR1.5 [73].

This chapter maps industrial practice, research, and education in terms of LCA based on the WP1 survey replies. In total, **87 valid responses** were recorded. The replies of each thematic block are analysed in the specific section of this document.

The background of the responding organisations is shown in Figure 11 and Figure 12. Organizations from 19 countries responded to the survey, including:

- companies (n = 37; 43%),
- research and technology organisations (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 12).

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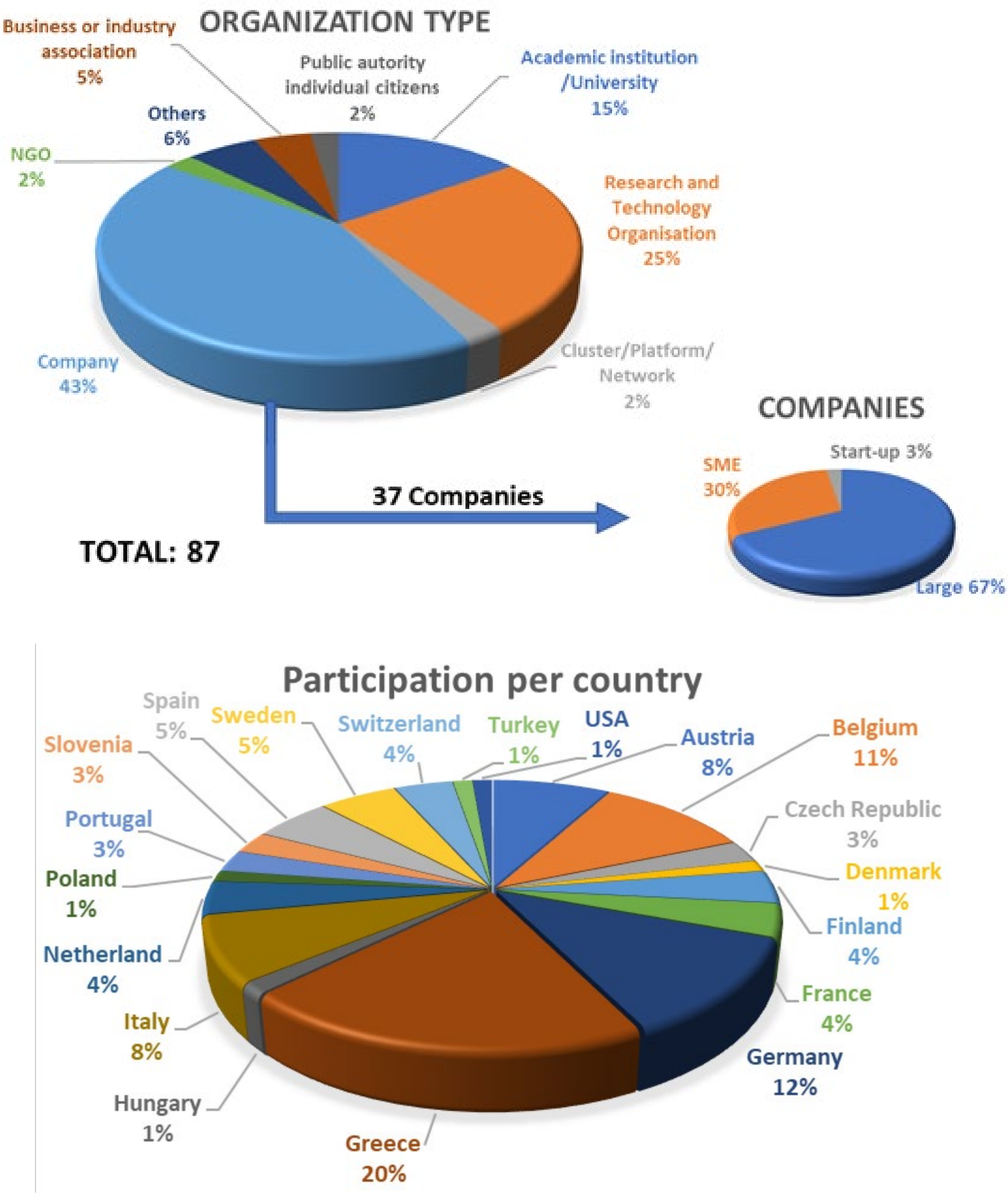

Figure 11 - Background of the respondents - organization type and country

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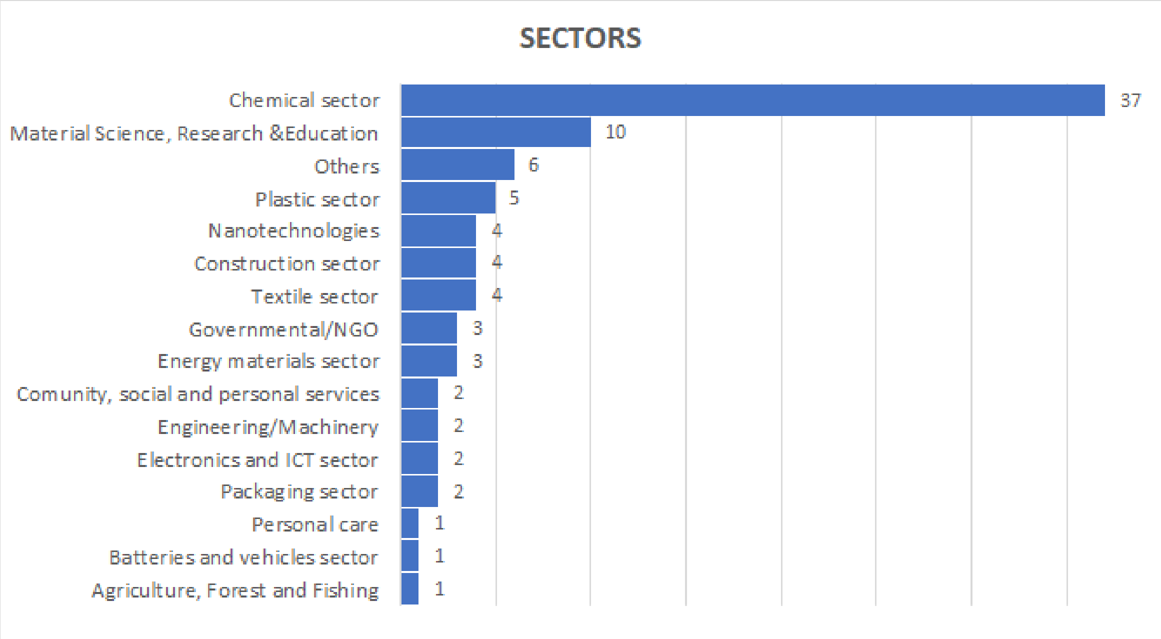

Figure 12 - Background of the respondents-Sectors.

Note: NGO: Non-governmental organization; ICT: Information and communication technologies.

6.2 Survey on the Environmental dimension

The analysis provided hereinafter is dedicated to evaluate the **sustainability environmental dimension** of the survey on the mapping of Safe and Sustainable by design (SSbD) initiatives. The questions of this survey section and the number of respondents obtained per question are summarized in Table 20 below.

Table 20 - Summary of responses in the survey section- sustainability Environmental Dimension: LCA

SURVEY SECTION - Sustainability Environmental Dimension: LCA			
Question number	Question	Number of respondents	
		Total	Companies
41	Does your company/institution/R&I project perform or intend to perform an Environmental Life Cycle Assessment (LCA) during the design or development phase of a material, product, process, or R&D activity?	87	37
42	Software: Do you use any specialized software tool to conduct Life Cycle Assessment of your materials, product, or processes?	46	21
43	Database: Do you use any Life Cycle inventory database to conduct the LCA analysis?	42	19
44	Impact Assessment Method	39	19
45	LCA phases: Indicate the phases considered or that you intend to consider in the environmental evaluation of your material, product, process, or R&D through a Life Cycle Assessment approach.	51	24
47	**Use stage aspects**: Indicate if you considered or intend to consider any of these aspects in the environmental evaluation of your material, product, process, or R&D through a Life Cycle Assessment approach.	42	19

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According to the survey results **64%** (n= 56) of the responding organizations (n=87) perform or intend to perform an Environmental Life Cycle Assessment (LCA) during the design or development phase of a material, product, or process (Figure 13).

From now on this section all the data will be referred to the 56 entities that use LCA.

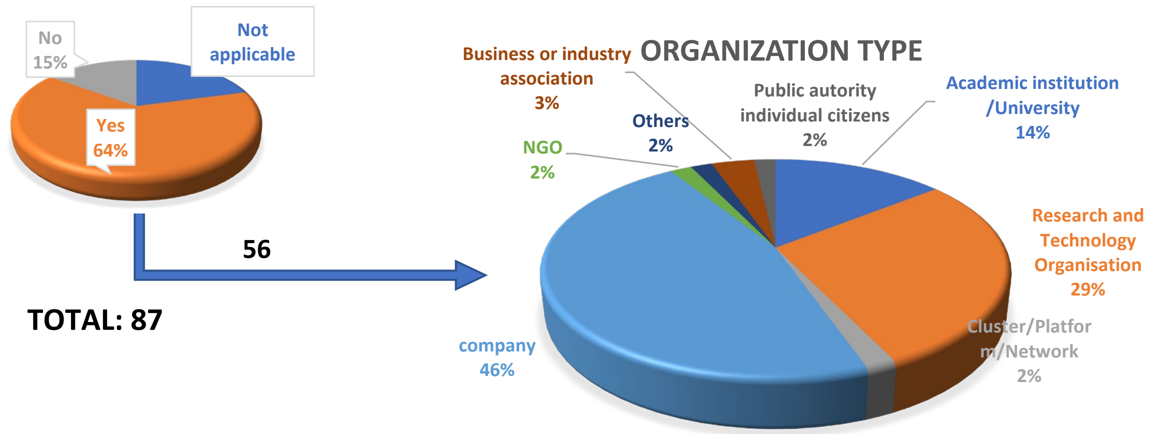

Figure 13 - Use of LCA during the design or development phase of a material, product, or process

Figure 14 shows the percentage of respondents that use LCA during the design or development phase (those who answered yes) broken down into the different organization types.

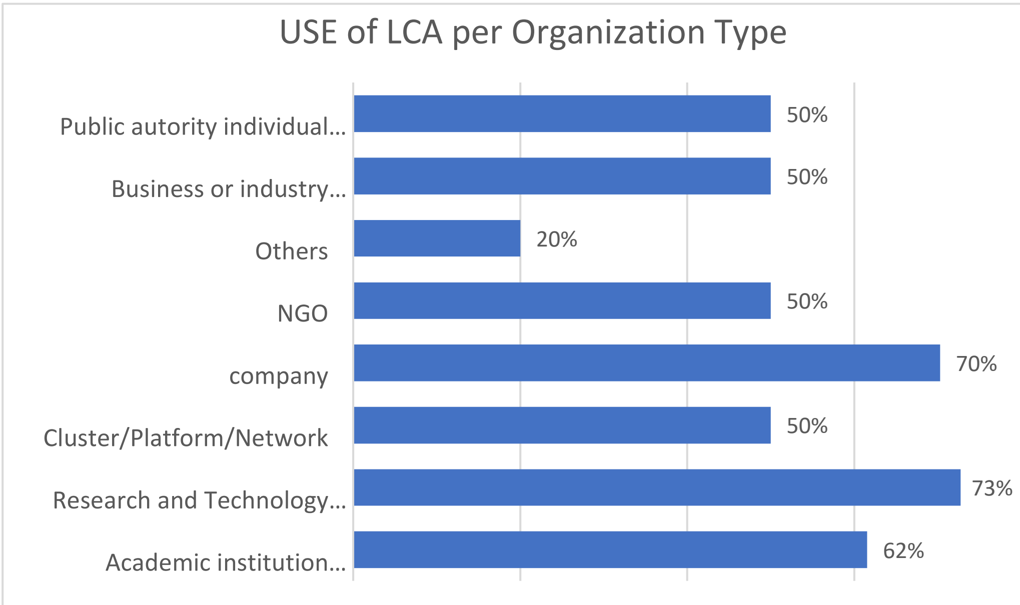

Figure 14 - Use of LCA per organization type

If we focus on the 37 companies, the percentage of the companies that use LCA assessment is surprisingly high (n=26, 70%). This may be due to the reason that the companies that fulfilled the survey are very conscious about the environmental related issues LCA and sustainability in general. However, there were much more companies that were invited to participate in this survey, but no response was obtained. Only a small percentage of companies invited was included in this survey, which may be not representative of the real industry situation. The survey was sent to 406 external stakeholders that joint a SSbD workshop organised by the IRISS project [74] as well as to the

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stakeholders and contacts of the associations involved in IRISS project [SusChem, ETP (EU Technology Platform for the Future of Textiles & Clothing), INL (International Iberian Laboratory), CLEPA(European Association of Automotive Suppliers), IPC-EPC4 (Industrial Technical Centre for Plastics and Composites; EFCC (European Federation for Construction Chemical)].

The large companies that responded to the survey use the LCA in a higher percentage than the SMEs (80% vs. 50%).

6.2.1 LCA Software

Table 21 summarizes the different LCA software used by the interviewed entities to perform LCA. From all the specialized LCA software available in the market, SimaPro and GaBi were the preferred ones used by the respondents, followed by OpenLCA. For the companies interviewed, the most used LCA software were SimaPro (43%), Gabi (33%) and OpenLCA (19%).

Table 21 - LCA software used by the entities interviewed

SOFTWARE	Total respondents		Companies	
	number	%	number	%
SimaPro	20	43%	8	36%
GaBi	15	33%	9	41%
OpenLCA	9	20%	4	18%
UMBERTO	3	7%	2	9%
TEAM	1	2%	0	0%
Activity-browser	1	2%	0	0%
Brightway2	1	2%	0	0%
Ecochain	1	2%	0	0

Total Entities	**46**	**22**

The number of entities using the different LCA software are presented in Figure 15.

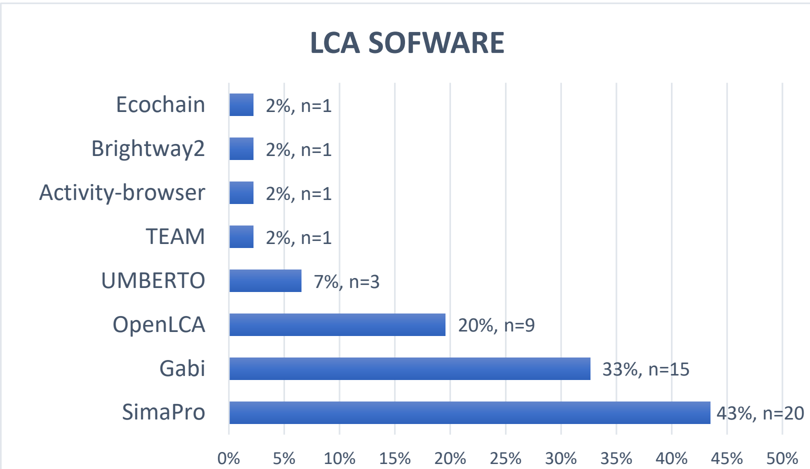

Figure 15 - LCA software used by the respondents.

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6.2.2 Databases

As shown in Table 22, ecoinvent was found to be the most commonly used database, followed by the GaBi software database.

Table 22 - LCA Databases used by the entities interviewed

DATABASE	Total respondents		Companies	
	number	%	number	%
ecoinvent	30	71%	14	70%
EPLCA	4	10%	0	0%
USLCI	1	2%	1	5%
LCA Food DK	1	2%	0	0%
ELCD	1	2%	1	5%
OTHERS	10	24%	10	50%
• GABI	5	12%	5	25%
• Agri -footprint/ Agrybase	2	5%	2	5%
• Sphera	1	2%	1	5%
• ILCD/EF	1	2%	1	5%
• internal procedures	1	2%	1	5%

Total Entities	**42**	**20**

6.2.3 Impact assessment methods

Concerning the impact assessment methods, EF (Environmental Footprint)/PEF was the most popular method, followed by ReCiPe and USEtox as it can be seen in Table 23.

Table 23 - Impact assessment method used by the entities interviewed

Impact Assessment Method	Total respondents		Companies	
	number	%	number	%
PEF /EF V3.0	**23**	59%	11	55%
ReCiPe	**17**	44%	9	45%
USEtox	9	23%	4	20%
CML	7	18%	6	30%
TRACI	1	3%	1	5%
IMPACT Word+	2	5%	1	5%
Others	3	8%	3	16%

Total Entities	**39**	**20**

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6.2.4 LCA stages

Table 24 and Figure 16 represent the different LCA stages considered by the entities interviewed. It can be concluded that the processing stage is considered in almost all LCA studies, however only 53% of the entities considered the use stage in their LCAs. The percentage was reduced to 48% for the companies.

Table 25 and Figure 17 show that the most important aspect considered during the use stage was the reduction of energy consumption. Functionality was also observed to be often used.

The durability and reusability were considered approximately by half of the respondents, but this value is reduced considerably for repairability (31%) and upgradability (21%).

Table 24 - LCA stages considered in LCA studies by the entities interviewed

LCA stages	Total respondents		Companies	
	number	%	number	%
Raw material extraction	38	78%	18	72%
Processing	46	94%	25	100%
Transport	38	78%	21	84%
Use Stage	26	53%	12	48%
End of life, recycling, reuse	34	69%	17	68%

Total Entities	**49**	**25**

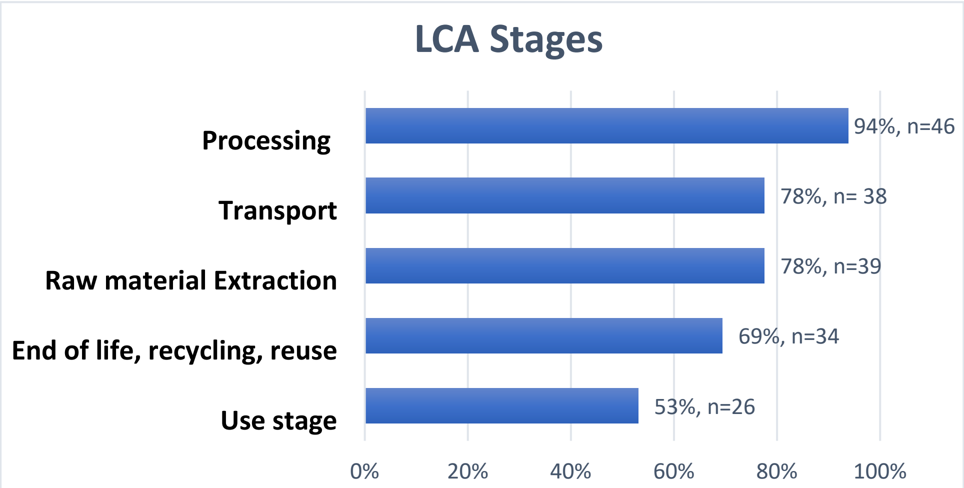

Figure 16 - LCA stages considered by the respondents

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Table 25 - Use stage aspects considered in LCA studies by the entities interviewed

Use stage aspects	Total respondents		Companies	
	number	%	number	%
Functionality (fitness for use)	27	64%	12	60%
Reduction of energy consumption	32	76%	16	80%
Reduction of water consumption	25	60%	12	60%
Durability	24	57%	10	50%
Reusability	22	52%	11	55%
Repairability	13	31%	5	25%
Upgradability	9	21%	4	20%

Total Entities	**42**	**20**

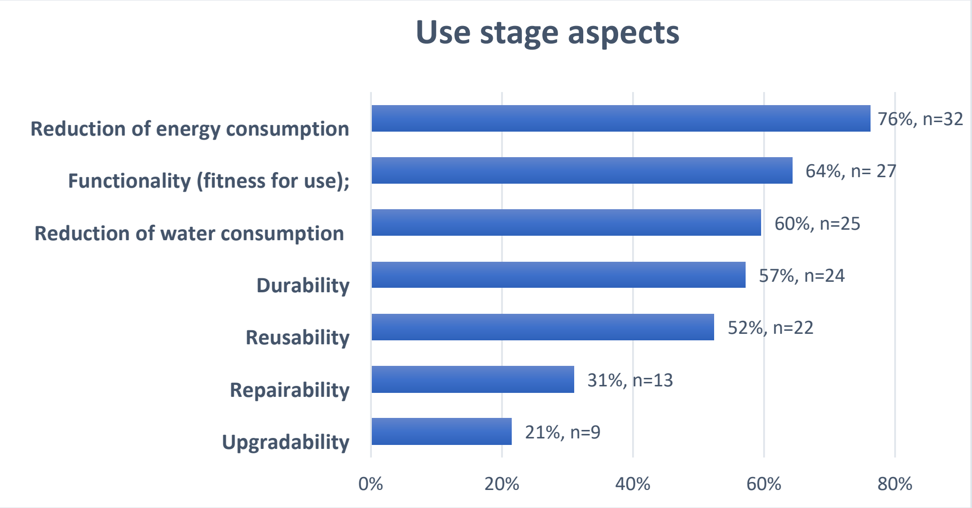

Figure 17 - Use stage aspects considered by the respondents

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7. EU projects analysis

In addition to the WP1 survey reported in Section 6, information from other EU-funded projects related to SSbD was also collected. For this, the project coordinators of the most relevant identified H2020 projects and HE projects were contacted and asked to complete the template presented in Annex B of PR1.5. This template was designed to obtain information about the application of SSbD principles, based on the JRC's SSbD framework as the leading SSbD document within WP1. The projects were contacted in January and February 2023. Efforts were mainly 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 **LCA aspects** considered in on-going EU projects. Fifteen projects completed the project template and two additional EU projects responded to the WP1 survey (Section 6) and were analysed in this chapter as well, resulting in **seventeen projects** in total briefly described in Table 26. A more detailed description of the projects is included in the preliminary report 1.2 [52].

Table 26 - List of projects that provided information

Project Acronym and Logo	Project Title, Short Description and expected environmental benefits
Horizon 2020 SSbD projects	
ASINA	***Title***: Antimicrobial and self-depolluting nano-structured coatings in clean technologies. ***Brief description***: Variations of Silver Nanomaterials (AgNPs) for coated antimicrobial functional textiles. Variations of active Titanium Dioxide Nanomaterials (TiO2) for coated photocatalytic functional textiles. ***LCA and expected environmental benefits.*** The Asina projects expects to generate environmental benefit. 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. ***Brief description***: BreadCell develop 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. ***LCA and expected environmental benefits.*** If the project is successful in substituting plastic derivatives materials for nanocellulose, then definitively this will be a benefit for the environment in the productions of biobased foams.
DIAGONAL	***Title***: Development and scaled Implementation of sAfe by design tools and Guidelines for multiCOmponent aNd hArn nanomateriaLs. ***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 stages. ***LCA and expected environmental benefits.***

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Project Acronym and Logo	Project Title, Short Description and expected environmental benefits
	This project expects to provide strategies and recommendations to the case studies but also to be expanded to other products containing MCNMs and HARNs, to make them more sustainable and safer, considering their function.
Gov4Nano	***Title:*** Implementation of Risk Governance: meeting the needs of nanotechnology. ***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. ***LCA and expected environmental benefits.*** As Gov4Nano is a governance project, it is not expected to generate environmental benefits.
HARMLESS	***Title:*** Advanced High Aspect Ratio and Multicomponent materials: towards comprehensive intelLigent tEsting and Safe by design Strategies. ***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. ***LCA and expected environmental benefits.*** The HARMLESS long-term vision is to move Safe-by-Design concepts from its current infancy state to a mature state that all companies – including SMEs – should be able to apply routinely. To make their vision come true, they collaborate across the entire nanosafety domain on international level. They Safe Innovation Approach will be delivered both as guidance and as e-tool. Harmless intends to perform LCA on each of the case studies.
i-TRIBOMAT	***Title***: Intelligent Open Test Bed for Materials Tribological Characterisation Services. ***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. ***LCA and expected environmental benefits.*** i-TRIBOMAT provide tools for a more accurate tribological characterisation of materials, which will affect positively to the environment. For example, improving friction properties reduces fossil fuel consumption and CO_2 emissions, which contributes positively against the climate change. The reduction in wear and larger longevity of materials contributes to minimum wastage, easy and low-cost reclamation or disposal, and minimum replenishment of lubricants. In addition, reduction of particles generated by wear has a positive effect by reducing toxic emissions, with obvious human health and environmental benefits.
NanoHarmony	***Title***: Towards harmonized test methods for nanomaterials. ***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. ***LCA and expected environmental benefits.***

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Project Acronym and Logo	Project Title, Short Description and expected environmental benefits
	The NanoHarmony expects to generate environmental benefits, by the support of the development OECD Test Guidelines related to environmental risk assessments.
NanoMECommons	***Title:*** Harmonisation of EU-wide nanomechanics protocols and relevant data exchange procedures, across representative cases; standardisation, interoperability, data workflow. ***Brief description:*** EU-funded NanoMECommons will form an EU-wide research and innovation network aiming to develop harmonised and widely accepted characterisation protocols, utilizing 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). ***LCA and expected environmental benefits.*** Nano-scale mechanical characterisation has been clearly identified, by both industrial and academic stakeholders, as one of the main tools for supporting the development and exploitation of nanomaterials in a very wide range of strategic sectors. This can be easily understood by the fact that modern devices, with central role in smart, energy-efficient, and environmentally friendly applications, very often consist of nanomaterials in miniaturized designs (as those exhibited by the industrial partners in nanoMECommons). The functional properties of nanomaterials in the form of e.g., nanostructured surfaces, coatings and thin films have received increased focus. However, their nanomechanical behavior is equally important as it ensures structural integrity and durability, whilst influencing their repairability and reusability. These are essential elements within a circular economy perspective and assume increased importance in the circular economy action plan and area 3 of the European Green Deal "Mobilising industry for a clean and circular economy".
ReSOLUTE	***Title***: Research empowerment on solute carriers ***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. ***LCA and expected environmental benefits.*** ReSOLUTE project has a work package devoted to LCA,. The End of life is important because the bio-products produced within ReSOLUTE are biodegradable, water and environmentally benign. So, when comparing with petrochemicals that are on the market, their end of life is far more positive.
RiskGONE	***Title***: Science-based Risk Governance of Nano-Technology. ***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. ***LCA and expected environmental benefits.*** RiskGONE developed guidance documents for LCA applied to ENMs.
SAbyNA	***Title***: Simple, robust, and cost-effective approaches to guide industry in the development of safer nanomaterials and nano-enabled products (SAbyNA). ***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

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Project Acronym and Logo	Project Title, Short Description and expected environmental benefits
	processes along the product life cycle, with advanced functionalities tailored to different industrial sectors (Paints and Additive Manufacturing). ***LCA and expected environmental benefits.*** The projects will include a module to evaluate environmental impacts proposing a simplified LCA tool tailored to two sectors: Paints and Additive manufacturing.
SbD4Nano	***Title***: Computing infrastructure for the definition, performance testing and implementation of safe-by-design approaches in nanotechnology supply chains. ***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. ***LCA and expected environmental benefits.*** Environmental benefits include: 1) less damage to the environment, 2) lower spending to remediate or compensate for environmental damage and, 3) lower risks of damage to the environment. The development of efficient procedures to control the exposure and the design of more stable and less toxic ENMs and NEPs will improve environmental safety, minimizing the release to the environment of ENMs with potential ecotoxic effects. Furthermore, the implementation of new and tested risk management measures will improve the effectiveness of the spill control system and the minimization of ENMs released to the environment in the manufacturing process, considering the emission via air, water, and soil.
Horizon Europe SSbD projects	
greenSME	***Title:*** Driving manufacturing SME transformation towards green, digital, and social sustainability. ***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 networking opportunities and tailored advisory services to SMEs. ***LCA and expected environmental benefits.*** GreenSME is a CSA type project, and its main goal is to promote and support sustainability related projects between SME, and Advanced technology and social innovation providers. GreenSME aims to reduce manufacturing activity environmental impact through the adoption of advanced technologies and social innovation principles.
RELIANCE	***Title***: Smart response self-disinfected biobased nanocoated surfaces for healthier environments. ***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. ***LCA and expected environmental benefits.*** Several antimicrobial coatings exist in the market; however, they are based mainly on the leaching of non-environmentally friendly chemicals. RELIACE develop highly durable nanocoatings with a smart response to the environment., avoiding the leaching of antibiotics and non-environmentally friendly chemicals.

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Project Acronym and Logo	Project Title, Short Description and expected environmental benefits
	RELIANCE will take care of the environmental aspects in all the stages of the value chain: from the innovative additive conception using bioactive compounds (Essential oils and Antimicrobial Peptides) coming from renewable resources, up to the obtaining and application of the nanocoatings, by using reactants coming from renewable sources for binders, fluorine free formulations or organic solvent-free application techniques.
SUSAAN	***Title:*** SUStainable Antimicrobial and Antiviral Nanocoating. ***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. ***LCA and expected environmental benefits.*** Integrated life cycle sustainability assessment (ILCSA) including LCA, LCC and SLCA will provide a practical approach to harmonize a parallel assessment of individual processes and products, scenarios, and system models in all the phases of the value chain. Regarding the environmental dimension, the expected benefits derive from: • Biobased materials able to perform a chemical substitution in the nanomaterial synthesis in an effective manner. • Screened set of materials or technologies and product applications to foster sustainable solutions from the design phase to the products end of life. • Selected alternatives, optimizing materials, water and energy resources use through more sustainable synthesis routes.
TransPharm	***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. ***LCA and expected environmental benefits.*** Transpharm will demonstrate the Benign-by-Design (BbD) concept, integrating improved environmental degradability into the lead discovery and optimization process from very early on whilst meeting effectiveness and patient safety. Antibiotics are used as an example to address the antibiotic crisis and antimicrobial resistance.
Other SSbD projects	
DaNa4.0	***Title***: Data on new, innovative, and safe application related materials. ***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. ***LCA and expected environmental benefits.*** The extracted 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.

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Application of LCA in projects

The 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 the Hotspot Scan. Only 5 projects identified the impact assessment method they use, being the **EF** the most popular (n=3) followed by USEtox (n=2).

LCA stages Figure 18 represent the different LCA stages considered by the projects analysed. It can be concluded that the processing stage is taken into account in all the projects performing LCA that have responded to this question (n=9, 100%) but this value is considerably lower for the use stage (n= 7, 78%) and end of life stage (n= 6, 68%).

When focussing on the use stage, according to the results showed in Figure 19, the most important aspect is the functionality (n=8, 100%). The reduction of energy consumption during use, reusability and durability is considered by half of the respondents, but these values are reduced considerably for repairability (n=1, 13%) and upgradability (n=1, 13%).

This in line with the study by Caldeira et al. that analyses the application of JRC SSbD framework to case studies [75] where one of the key conclusions was the need to include in the assessment methodology sector specific performance assessment (e.g., surface conductivity, durability). High performance has a positive impact on the overall sustainability.

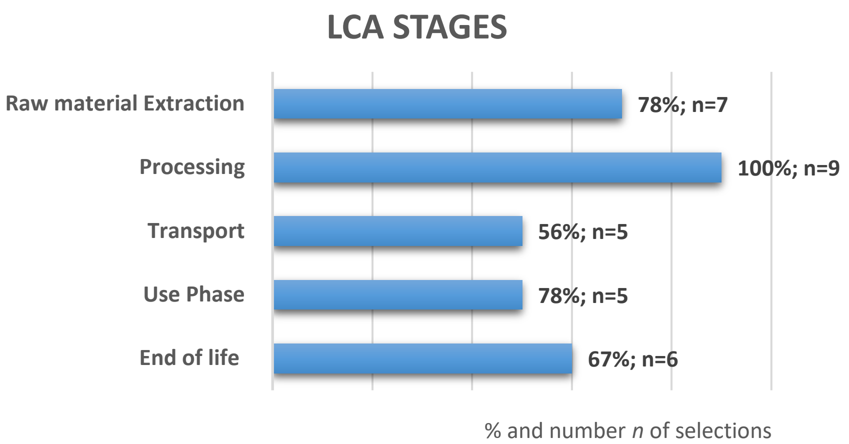

Figure 18 - LCA stages, considered in LCA studies by the analysed projects

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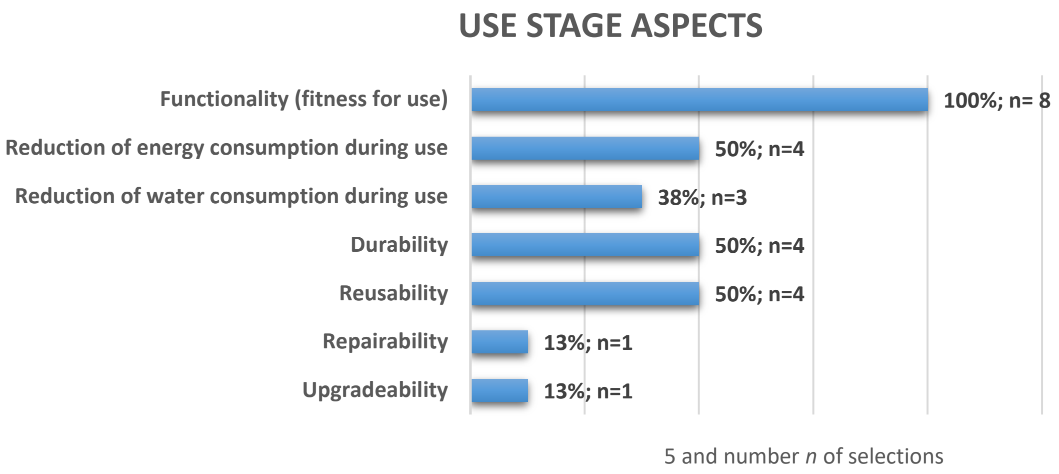

Figure 19 - Use stage aspects considered in LCA studies by the projects.

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8. CONCLUSIONS

Safe and Sustainable-by-Design (SSbD) is a key component of the European Commission's Chemical Strategy for Sustainability (CSS) and it is a pre-market approach that aims to integrate safety and sustainability as early as possible in the innovation process and throughout the entire product lifecycle. The concept of SSbD aims to ensure that chemical materials and products are designed, produced, and used in a way that does not harm people and does not harm environment.

Life Cycle Assessment (LCA) plays a crucial role in SSbD providing a comprehensive analysis of the environmental impacts associated with a material, product, or process throughout its entire life cycle, covering the assessment of environmental sustainability aspects.

ISO 10040 and ISO 14044 are the two main standards that are widely accepted and serve as a basis for LCA studies globally. In addition, there are several regional and sector-specific LCA guidelines and standards. LCA practitioners should be aware of any additional guidelines or standards specific to their industry or region to ensure compliance and accuracy in their assessments. For a small and medium-sized enterprise (SME), selecting the suitable LCA standard and guideline for a specific product can be a challenging task. Some standards may require extensive data collection, analysis, or modelling, which can be not affordable for SMEs, typically with limited resources. The roadmaps that will be developed within WP3 of IRISS projects should address this issue and propose an LCA methodology that strikes a balance between scientific rigor and practicality for the SMEs.

One widely used application where the LCA methodology is required is the Environmental Product Declaration (**EPD).** The EPDs, also called type III environmental declaration that is compliant with the ISO 14025, are used by companies to demonstrate and communicate the environmental quality of their products and services. The Life Cycle Assessment (LCA), forming the basis of the EPDs, must be conducted in accordance with specific **Product Category Rules (PCR**). The EPD is a mature method and comprises a significant number of PCR for different sectors, with **construction** having the highest number of PCRs, followed by the food & beverages sector. However, in other sectors, the number of existing PCRs is very limited or non-existent. This can be attributed to factors such as industry focus, complexity, resource constraints, emerging or niche status, and regional variations. Over time, as sustainability practices become more widespread and industry demand increases, efforts can be made to develop PCRs in these sectors to enhance transparency and facilitate environmental assessments.

The International EPD System proposes to use a list of the default environmental impact and inventory indicators, however requirements or recommendations in a PCR may deviate from the default list. The most recently environmental indicators proposed by the International EPD system are based on **EF (Environmental Footprint)** impact assessment methodology.

Recently, the European Commission has created the **Product Environmental Footprint (PEF)** methodology, which is a LCA based method to measure and communicate the potential life cycle environmental impact of products (goods or services) and organizations, respectively. The PEF program intends to improve comparability of the environmental performance of a product based on a strictly defined Life Cycle Assessment method that is based on **Product Environmental Footprint Category Rules (PEFCR).** This program is under development and during the pilot phase, twenty-one PEFCRs/OEFSRs have been generated; however, the number of PEFCRs is still very limited. Despite the low number of PEFCRs, efforts are being made to increase their development, particularly in sectors of high environmental significance or where demand for environmental performance information is growing. In the EF all the life cycle stages are mandatory (raw material acquisition and pre-processing, manufacturing, distribution, use stage, end of life); however, for

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certain products (i.e., intermediate), a cradle to gate assessment can be performed. The EF impact assessment methodology comprises 16 impact category indicators**.**

To ensure comparability of LCA studies that are used in the **SSbD context**, specific guidelines should be developed but in the meanwhile the **JRC SSbD framework recommends using the PEF method,** which is the European Commission recommended method to assess life cycle environmental performance of products on the market. [30]

There are several tools that can assist in performing a LCA study, including databases, software, impact assessment methodologies, and environmental indicators. LCA databases contain extensive data on the life cycle inventory (LCI) of various materials, products, and processes. Impact assessment methodologies help to quantify environmental impacts, translating LCI data into environmental indicators that measure impacts across different categories, such as climate change, resource depletion, and human health. Specialized LCA software integrates databases, environmental indicators, and calculation engines, facilitating modeling, analysis, and interpretation of LCA studies.

Database: Availability of data (of good quality) is one key aspect for Life Cycle modelling. There are different initiatives working in this direction aiming to achieve a wide usage of LCA through better accessibility and interoperability of LCA data. Among them the **GLAD (Global LCA Data Access network)** and **open LCA NEXUS** initiatives can be highlighted.

The most widely used database according to the bibliographical search, the survey and the EU project analysis is **ecoinvent**, which is the one with the highest number of datasets. According to the database mapping analysis, the available information along the life cycle indicates that the product conception step (extraction of raw materials, energy, processing, and transport) has more information than the other steps (use and end of life). Analysing the distribution of information by sectors, the textile, electronics, and battery sectors have the lowest LCA data information volume, while the automotive, chemical products and agriculture sectors have the most.

Software: Currently, there are several LCA software tools available in the market, some of them, can be purchased and other are free (e.g., OpenLCA). The most widely used software according to the literature review, survey and EU projects analysis is **SimaPro,** followed by GaBi and OpenLCA.

Impact Assessment method and environmental indicators: According to the survey results, and the methodologies proposed by on-going Horizon Europe projects, the most used impact assessment methodology is the **EF**. This is in line with the methodology proposed by the JRC SSbD framework. The EF methodology comprises 16 environmental impact assessment indicators, which are also covered by the **ReCiPe** methodology (the second most used impact assessment method in the survey analysis and the most popular in the bibliographical review), but each methodology has its particularities.

LCA stages and circular economy: An LCA assesses the environmental impacts of goods and processes from **"cradle to grave"** quantitatively, which covers raw material extraction (also called the "cradle"), processing, transportation, use and end of life ("grave"). Since "**circular economy**" is increasing international attention, **"cradle-to-cradle"** emerged as the ideal for products' life cycles. It exchanges the end-of-life stage with a recycling process that makes it reusable for another product – essentially closing the loop. This tendency is also observed in the literature review where the terms "Renewable", "Recovery" and "Reusability" are gaining attention, together with "Durability". In the PEF method, one crucial aspect in LCA studies is to accurately and consistently model waste and recycled materials, and the **Circular Footprint Formula** (CFF) has been developed for this purpose.

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However, in practice, according to the survey results[2] and the EU projects analysis, the LCA studies continue focusing mainly on production, but not all studies consider the end-of-life. Just some of survey respondents consider the use stage (the inclusion of use stage is higher within EU projects). The most important aspects considered during use stage are the **functionality and the reduction of energy consumption.** This is in line with the work that analyses the application of JRC SSbD framework to case studies [75], where one key aspect identified was the need to include sector specific performance assessment (e.g., surface conductivity, durability) in the assessment methodology. High performance has a positive impact on the overall sustainability. The durability and repairability are considered approximately by half of the respondents in both the survey and EU projects analysis, but this value is considerably reduced for repairability and upgradability.

Conducting an LCA within the SSbD context poses specific challenges, particularly concerning the low TRL of the technologies involved. When a technology is in an early stage of development with limited maturity, conducting a robust LCA becomes a difficult task due to the high degree of uncertainty regarding specifications at the industrial scale, and the absence of comprehensive large-scale process data. To fill this gap, ex-ante LCA has evolved in recent years, aiming to assess emerging technologies at an early stage of development by exploring, among others, possible scenarios of their future industrial scale implementation. The key principle of ex-ante LCA is to identify and analyse the potential environmental impacts of different design choices and alternatives before they are implemented. Data derived from process simulations and produced from lab or bench scale apparatuses are used to perform ex-ante LCA studies of emerging technologies. However, when using small scales, uncertainty is added and can result in large differences in process efficiencies and operating conditions.

In summary, environmental LCA is vital in SSbD as it helps to identify environmental hotspots, quantify impacts, support decision-making during the design phase, and enhance transparency and accountability. By integrating LCA into the design and management of supply chains, companies can make more sustainable choices, reduce environmental impacts, and contribute to a greener future. However, there are still several methodological challenges that needs to be addressed and will be further analysed within IRISS WP2-“gap analysis”.

[2] The survey may be not representative for Europe as just a few percent of the companies and stakeholder contacted, answered the questionnaire.These stakeholders, 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.

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9. REFERENCES

[1] (JRC, 2022), Caldeira, C., Farcal, R., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Riego Sintes, J. and Sala, S., Safe and sustainable by design chemicals and materials - Framework for the definition of criteria and evaluation procedure for chemicals and materials, EUR 31100 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-53280-4, DOI 10.2760/487955 (online)

[2] (Caldeira, 2022) Caldeira, Farcal R, Moretti C, Mancini L, Rauscher H, Rasmussen K, et al. Safe and Sustainable chemicals by design chemicals and materials, Review of safety and sustainability dimensions, aspects, methods, indicators, and tools. 2022. https://doi.org/10.2760/68587.

[3] Bjørn, A., Owsianiak, M., Molin, C., Laurent, A., 2018. Main characteristics of LCA. In: Hauschild, M.Z., Rosenbaum, R.K., Irvin Olsen, S. (Eds.), Life Cycle Assessment - Theory and Practice. Springer International Publishing AG, NY, pp. 9–16. ISBN 978-3-319-56474-6

[4] (2021, Toniolo) Sara Toniolo, Lorenzo Borsoi, Daniela Camana, Life cycle assessment: methods, limitations, and illustrations. Chapter 7 Methods in Sustainability Science Assessment, Prioritization, Improvement, Design and Optimization. https://doi.org/10.1016/C2020-0-00430-5

[5] https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

[6] https://c2ccertified.org/

[7] (SETAC, 1993) SETAC, 1993. Guidelines for Life - Cycle Assessment: A 'Code of Practice. SETAC, Brussels. Toniolo, S., Tosato, R.C., Gambaro, F., Ren, J., 2020. Life cycle thinking tools: life cycle assessment, life cycle costing and social life cycle assessment. In: Ren, J., Toniolo, S. (Eds.), Life Cycle Sustainability Assessment for Decision-Making. Methodologies and Case Studies. Elsevier, Amsterdam, pp. 39–56. ISBN 9780128183557

[8] (ISO, 2020). ISO 14040:2006/AMD 1:2020. Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization, Geneva, Switzerland.

[9] 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations Text with EEA relevance - EU monitor

[10] Ekvall, T., Azapagic, A., Finnveden, G. et al. Attributional and consequential LCA in the ILCD handbook. Int J Life Cycle Assess 21, 293–296 (2016). https://doi.org/10.1007/s11367-015-1026-0.

[11] Marc-Andree Wolf, Rana Pant, Kirana Chomkhamsri, Serenella Sala, David Pennington (2012): International Reference Life Cycle Data System (ILCD) Handbook – Towards more sustainable production and consumption for a resource-efficient Europe. JRC Reference Report, EUR 24982 EN. European Commission – Joint Research Centre. Luxembourg. Publications Office of the European Union; 2012. DOI: 10.2788/85727 https://eplca.jrc.ec.europa.eu/uploads/JRC-Reference-Report-ILCD-Handbook-Towards-more-sustainable-production-and-consumption-for-a-resource-efficient-Europe.pdf

[12] Global Footprint Network Standards Committee (2009) Ecological Footprint Standards 2009. WRI/WBCSD 2011, Greenhouse Gas Protocol – Product Life Cycle Accounting and Reporting Standard.

Funded by the European Union

The project receives funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement n° 101058245. UK participants in Project IRISS are supported by UKRI grant 10038816. CH participants in Project IRISS receive funding from the Swiss State Secretariat for Education, Research, and Innovation (SERI).

https://www.footprintnetwork.org/content/uploads/2019/05/Ecological_Footprint_Standards_2009.pdf

[13] Greenhouse Gas Protocol - Product Life Cycle Accounting and Reporting Standard (WRI/ WBCSD, 2011. http://docs.wbcsd.org/2011/09/Product_Life_Cycle_Accounting_Reporting_Standard.pdf

[14] PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services - European Standards. https://www.en-standard.eu/pas-2050-2011-specification-for-the-assessment-of-the-life-cycle-greenhouse-gas-emissions-of-goods-and-services/; https://website-production-s3bucket-1nevfd7531z8u.s3.eu-west-1.amazonaws.com/public/website/download/79ef13ea-6a07-4d0c-95d7-3ee3b8769595/2012-PAS_2050-1_2012.pdf

[15] ENVIFOOD Protocol, Environmental Assessment of Food and Drink Protocol, European Food Sustainable Consumption and Production Round Table (SCP RT), Working Group 1, Brussels, Belgium.

[16] Analysis of Existing Environmental Footprint methodologies for Products and Organizations: Recommendations, Rationale, and Alignment. EC – IES - JRC, Ispra, November 2011. https://ec.europa.eu/environment/eussd/pdf/Deliverable.pdf

[17] The International EPD System. EPD International AB. EPD Library: https://epdweb3.azurewebsites.net/library

[18] https://www.environdec.com/all-about-epds/the-epd

[19] Johnsen FM, Tellnes LGF. Verification of Environmental Product Declarations (EPDs) – how strict should it be? E3S Web Conf 2022; 349:08002. https://doi.org/10.1051/e3sconf/202234908002.

[20] https://gccassociation.org/sustainability-innovation/environmental-product-declarations/

[21] https://www.datocms-assets.com/37502/1683549835-gunnar-prefab.pdf

[22] https://www.oneclicklca.com/pre-verified-epd-generator/

[23] https://www.datocms-assets.com/37502/1682439613-tmf-kitchen-and-bathroom.pdf

[24] https://www.environdec.com/resources/indicators

[25] https://eplca.jrc.ec.europa.eu/LCDN/EN15804.xhtml

[26] Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S. and Ardente, F., Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method, EUR 31414 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-76-99069-7, doi:10.2760/798894, JRC130796.

[27] Andrea Zellmeyer, Analysing textile labels and the European Product Environmental Footprint (PEF) for environmental sustainability. MAS Thesis 2021 https://www.fhnw.ch/de/weiterbildung/lifesciences/mas-umwelttechnik-und-management/mas-thesen

[28] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021H2279

[29] (2019, Pant) European Commission, Joint Research Centre, Pant, R., Zampori, L., Suggestions for updating the organization environmental footprint (OEF) method, Publications Office, 2019, https://data.europa.eu/doi/10.2760/424613

Funded by the European Union

The project receives funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement n° 101058245. UK participants in Project IRISS are supported by UKRI grant 10038816. CH participants in Project IRISS receive funding from the Swiss State Secretariat for Education, Research, and Innovation (SERI).

[30] European Commision recommendations of 16-12-2021 on the use of Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organizations, COM (2021)9332

[31] PEFCR under development EU webpage: https://ec.europa.eu/environment/eussd/smgp/ef_transition.htm

[32] PEFCR EU webpage: https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

[33] (2021, JRC) Understanding Product Environmental Footprint and Organization Environmental Footprint methods. Available at: https://green-business.ec.europa.eu/environmental-footprint-methods_en

[34] JRC, "Product Environmental Footprint (PEF) Guide", preliminary report 2 and 4A of the Administrative Arrangement between DG Environment and the Joint Research Centre No N 070307/2009/552517, including Amendment No 1 from December 2010. (Ref. Ares(2012)873782 - 17/07/2012)

[35] https://www.europarl.europa.eu/cmsdata/267264/Presentation%20Bo%20WEIDEMA%20.pdf

[36] ORIENTING (Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy (https://orienting.eu/) (https://cordis.europa.eu/project/id/958231)

[37] GLAD - Global LCA Data Access network https://www.globallcadataaccess.org/

[38] https://github.com/UNEP-Economy-Division

[39] https://nexus.openlca.org/

[40] https://nexus.openlca.org/databases

[41] https://www.researchandmarkets.com/

[42] https://eplca.jrc.ec.europa.eu/ResourceDirectory/faces/tools/toolList.xhtml

[43] https://ecoinvent.org/the-ecoinvent-association/software-tools/

[44] Lopes Silva DA, Oliveira Nunes A, da Silva Moris VA, Moro Piekarski C, Oliveira Rodrigues T. How important is the LCA software tool you choose? Comparative results from GaBi, openLCA, SimaPro and Umberto. Cilca 2017.

[45] Mylène Pongérard, Flavien San Augustin, Manuel Paredes. Comparison of Tools for Simplified Life Cycle Assessment in Mechanical Engineering. Advances in Design Engineering II, Springer International Publishing, pp.71-80, 2022, Lecture Notes in Mechanical Engineering. Comparison of tools for simplified Life Cycle. https://doi.org/10.1007/978-3-030-92426-3_9

[46] ARTOGREEN Homepage, http://www.artogreen.com/

[47] Base IMPACTS Homepage, http://www.base-impacts.ademe.fr/

[48] https://impactdatabase.eu/

[49] ECOdesign Studio Homepage, https://www.ecodesign-studio.com/

[50] Ifu Hamburg Homepage, https://www.ifu.com/en/umberto

[51] https://susproc.jrc.ec.europa.eu/product-bureau//sites/default/files/2021-07/UM3_Indicator-1.2_list_of_LCA_software_and_databases.pdf

Funded by the European Union

The project receives funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement n° 101058245. UK participants in Project IRISS are supported by UKRI grant 10038816. CH participants in Project IRISS receive funding from the Swiss State Secretariat for Education, Research, and Innovation (SERI).

[52] Mendoza G, Igartua A, Sarasua JA, Cerrillo C, Apel C, Kümmerer K, Sudheshwar A, Lihammar R. 2023. PR1.2 Sustainable by design methods and criteria mapping. IRISS – International ecosystem for accelerating the transition to Safe-and-Sustainable-by-Design materials, products, and processes. Grant agreement n° 101058245.

[53] Heijungs R, Guinée JB, Huppes G, Lankreijer RM, Ansems AMM, Eggels PG, van Duin R, de Goede HP (1991): Manual for the Environmental Life Cycle Assessment of Products. Second interim version approved by the supervisory commission. Ms., Leiden

[54] Seen B, Arvidsson P, Nobel Gunnar Borg A, et al. (1999a) A systematic approach to environmental priority strategies in product develop- ment (EPS). Version 2000 – General system characteristics. Centre for Environmental Assessment of Products and Material Systems. Chalmers University of Technology, Technical Environmental Planning

[55] Steen B, Arvidsson P, Nobel Gunnar Borg A et al. (1999b) A systematic approach to environmental priority strategies in product develop- ment (EPS). Version 2000 – Models and data ofthe default method. Centre for Environmental Assessment of Products and Material Systems. Chalmers University of Technology, Technical Environmental Planning, Gothenburg

[56] Müller-Wenk R (1978) Die ökologische Buchhaltung: Ein Informations- und S t euerungsinstrument für umweltkonforme Unternehmenspolitik. Campus-Verlag, Frankfurt

[57] Heijungs R (ed), Guinée GB, Huppes G, Lankreijer RM, Udo de Haes HA, Wegener Sleeswijk A, Ansems AMM, Eggels PG, van Duin R, de Goede HP (1993): Environmental Life Cycle Assessment of Products. Guide, October 1992, Leiden

[58] http://cml.leiden.edu/software/data-cmlia.htm

[59] https://www.usetox.org/

[60] http://www.ecoinvent.org/contact/

[61] http://www.ipcc.ch/contact/contact

[62] R. Lihammar, K. Geidenmark, A. Ghasemi, S. Willskytt, M. Häggström , G. Mendoza, J. Sarasua, C. Apel, K. Kümmerer, A. Sudheshwar, B. Pinlova. 2023. PR1.4 Design for circular economy – International ecosystem for accelerating the transition to Safe-and-Sustainable-by-Design materials, products and processes. Grant agreement n° 101058245.

[63] Wender BA, Foley RW, Hottle TA,SadowskiJ,Prado-Lopez V, Eisenberg DA, Laurin L, Seager TP (2014) Anticipatory life-cycle assessment for responsible research and innovation. J Responsible Innov 1:200–207. https://doi.org/10.1080/23299460.2014.920121

[64] Pallas G, Peijnenburg WJGM,Guinée JB, Heijungs R, VijverMG (2018) Green and clean: reviewing the justification of claims for nanomaterials from a sustainability point of view. Sustainability (Switzerland) 10. https://doi.org/10.3390/su10030689

[65] Cucurachi, S., van der Giesen, C., Guin´ee, J., 2018. Ex-ante LCA of emerging technologies. Procedia CIRP, 25th CIRP life cycle engineering (LCE) conference, 30 April –2 May 2018, Copenhagen, Denmark 69, 463–468. 10.1016/j. procir.2017.11.005.

[66] Buyle M, Audenaert A, Billen P, Boonen K, Van Passel S. The future of ex-ante LCA? Lessons learned and practical recommendations. Sustain 2019;11:1–24. https://doi.org/10.3390/su11195456.

[67] Tsoy N, Steubing B, van der Giesen C, Guinée J. Upscaling methods used in ex ante life cycle assessment of emerging technologies: a review. Int J Life Cycle Assess 2020;25:1680–92. https://doi.org/10.1007/s11367-020-01796-8.

Funded by the European Union

The project receives funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement n° 101058245. UK participants in Project IRISS are supported by UKRI grant 10038816. CH participants in Project IRISS receive funding from the Swiss State Secretariat for Education, Research, and Innovation (SERI).

[68] Tsalidis GA, Korevaar G. Environmental assessments of scales: The effect of ex-ante and ex-post data on life cycle assessment of wood torrefaction. Resour Conserv Recycl 2022;176:105906. https://doi.org/10.1016/j.resconrec.2021.105906.

[69] Van der Giesen, C., Cucurachi, S., Guin´ee, J., Kramer, G.J., Tukker, A., 2020. A critical view on the current application of LCA for new technologies and recommendations for improved practice. J. Clean. Prod. 259, 120904 https://doi.org/10.1016/j. jclepro.2020.12090

[70] Parvatker, A.G., Eckelman, M.J., 2019. Comparative evaluation of chemical life cycle inventory generation methods and implications for life cycle assessment results. ACS Sustain. Chem. Eng. 7, 350–367. https://doi.org/10.1021/acssuschemeng.8b03656

[71] van der Hulst, M.K., Huijbregts, M.A.J., van Loon, N., Theelen, M., Kootstra, L., Bergesen, J.D., Hauck, M., 2020. A systematic approach to assess the environmental impact of emerging technologies: a case study for the GHG footprint of CIGS solar photovoltaic laminate. J. Ind. Ecol. 24, 1234–1249. https://doi.org/10.1111/ jiec.13027

[72] Tan, L., Mandley, S.J., Peijnenburg, W., Waaijers-van der Loop, S.L., Giesen, D., Legradi, J.B., Shen, L., 2018. Combining ex-ante LCA and EHS screening to assist green design: a case study of cellulose nanocrystal foam. J. Clean. Prod. 178, 494–506. https://doi.org/10.1016/j.jclepro.2017.12.243

[73] Apel C, Mendoza G, Igartua A, Krouwel S, Sudheshwar A, Lihammar R, Kümmerer K. 2023. PR1.5 Mapping of Skills. IRISS – International ecosystem for accelerating the transition to Safe-and-Sustainable-by-Design materials, products and processes. Grant agreement n° 101058245.

[74] Workshop on the application of SSbD concept in materials and chemicals, 25-11-22. https://www.ivl.se/evenemang/221125-join-the-first-iriss-workshop.html

[75] Caldeira, C., Garmendia Aguirre, I., Tosches, D., Farcal, R., Mancini, L., Lipsa, D., Rasmussen, K., Rauscher, H., Riego Sintes, J., Sala, S, (2023) Safe and Sustainable by Design chemicals and materials. Application of the SSbD framework to case studies. JRC technical report for consultation. JRC131878

[76] Muhl M. Distance-to-target weighting in LCA — A matter of perspective 2021:114–26.

Funded by the European Union

The project receives funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement n° 101058245. UK participants in Project IRISS are supported by UKRI grant 10038816. CH participants in Project IRISS receive funding from the Swiss State Secretariat for Education, Research, and Innovation (SERI).

10. ANNEX I-List of references used in the literature review performed within PR1.2

[77] 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. Build Environ 2022;209. https://doi.org/10.1016/j.buildenv.2021.108656.

[78] 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. J Clean Prod 2022;379:134829. https://doi.org/10.1016/j.jclepro.2022.134829.

[79] 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. Archit Eng Des Manag 2022;18:545–70. https://doi.org/10.1080/17452007.2021.2001307.

[80] Ding Y. New Technological Measures of Sustainable Buildings in Triple Bottom-Line Analysis. Mathematical Problems in Engineering 2023. https://doi.org/10.1155/2022/7750056.

[81] Ferreira A, Pinheiro MD, Brito J de, Mateus R. A critical analysis of LEED, BREEAM and DGNB as sustainability assessment methods for retail buildings. J Build Eng 2023;66:105825. https://doi.org/10.1016/j.jobe.2023.105825.

[82] Larsen VG, Tollin N, Antoniucci V, Birkved M, Sattrup PA, Holmboe T, et al. Filling the gaps Circular transition of affordable housing in Denmark. IOP Conf Ser Earth Environ Sci 2022;1078:0–12. https://doi.org/10.1088/1755-1315/1078/1/012078.

[83] Larsen VG, Tollin N, Sattrup PA, 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. J Build Eng 2022;50:104203. https://doi.org/10.1016/j.jobe.2022.104203.

[84] 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. J Constr Eng Manag 2022;148. https://doi.org/10.1061/(asce)co.1943-7862.0002281.

[85] Mohamed AS, Xiao F, Hettiarachchi C. Project Level Management Decisions in Construction and Rehabilitation of Flexible Pavements. Autom Constr 2022;133:104035. https://doi.org/10.1016/j.autcon.2021.104035.

[86] 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. J Clean Prod 2022;371:133615. https://doi.org/10.1016/j.jclepro.2022.133615.

[87] Sánchez-Garrido AJ, Navarro IJ, Yepes V. Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction. J Clean Prod 2022;330. https://doi.org/10.1016/j.jclepro.2021.129724.

[88] Scolaro TP, Ghisi E. Life cycle assessment of green roofs: A literature review of layers materials and purposes. Sci Total Environ 2022;829:154650. https://doi.org/10.1016/j.scitotenv.2022.154650.

Funded by the European Union

The project receives funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement n° 101058245. UK participants in Project IRISS are supported by UKRI grant 10038816. CH participants in Project IRISS receive funding from the Swiss State Secretariat for Education, Research, and Innovation (SERI).

[89] 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. J Build Eng 2022;45:103516. https://doi.org/10.1016/j.jobe.2021.103516.

[90] Sutantio A, Anwar N, Wiguna IPA, Suryani E. A System Dynamics Model of Sustainable Construction for High rise Residential Projects in Developing Countries: Case of Indonesia. The Open Civil Engineering Journal 2022; 16. https://doi.org/10.2174/18741495-v16-e2205300.

[91] Sutantio A, Anwar N, Wiguna IPA, Suryani E. DEVELOPING A MODEL OF SUSTAINABLE CONSTRUCTION FOR CONDOMINIUM PROJECTS IN DEVELOPING COUNTRIES; CASE OF INDONESIA. GEOMATE Journal 2022;23(96):85–94. https://doi.org/10.21660/2022.96.3319.

[92] Tempa K, Chettri N, Thapa G, Phurba, Gyeltshen C, Norbu D, et al. An experimental study and sustainability assessment of plastic waste as a binding material for producing economical cement-less paver blocks. Eng Sci Technol an Int J 2022;26:101008. https://doi.org/10.1016/j.jestch.2021.05.012.

[93] 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. Energy Build 2022;254:111600. https://doi.org/10.1016/j.enbuild.2021.111600.

[94] Yuliatti MME, Husin AE, Sutikno. Improved Performance of Toll Road Projects Based on System Dynamics Integrated Life Cycle Cost Analysis Green Retrofitting. Civil Engineering and Architecture 2022;10(6):2713-2730. https://doi.org/10.13189/cea.2022.100635.

[95] 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. J Clean Prod 2022;340:130791. https://doi.org/10.1016/j.jclepro.2022.130791.

[96] Zhao J, Li S. Life cycle cost assessment and multi-criteria decision analysis of environment-friendly building insulation materials - A review. Energy Build 2022;254:111582. https://doi.org/10.1016/j.enbuild.2021.111582.

[97] Zhou Z, Alcalá J, Yepes V. Research on Sustainable Development of the Regional Construction Industry Based on Entropy Theory. Sustain 2022;14. https://doi.org/10.3390/su142416645.

[98] Barahmand Z, Eikeland MS. A Scoping Review on Environmental, Economic, and Social Impacts of the Gasification Processes. Environ - MDPI 2022;9. https://doi.org/10.3390/environments9070092.

[99] Haase M, Wulf C, Baumann M et al. Prospective assessment of energy technologies: a comprehensive approach for sustainability assessment. Energ Sustain Soc 2022;12:20. https://doi.org/10.1186/s13705-022-00344-6.

[100] Li J, Tarpani RRZ, Stamford L, Gallego-Schmid A. Life cycle sustainability assessment and circularity of geothermal power plants. Sustain Prod Consum 2023;35:141–56. https://doi.org/10.1016/j.spc.2022.10.027.

[101] Nubi O, Morse S, Murphy RJ. Life Cycle Sustainability Assessment of Electricity Generation from Municipal Solid Waste in Nigeria: A Prospective Study. Energies 2022;15(23):9173. https://doi.org/10.3390/en15239173.

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[102] Ramos A, Rouboa A. Life cycle thinking of plasma gasification as a waste-to-energy tool: Review on environmental, economic and social aspects. Renew Sustain Energy Rev 2022;153:111762. https://doi.org/10.1016/j.rser.2021.111762.

[103] Rezazadeh Kalehbasti P, Lepech MD, Criddle CS. Integrated Design and Optimization of Water-Energy Nexus: Combining Wastewater Treatment and Energy System. Front Sustain Cities 2022;4:1–23. https://doi.org/10.3389/frsc.2022.856996.

[104] Salim KMA, Maelah R, Hishamuddin H, Amir AM, Ab Rahman MN. Two Decades of Life Cycle Sustainability Assessment of Solid Oxide Fuel Cells (SOFCs): A Review. Sustainability 2022; 14(19):12380. https://doi.org/10.3390/su141912380.

[105] Sevindik S, Spataru C. An Integrated Methodology for Scenarios Analysis of Low Carbon Technologies Uptake towards a Circular Economy: The Case of Orkney. Energies 2023;16(1):419. https://doi.org/10.3390/en16010419.

[106] Tushar Q, Bhuiyan MA, Zhang G. Energy simulation and modeling for window system: A comparative study of life cycle assessment and life cycle costing. J Clean Prod 2022;330:129936. https://doi.org/10.1016/j.jclepro.2021.129936.

[107] Wijayasekera SC, Hewage K, Hettiaratchi P, Siddiqui O, Razi F, Pokhrel D, et al. Sustainability of waste-to-hydrogen conversion pathways: A life cycle thinking-based assessment. Energy Convers Manag 2022;270:116218. https://doi.org/10.1016/j.enconman.2022.116218.

[108] 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. J Energy Storage 2022;55. https://doi.org/10.1016/j.est.2022.105823.

[109] Mele M, Campana G. Advancing towards sustainability in liquid crystal display 3D printing via adaptive slicing. Sustain Prod Consum 2022;30:488–505. https://doi.org/10.1016/j.spc.2021.12.024.

[110] Olsthoorn M, Schleich J, Guetlein MC, Durand A, Faure C. Beyond energy efficiency: Do consumers care about life-cycle properties of household appliances? Energy Policy 2023;174:113430. https://doi.org/10.1016/j.enpol.2023.113430.

[111] Roci M, Salehi N, Amir S, Shoaib-ul-Hasan S, Asif FMA, Mihelič A, et al. Towards circular manufacturing systems implementation: A complex adaptive systems perspective using modelling and simulation as a quantitative analysis tool. Sustain Prod Consum 2022;31:97–112. https://doi.org/10.1016/j.spc.2022.01.033.

[112] A. Woodcock et al. (eds.), Capacity Building in Local Authorities for Sustainable Transport Planning, Smart Innovation, Systems and Technologies 319, 2022. https://doi.org/10.1007/978-981-19-6962-1_13

[113] Sarkar D, Sheth A, Ranganath N. Social Benefit-Cost Analysis for Electric BRTS in Ahmedabad. Int J Technol 2023;14:54–64. https://doi.org/10.14716/ijtech.v14i1.3028.

[114] Stefanini R, Vignali G. The Environmental, Economic and Social Impact of Industry 4.0 in the Food Sector: a Descriptive Literature Review. IFAC-PapersOnLine 2022;55:1497–502. https://doi.org/10.1016/j.ifacol.2022.09.602.

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[115] Degieter M, Gellynck X, Goyal S, Ott D, De Steur H. Life cycle cost analysis of agri-food products: A systematic review. Sci Total Environ 2022;850:158012. https://doi.org/10.1016/j.scitotenv.2022.158012.

[116] Peña A, Rovira-Val MR, Mendoza JMF. Life cycle cost analysis of tomato production in innovative urban agriculture systems. J Clean Prod 2022;367. https://doi.org/10.1016/j.jclepro.2022.133037.

[117] Stefanini R, Vignali G. Environmental and economic sustainability assessment of an industry 4.0 application: the AGV implementation in a food industry. Int J Adv Manuf Technol 2022;120:2937–59. https://doi.org/10.1007/s00170-022-08950-6.

[118] Maffia A, Palese AM, Pergola M, Altieri G, Celano G. The Olive-Oil Chain of Salerno Province (Southern Italy): A Life Cycle Sustainability Framework. Horticulturae 2022;8:1054. https://doi.org/10.3390/horticulturae8111054.

[119] Stillitano T, Falcone G, Iofrida N, Spada E, Gulisano G, De Luca AI. A customized multi-cycle model for measuring the sustainability of circular pathways in agri-food supply chains. Sci Total Environ 2022;844:157229. https://doi.org/10.1016/j.scitotenv.2022.157229.

[120] Papo M, Corona B. Life cycle sustainability assessment of non-beverage bottles made of recycled High Density Polyethylene. J Clean Prod 2022;378:134442. https://doi.org/10.1016/j.jclepro.2022.134442.

[121] Jayawardane H, Davies IJ, Gamage JR et al. Investigating the 'techno-eco-efficiency' performance of pump impellers: metal 3D printing vs. CNC machining. Int J Adv Manuf Technol 2022;121:6811–6836. https://doi.org/10.1007/s00170-022-09748-2.

[122] Daniela-Abigail HL, Tariq R, Mekaoui A El, Bassam A, Vega De Lille M, J Ricalde L, et al. Does recycling solar panels make this renewable resource sustainable? Evidence supported by environmental, economic, and social dimensions. Sustain Cities Soc 2022;77. https://doi.org/10.1016/j.scs.2021.103539.

[123] Sauve G, Esguerra JL, Laner D, Johansson J, Svensson N, Van Passel S, et al. Integrated early-stage environmental and economic assessment of emerging technologies and its applicability to the case of plasma gasification. J Clean Prod 2022;382:134684. https://doi.org/10.1016/j.jclepro.2022.134684.

[124] Xiao H, Zhang D, Tang Z, Li K, Guo H, Niu X, et al. Comparative environmental and economic life cycle assessment of dry and wet anaerobic digestion for treating food waste and biogas digestate. J Clean Prod 2022;338:130674. https://doi.org/10.1016/j.jclepro.2022.130674.

[125] Zhang N, Zhang D, Zuo J, Miller TR, Duan H, Schiller G. Potential for CO2 mitigation and economic benefits from accelerated carbonation of construction and demolition waste. Renew Sustain Energy Rev 2022;169:112920. https://doi.org/10.1016/j.rser.2022.112920.

[126] Gulcimen S, Qadri S, Donmez RO et al. A holistic sustainability assessment of a university campus using life cycle approach. Int J Environ Sci Technol 2023;20:3309-3322. https://doi.org/10.1007/s13762-022-04214-8.

[127] Kazemi F, Hossein pour N, Mahdizadeh H. Sustainable low-input urban park design based on some decision-making methods. Land Use Policy 2022;117:106092. https://doi.org/10.1016/j.landusepol.2022.106092.

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[128] Rizan C, Brophy T, Lillywhite R et al. Life cycle assessment and life cycle cost of repairing surgical scissors. Int J Life Cycle Assess 2022;27:780-795. https://doi.org/10.1007/s11367-022-02064-7.

[129] Allotey DK, Kwofie EM, Adewale P, Lam E, Ngadi M. Life cycle sustainability assessment outlook of plant-based protein processing and product formulations. Sustain Prod Consum 2023;36:108–25. https://doi.org/10.1016/j.spc.2022.12.021.

[130] Collotta M, Tomasoni G, Champagne P, Mabee W. Life cycle approach for the sustainability assessment of intensified biorefineries. Elsevier Inc.; 2022. https://doi.org/10.1016/B978-0-12-824117-2.00013-2.

[131] Singh PK, Sarkar P. An artificial neural network tool to support the decision making of designers for environmentally conscious product development. Expert Syst Appl 2023;212:118679. https://doi.org/10.1016/j.eswa.2022.118679.

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