ROADMAP
FOR SUSTAINABILITY ASSESSMENT IN EUROPEAN PROCESS INDUSTRIES
This document represents a vision for development of life cycle-based sustainability assessment in the European process industries over the 2017-2023 period. The roadmap summarises the experience and views of a large number of stakeholders from industry, industry associations, governmental authorities, academia and consultancies, as well as from recent academic and industrial literature. The roadmap identified a number of key barriers to consistent use of sustainability assessment within industry and several immediate research challenges.

The document addresses three topics:

- Open issues in life cycle sustainability and resource efficiency assessment as they are currently applied in European process industries;
- Cross-sectorial issues in Life Cycle Assessment (LCA) based sustainability assessment within process industries; and
- The use of life cycle methods in process design and innovation; LCA-based decision support methods for Sustainable Process Industry through Resource and Energy Efficiency public-private partnership (SPIRE PPP) projects.

The roadmap document contains links to detailed background documents and training materials in specific topics. It is intended for senior sustainability and research managers, research policy makers, the European Commission (EC), the SPIRE PPP community as well as LCA method developers and practitioners.
The roadmap was developed within the European project MEASURE, a coordination and supporting action within the SPIRE PPP in the Horizon 2020 framework. MEASURE is one of three coordination & support actions within SPIRE 2015-2016 research programme: projects STYLE and SAMT are dealing with non-LCA tools for sustainability assessment and practical evaluation of tools in the context of cross-sectorial harmonisation, respectively.

The MEASURE project used web-based surveys, personal interviews, conferences, in-depth literature reviews, specific case studies and face-to-face stakeholder workshops to generate the objective picture of the current state-of-the-art in the use of LCA methods across process industries in Europe and to formulate key challenges and research needs.
The challenges faced by Europe in economy, environmental pollution, climate change and structure of the society require an urgent transformation of all decision-making processes towards sustainability. Our current decision support tools are well developed in the areas of product or process-specific economic and environmental assessments. However, for support of decision making in developing a more sustainable society we require robust methods of evaluation of societal, economic and environmental factors within the life cycle framework.

This document is the first in the series of three joint studies (MEASURE-STYLE-SAMT) on sustainability assessment within European process industries, funded within the SPIRE PPP of the Horizon 2020 programme. Here we summarise the views of over 200 experts in different aspects of life cycle assessment as well as wider stakeholders in industry, policy and academia. These views are organised within three core areas. In each core area open issues and R&D needs, which require urgent development within the timeline of the Horizon 2020 programme, are identified in order to achieve a real impact on the innovation and sustainability targets of Europe.

The three core areas are summarised below with full details and links to background and training documents provided later in the report.

**LCA methodology developments**

Life cycle sustainability assessment (LCSA) methods lack standards, databases and mature impact assessment methods. Many aspects of evaluation of resources in current LCA methods are underdeveloped including defining criticality, availability, resource efficiency and the socio-economic impacts of resource use. Data quality and availability, and LCA model uncertainty remain significant challenges.

**Cross-sectorial issues in application of LC(S)A tools and methods along value chains**

Full and coherent integration of life cycle metrics into business processes and decision-making is found only in a few frontrunner companies. This is due to high complexity of the problems, data uncertainty, lack of resources and lack of external incentives. Across different sectors of the process industry, those with "classical" products have more similarities among each other than industries with multiple inputs and outputs, regional and regulatory-specific boundary conditions, e.g. waste sector. Life cycle inventory data exchange between industries, established co-operation along the value chains and cross-sectorial collaboration in LC(S)A studies exist, but are not broadly implemented in practice.

**LCA as a decision support tool and innovation driver in R&D projects**

Easy-to-use life-cycle based methods applied at different development stages and scales can guide innovation processes to a more sustainable future. Coupling sustainability assessment approaches with engineering software tools would allow for synergies and holistic understanding of innovation potentials. However, a harmonisation of indicators and benchmarking is needed for a sound comparison of emerging new technologies. The sustainability targets of the SPIRE community have to be translated into operational, broadly accepted and clearly defined indicators, allowing a quantitative monitoring of the progress towards the challenging targets.
Based on the open issues and R&D needs revealed by the analysis of these three areas, the following points of action are strongly encouraged.

1. **ENABLE THE USE OF LIFE-CYCLE-THINKING (LCT) BASED TOOLS IN THE SPIRE CONTEXT FOR GUIDANCE AND ASSESSMENT OF INNOVATION PROJECTS**

   The use of LCT-based tools for the assessment of innovation in the context of European collaborative projects can gain significant benefits in terms of more sustainable process design and should be intensified in the SPIRE PPP. Those industry-oriented projects have to focus strongly on the future impact potentials of new technologies and should be more intensely used to demonstrate the chances of coupling engineering, design, decision-making and LCT.

2. **PROMOTE A WIDER USE OF LCT-BASED TOOLS AMONG PROCESS INDUSTRY FOR REGULAR DECISION-MAKING**

   In order to reach the European sustainability targets, a wider use of LCT-based tools among the different sectors of the European process industry is needed for regular decision-making, as well as for innovation management.

3. **DRIVE MORE HARMONISATION**

   There is a distinct need for more harmonisation of LC(S)A databases, methodological choices and communication approaches in the industrial as well as in the research funding environment.

4. **SUPPORT DATA EXCHANGE AND CROSS-SECTORIAL COLLABORATION**

   Data exchange between industries and cross-sectorial collaboration in LC(S)A studies requires standardisation, a certain level of confidentiality and the willingness from all parties involved to establish a common practice.
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**ICONS USED IN THE ROADMAP**

- Industry
- Legislation
- Academia
- Industrial association
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Europe is facing a series of crucial challenges: low growth, insufficient innovation, degradation of environment and many societal changes.[1] The European Union (EU) recognized the urgency of the situation and responded with the Europe 2020 strategy, as well as a new funding programme, called Horizon 2020. They include increasing investments in research and development (R&D) and innovation, as well as a refocus of R&D and innovation policy on the major societal challenges, such as climate change, energy and resource efficiency, health and demographic change. Furthermore, the programme is aimed at strengthening the links in the innovation cycle from frontier research right through to commercialisation. Public-private partnerships (PPPs) in research and innovation were agreed upon for the Horizon 2020 funding programme in order to enable a more long-term, strategic approach to research and innovation.[1] PPPs shall enable innovative technologies to get to the market faster, by allowing companies to collaborate and share information, thereby accelerating the learning process. They shall further facilitate the scale of research and innovation effort needed to address the critical societal challenges and major EU policy objectives.

In December 2013, the European Commission (EC) launched eight contractual PPPs. One of them is the Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) partnership between different sectors of the European process industry and applied research and development in European academia. There are two main reasons for the focus of the EC on the European process industry, representing 20 % of the European manufacturing base. On the one hand these are very energy and resource intensive industrial production processes, having a significant impact on resource depletion and on emissions, causing environmental effects.[2] On the other hand, the European process industry currently suffers from a lack of competitiveness on a world scale due to the facts that a significant part of raw materials is imported and energy prices in Europe are subject to fluctuations. A further decrease of sales would

**SPIRE can enable the development of a truly sustainable European economic system in which economic growth is permanently decoupled from environmental impact.**

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seriously affect other industrial sectors as well, since the process industry is at the core of many European manufacturing value chains.

SPIRE aims to make a difference. An internationally competitive, and at the same time sustainable, process industry in Europe is projected as the outcome of 900 million € funding within the Horizon 2020 framework and a matching contribution provided by the private stakeholders of the initiative. A successful realisation of the SPIRE vision is seen as essential from all actors involved in rejuvenation of the European process industry.

The expectations are high. By means of a partnership, not seen before to such an extent, substantial new ground shall be explored and breakthrough technologies shall be developed at an interface of several disciplines. A new, cross-sectorial cooperation among different sectors of the European process industry is needed. A substantial improvement of resource efficiency and sustainability of production processes are seen as the key for success. Consequently, a sound assessment methodology is required to quantify the effects of new technologies and evaluate the effects from a life cycle perspective.
Eight sectors of the European process industry are engaged in SPIRE in the development of novel technologies for improved resource and energy efficiency: chemicals, cement, ceramics, minerals, steel, non-ferrous metals, industrial water and process engineering. The ambitious SPIRE initiative aims to:

- Reduce the energy consumption in the European process industry by 30%;
- Reduce the utilisation of primary (non-renewable) raw materials by 20%; and as a result
- Improve efficiency in terms of CO₂ - equivalent footprint of up to 40% until 2030 compared with the period of 2008 – 2011.[3]

These aims shall be met through:

- An optimal valorisation and smarter use of raw materials and energy as well as more efficient processing and energy systems by, e.g., higher yields and/or using secondary and renewable raw materials, the introduction of novel energy-saving processes, monitoring and modelling via Information and Communication Technologies (ICT) tools, process intensification, energy recovery, sustainable water management and alternative (renewable) energy sources;
- Industrial symbiosis and cross-sectorial application of technologies throughout the value chains and
- The avoidance, valorisation and re-use of waste streams using optimised recycling processes within and across sectors.

The overall concept is summarised in Figure 1.

The SPIRE PPP brings together all actors along the value chain, from feedstock supply through industrial transformation into intermediate products and applications. The target is doing more and/or better with less considering the complete system. It is understood that for a successful implementation, the major components in the process industry holistic value chain should work together.
Figure 1: Illustration of the SPIRE concept.\textsuperscript{13}

CROSS-SECTORIAL AND VALUE CHAIN LIFE CYCLE COST THINKING, TARGETING AND STEERING

STAGE 3: LONGER TERM R&D TO DRastically CHANGE THE PROCESS BASE
STAGE 2: MEDIUM TERM R&D AND DEPLOYMENT TO INTEGRATE IN THE INSTALLED PROCESS BASE
STAGE 1: SHORT TO MEDIUM TERM DEPLOYMENT AND REPLICATION IN THE INSTALLED PROCESS BASE

STEEL
NON FERROUS
MINERALS
CERAMICS
CHEMICAL
CEMENT

ADAPT & TRANSFER
WATER
ENGINEERING

CROSS SECTORIAL INNOVATIONS

RE-USE & RE-CYCLE
SYSTEMIC ANALYSES, VALORISATION, CASCADING AND MANAGEMENT OF RESOURCE STREAMS (INCLUDING WASTE STREAMS)

REINVENT
RESOURCES EFFICIENT AND COMPETITIVE APPLICATIONS

20% REDUCTION OF NON-RENEWABLE, PRIMARY RAW MATERIAL INTENSITY
30% REDUCTION OF FOSSIL ENERGY CONSUMPTION

CHANGING RESOURCE BASE
FOSSIL, RENEWABLE MINERALS BIO
USE & REDUCE

20% REDUCTION OF NON-RENEWABLE, PRIMARY RAW MATERIAL INTENSITY
30% REDUCTION OF FOSSIL ENERGY CONSUMPTION
1.2. THE NEED FOR LIFE CYCLE-BASED, HARMONISED EVALUATION CONCEPTS

Such a broad and challenging vision forces all actors (industry, researchers, practitioners in sustainability assessment, members of the EC, etc.) to rethink their often too specific and narrow approaches and toolboxes. The translation of advances in science into successful industrial implementations that would lead to simultaneous improvements in productivity, reduction in environmental impacts and to economic growth at European scale in the envisaged time-frame requires the courage of fundamental changes in decision-making. This is a significant departure from more traditional research projects aimed at developing fundamental understanding, discovery of new materials or phenomena, or developing completely new methods, which may induce effects on industry in a mid- or long-term time scale. The new type of research projects within the Horizon 2020 programme will require guidance. In parallel, current methods from hot-spot analysis to applying life cycle thinking (LCT) to in-depth life-cycle based methods (depending on the stage of development) may need to be restructured and agreed on between project teams from different sectors. Specifically, a standardisation of approaches and methods used is required for a comparison of the overall benefit of alternative strategies on an equal basis, avoiding problem shifts or double counting of improvements.

Knowledge, methods and effective tools for decision-making are required to support the comprehensive transition to a more sustainable economy. Measuring and assessing progress as well as providing information, forecasts and projections will be essential for success of each collaborative SPIRE project. Moreover, the EC is in need of Key Performance Indicators (KPIs) for monitoring and reviewing the progress of Horizon 2020 projects.[1]

In the following chapters, open issues in sustainability assessment within process industries will be addressed, before additional challenges in cross-sectorial sustainability assessment and sustainable process design and innovation are discussed. Recommendations for how to overcome them within the timeframe of 2017-2023 will be given.

**SPIRE will aim for the targets [...] by identifying, selecting, adapting, developing, deploying and replicating cost efficient solutions that have a resource and energy efficient impact based on Life Cycle and Cost thinking [...].**

**SPIRE Roadmap**
OPEN ISSUES IN SUSTAINABILITY ASSESSMENT WITHIN PROCESS INDUSTRIES
• The assessment of environmental impacts shifts towards sustainability assessment, but:
  • Social LCA (SLCA) and Life Cycle Costing (LCC) methods are still underdeveloped; the number of SLCA and full Life Cycle Sustainability Assessment (LCSA) studies is limited; there are too few tools and fully developed databases for SLCA and LCC; there is no proven approach for full LCSA.
  • SLCA are rarely conducted at the product level in process industries.

• In order to reach the European sustainability targets, a wider use of LCT-based tools among the different sectors of the European process industry is needed for regular decision-making, as well as for innovation management.

• There is a distinct need for more harmonisation of LC(S)A databases, methodological choices, and different pieces of EU environmental regulations.
  • All methodologies applied should be based on standards. ISO 14040/44 present the widely accepted framework for LCA; all environmental life cycle-based methods should be based on it.
  • Although a number of environmental impact categories are agreed (e.g. GWP, AP, EP, PED), some indicators still lack maturity and general acceptance.
  • SLCA and LCC should be standardised in the same way as LCA.
• Parallel developments on future sustainability assessment methods for European industry are disconnected and risk introducing further proliferation and segmentation.

• Communication of sustainability assessment results remains a significant challenge, considering the divergences in demands for B2B and B2C; a balance has to be found between the transparency of complex results and a pragmatic way to communicate results comprehensively.

• Today there is no consensus on how to determine resource efficiency and no agreement on the definitions of resources themselves (e.g. different vocabulary in EC policy and SPIRE documents).

• Resource availability is increasingly recognized as mainly dependent of socio-economic parameters and not only physical availability in the Earth crust: work on integrating criticality in the LCA framework is being conducted and separate criticality indicators are more and more used.

• There is no fully operational method to consider the different parameters on which resource availability depends.

• The uptake of tools for multi-criteria decision making, taking into account the full complexity of life cycle-based assessment is low.
A thorough analysis of the current implementation of life-cycle based methods in European process industries and related industry-driven research projects, clearly pointed out that the general understanding of sustainability assessment is quite similar across all sectors of processing industries. Life-cycle based tools are applied in all industrial sectors, becoming increasingly mainstream at least among larger enterprises and some proactive small and medium-sized enterprises (SMEs) in specific sectors. Thanks to the ISO 14040/44 standards, all industry approaches follow the same general rules as far as the product-based LCA methodology is concerned. Many tools and assessment methods for environmental and sustainability performance have been developed in the recent years (see also background document “Current state of LCSA”). In parallel, the society is undergoing a “paradigm shift” from pure environmental protection towards sustainability.[4] Having LCT as a fundament of this shift and going through ‘single-issue-LCAs’ like carbon- and water footprinting methods, and further to more holistic and multi-aspect LCAs, LCSA could be considered the uppermost evaluation approach.

While sustainability is nowadays accepted by all stakeholders as a guiding principle, the challenge to unambiguously determine and measure sustainability performance does remain, especially for products and processes.
2.1. CURRENT STATE IN LCSA

Environmental LCA is acknowledged to be one of the most appropriate and robust assessment frameworks for the evaluation of the potential impacts of a product’s entire life cycle – from raw materials extraction to final disposal. However, products are also linked to production and consumption impacts on the workers, the local communities, the consumers, the society and all value chain actors. In this regard, SLCA has gained popularity in recent years as an approach aiming at evaluating social and socio-economic aspects, and their potential positive and negative impacts over the life cycle of products.

In economic terms, LCC gives the possibility to identify economic hotspots, which can be valuable for the decision making process within a full sustainability assessment. In combining those, a sustainability and life-cycle based approach can be integrated under a LCSA framework. Thus, the method consists of a contemporary implementation of (environmental) LCA, LCC and SLCA.

Kloepffer has put the LCSA framework into the formula: LCSA = LCA + LCC + SLCA, see Figure 2. In order for the equation to be valid and the three pillars to be evaluated together, they all shall have a common goal and scope defined, including an identical functional unit and equivalent system boundaries.

Despite the proposed and accepted LCSA framework, challenges in the particular pillars exist. LCA is now approaching broad acceptance and after many years of method development, case studies, international standardisation, database and software development, environmental LCA is mature and robust enough to inform decision-making.
However, both the international standards of LCA and the scientific literature are quite transparent with regard to the gaps and challenges of the method. LCA does not provide the ‘full environmental truth’, at least not just yet. ISO 14040/44 standards clearly acknowledge that any LCA study has its limitations.[9] Nevertheless, despite the large number of gaps and challenges identified, LCA is still the “…best framework for assessing the potential environmental impacts of products currently available”. [10]

Against this, SLCA still suffers from a lack of scientific consensus and definitions, including proper impact assessment and thus, broader practical implementation.[11] The challenges regarding the inventory, limited data availability and lack of applicable methods and tools result in an absence of studies that completely address the life cycle of a product as they often just focus on one life cycle phase. Social aspects of materials or products are still hard to quantify from a life cycle perspective and are mainly covered by specific supplier audits on a company level. Consequently, SLCA and LCC on product base are rarely used in process industries, although site and company related social/sustainability audits are rather common (e.g. SEDEX, Together for Sustainability (TfS)/Ecovadis) and cost accounting is certainly a core topic. The valuation of natural capital is a rather new subject matter, which some companies from the sectors are currently exploring.

Within the scope of MEASURE, two stakeholder surveys were conducted. One of them being a joint SPIRE survey (see Section 5 and background document ‘MEASURE survey results’). From this survey, similar conclusions can be drawn: whereas around 80 % of the industry answered positively if they perform environmental LCA, SLCA is performed by less than 20 %. In this regard, SLCA is considered to be not fully operational today.

In terms of the economic dimension, a plethora of methods to assess the economic aspects of sustainability exist, ranging from cost accounting of internal costs over mixed types to exclusive calculation of external costs, but they still lack consistent terminology and methodological harmonisation.

Overall, the maturity of methods and tools is different for the three sustainability dimensions. While the environmental dimension can be covered quite well today, the economic and social indicators and evaluation methods still need fundamental scientific progress.[4, 11] The number of applications of LCSA is still limited, and the majority of the examples occur at the interface of environmental and economic aspects.[12]
In the stakeholder surveys, questions related to the identification of the most used life-cycle based tools and impact assessment methods were raised. Often requiring a high level of expertise, tools and methods were overviewed and analysed based on few criteria, such as system boundaries, specific data requirement, their acceptance and the pillar of sustainability they cover (see Section 5).

Among the tools, LCA, Carbon footprint and Cumulative Energy Demand (CED) are the ones that are widely used, whereas less applicability has been given to tools such as SLCA, Cost Benefit Analysis (CBA), Ecological Footprint, Full Cost Accounting and Water Footprint (see background document “Current state of LCSA”). At this, attributional LCA is currently much more common than consequential LCA. The Product Environmental Footprint (PEF) initiative of the EC has also been mentioned. However, it is still in a pilot phase and thus not widely applicable yet (for more information on PEF see also Section 2.3.).

When summarising the most used and established LCIA methods, CML 2001[13] and ReCiPe[14] collect the majority of stakeholders’ answers. Methods related to human- and ecotoxicity such as USEtox are very popular and debated, but still are not largely applied due to their immaturity (see background document “MEASURE survey results”). The International Reference Life Cycle Data (ILCD) system handbook constitutes a broadly accepted valuation document supporting the choice of LCIA indicators.[15]
International standards on LCA and relation with other standards

Nowadays, ISO 14040 and 14044 are considered to be the constitutional standards of LCA. Currently in their second generation, the two standards represent a full global stakeholder consensus of over 160 countries. Based on them, new approaches have been developed in the recent years, leading to some spin-off-standards, covering issues including:

• “Single-issue-LCAs”, such as carbon footprinting and ISO 14067 or water footprinting and ISO 14046
• “Beyond environment-LCAs”, like LCC, SLCA, or eco-efficiency assessment and ISO 14045
• “Beyond product-LCAs”, like scope 3 type LCAs of organization and ISO 14072
• “Beyond quantification-LCAs”, like Type III product declarations and ISO 14025.

Apart from a few initiatives, it is acknowledged that the majority of standardisation activities follow ISO 14040/44, building synergies with national, regional, sector specific standards. As long as new standards and/or other harmonisation activities are not in conflict with the constitution of LCA, the provision of additional specifications due to regional or sector specifics should be supported. Moreover, continuous improvement by LCA implementation of different actors in all parts of the world and for a variety of applications is considered to be more important and encouraged, than polishing the sophistication level and introducing LCA “dictatorship” of the one and only right way to do it.

Product Environmental Footprint

Considered as an important attempt for harmonisation led by the EC, PEF has been analysed in view of its relation to the goals of SPIRE (see background information “Current state of LCSA”). Important aspects when comparing the SPIRE requirements and the perceived PEF objectives have been overviewed. The evaluation concludes that the EU PEF project has no direct or formal link with the objectives of SPIRE. Nevertheless, both initiatives aim to impact LCA adoption and modus operandi. The EC promotes the use of PEF for measuring and communicating (business-to-business (B2B) and business-to-consumer (B2C)) environmental life cycle performance of products and organisations. However, the analysis concludes that information obtained must be based on a solid methodology, and appropriate communication tools must be used, which is not evident yet. However, it is acknowledged that the PEF process is still at the pilot stage. In order to promote harmonisation in future, and also globally, PEF has to be based on solid internationally agreed references, in contrast to the current version that may lead to further segmentation, but not harmonisation. Approaches striving for providing a one-stop-shop solution for all methodological issues bear the potential to bring things forward from the basic idea, but seem to be contra productive in a top-down perspective, lacking necessary flexibility and close alignment with other existing practices and regulations in different markets.
No uniform or one-size-fits-all solution has been identified so far, but some approaches seem to work better than others, when it comes to presentation and communication of results. Communication of LC(S)A results in an industrial environment has so far been found to take place internally and in academic or B2B settings (for more information see background document “Current state of LCSA”). In such situations, the focus is usually on the most relevant or prominent indicators and uncertainty is generally taken into account but not quantified or graphically represented. Relative comparisons between alternatives are favoured in order to have a reference point, and to reduce the effect of uncertainty due to input data. Communication of LC(S)A outcomes to consumers (B2C) is only in its infancy, though already tested in certain countries (e.g. the French Grenelle Law). The main challenges faced relate to the non-expertise profile of the final consumer and the risk of “green washing” thereof.

Furthermore, it has been concluded that external communication based on end-points and single score indicators is a pragmatic approach addressing non-LCA experts, but does not give a full picture on the environmental performance and important information might be neglected or lost along the value chain.[17] Additionally, the acceptance of presenting aggregated or even single score results (end-points) is low in the LCM community, considering that there is no scientific basis for value choices. These kinds of aggregations and/or normalisation approaches have the advantage to be easy to understand at first sight, but the risk of information losses are high and comparability and relevance are not supported. Nevertheless, efforts should be spent on “demystifying” the complexity of LC(S)A by translating the results into language and units targeted to the specific stakeholder group.
The improvement of resource efficiency (RE) is an objective set by most EU calls for innovation projects nowadays. However, there is still little consensus on how to determine RE (for more information, see Section 4.3 and background document “Current state in resource efficiency indicator evaluation”).

First, there is a wide range of definitions of resources. Some stakeholders consider resources in the broad sense, thus considering the natural environment as a sink for emissions, while others consider resources in the strict sense, i.e. consider resources as inputs entering a system. This last definition is mostly followed by industry, where impacts of emissions are considered separately from the consumption of resources.

Secondly, even though most stakeholders agree on the fact that RE is the ratio of the terms benefits (from resource use) and (impacts from) resource use, so far there is no consensus on how to exactly determine the terms of this ratio. The definition of the benefits (from resource use) is based on measuring benefits (e.g. monetary or functional). The (impacts from) resource use depends on the scale of the system under study (micro, meso, macro), the level of the analysis (i.e. gate-to-gate analysis or life cycle based analysis) as well as the method used to quantify (impacts from) resource use. Different databases can be used to model the studied system, e.g. input-output tables are used when macro scale systems are analysed (e.g. Exiobase[18] or the World Input-Output database[19]), and LCA databases such as ecoinvent[20], ELCD[21], or GaBi[22] are used when analysing systems at micro scale. Macro scale evaluation is mainly conducted in the framework of policy making whereas micro and meso scale assessments are mostly conducted within process industry. Thus, this part focuses on micro and meso scale RE evaluation (for more information on RE evaluation at macro scale see references[23], [24]).

A wide range of methods exist to quantify (impacts from) resource use. These can be classified into two main categories: 1) resource accounting methods, which account for resources based on their physical properties; 2) impact assessment methods, which characterize the impact of resource consumption[25].
Existing resource accounting methods can be conducted at both gate-to-gate and life cycle levels and are mainly based on the four physical properties of resources: mass/volume (e.g., Material Flow Analysis\textsuperscript{26}), energy (e.g., Cumulative Energy Demand\textsuperscript{22}), exergy (e.g., Cumulative Exergy Demand\textsuperscript{27}) and area (e.g., Ecological Footprint\textsuperscript{28}).

Several types of impact assessment methods are being used for assessing resource use over the life cycle of a product or service\textsuperscript{29}. Methods based on the quantity of reserves and/or annual extraction rates (e.g., ADP\textsuperscript{30}), distance-to-target (e.g., Ecological Scarcity method\textsuperscript{31}), willingness to pay (e.g., EPS2000\textsuperscript{32}) and possible future consequences of current resource use – surplus energy (e.g., Impact 2002+\textsuperscript{33}) and marginal costs (e.g., ReCiPe\textsuperscript{34}).

Not all impact assessment methods consider the same categories of resource: some only consider abiotic resources (e.g., ADP) whereas other methods consider both abiotic and biotic resources (e.g., Ecological Scarcity method). Moreover, even if two methods consider the same resource category, different resources can be covered in this category (e.g. in the same category “fossil fuels”, some methods consider peat whereas others do not). In addition, depending on the method, resources can be classified differently (e.g., uranium is classified as a “metal” or as “non-renewable energy”). These specificities are mostly not taken into account when applying methods for determining (impacts of) resource use.

Resource availability is increasingly recognized as mainly dependent of socio-economic parameters and not only physical availability in the Earth crust. Work on integrating criticality in the evaluation of resource availability is being conducted. Today, there is no fully operational method to consider the availability of resources in the anthropogenic stock, even though attempts have been conducted.\textsuperscript{35}

Overall, gaps and challenges in sustainability and resource efficiency assessment still exist. Consequently, the scientific community is still divided over the best way to quantify the complex and fast changing interrelationships. An increased use of resource based indicators (as opposed to emissions based) such as exergy or scarcity based concepts might help to alleviate some of the problems raised regarding the uncertainty of characterisation models.
CHALLENGES OF CROSS-SECTORIAL SUSTAINABILITY ASSESSMENT IN EUROPEAN PROCESS INDUSTRIES
3

CHALLENGES

OF CROSS-SECTORIAL
SUSTAINABILITY ASSESS-
MENT IN EUROPEAN
PROCESS INDUSTRIES
A good degree of consistency in tools, methods and impact categories used for sustainability assessment exists in the different sectors. However, some sector-specific issues still remain.

There is a need for cooperation in sustainability assessment along the value chain; although confidentiality issues exist, workable solutions to overcome them are available.

Good data documentation will allow a better consistency for cross-sectorial LCA involving actors from across the whole supply chain.

The LCA of renewable materials presents specific challenges due to current non-agreements in the consideration of direct and indirect Land Use Changes (dLUC and iLUC) and some methodological difficulties for assessing biogenic carbon.

Data uncertainty is currently a major challenge for performing and communicating LCA data over the supply chain and can result in misleading interpretations or major difficulties for decision-making. Improved data documentation is critical.
R&D NEEDS

- Agreements and harmonisation activities within industry sectors and along industrial supply chains (e.g. Product Category Rules (PCR)) should be supported, and periodically re-assessed and updated. ISO 14040/44 has to be the basis.
- There is a need for harmonisation of the use of allocation rules between sectors. The development of PCRs can be an option.
- Sector-specific and cross-sectorial agreements for handling of recycling in LCSA are needed.
- To get the full picture of a product’s performance and to avoid burden shifting the End-of-Life (EoL) stage has to be analysed. Material specific properties and changes in quality should be reflected by an appropriate recycling approach.
- Development of aggregated datasets by industries of specific sectors (industrial averages) is highly valuable and should be encouraged via voluntary or mandatory regulatory schemes.
- A pragmatic framework to assess uncertainty in LCA should be developed for industry. Tools and databases to simplify uncertainty analysis are required: development of LCA software tools to enable the use of a wider range of methods for uncertainty propagation; identification of the probability function of key parameters and possible model simplifications in sector specific projects.
Full and coherent integration of life cycle metrics into business processes and decision-making in European process industries could be found only in a few frontrunner companies. The reasons for this include the high complexity, data uncertainty, lack of resources and lack of external incentives. Consumer and market pressures have not reached every business in the process industry on the B2B level yet. Life cycle inventory (LCI) data exchange between industries at B2B level, established cooperation along the value chains and even more - cross-sectorial collaboration in LC(S)A studies exist, but are not broadly implemented in practice. Instead, an “opportunistic” use of life cycle approaches seems to be still dominating. One reason is that today’s LCSA methods and tools are still lacking agreements, databases and mature impact assessment methods to be used as standard. However, such standards and agreements along the value chain are needed in the view of a more circular economy and the increasing valorisation of waste. When assessing a complete product life cycle, many different actors and sectors are typically involved, see example in Figure 3. Thus, cross-sectorial sustainability assessment along the supply chain is gaining importance as the idea of LCT is being implemented deeper in businesses. However, a uniform way of assessing sustainability in all segments of the supply chain is still developing.

In the example of the cradle-to-grave life cycle of a detergent shown in Figure 3, it is evident that for companies that want to optimize the inherent sustainability profile of their products, it is of interest to evaluate how the sustainability performance of upstream and downstream supply chain partners influences their final products. Therefore, collaboration and data sharing of all actors is needed. Ultimately, the outcome has to be captured in a way that is understandable to all, including non-specialists. Consequently, reliable assessment methods and data sharing practices along the value chain are required. Such collaboration is already taking place today, but several practical challenges have to be tackled to ensure that data exchange is also efficient and effective. Moreover, future SPIRE projects will cover various sectors of process industries. In order to have consistent and comparable sustainability assessments across these sectors it is essential that the same methods and tools are used, and that common evaluation and interpretation rules exist.

A cross-sectorial analysis has to be based on an agreement of common rules. According to the MEASURE surveys, all represented industry sectors accept ISO 14040/44 as their basis for LCA studies. In addition, there are further regional or sectorial standards
available (for example the “Life Cycle Metrics for Chemical Products” guideline of WBCSD[36]), which are based on ISO 14040/44. These documents aim to facilitate practical implementation by means of best practice guidance and illustrative examples (see also background document “sector report: chemistry and FMCGs”).

Agreements on how to elaborate (environmental) sustainability assessments for specific product categories are currently available within certain sectors (e.g. PCRs according to ISO 14025, for analysis of building materials), but the cross-sectorial conformity is often missing. When comparing products or projects from various sectors in the SPIRE context, or when using data from other sectors, it is important to check if no contradictory rules, assumptions or methods have been used.

In different sectors, specific points turn out to be critical in a sustainability assessment. In cross-sectorial collaborations these factors influence the whole value chain and therefore gain importance, especially when sectors that have a completely different approach to certain methodological issues are collaborating. Examples include the assessment of bio-based products, the choice of allocation approaches, or the accounting of recycling (Section 3.3).

Further development of rules and agreements within industry sectors and along industrial supply chains should be supported. Already achieved agreements have to be taken into account as models for future assessments and regulations.

Based on surveys and workshops conducted by MEASURE, an encouraging level of conformity was identified between the different sectors in term of tools and methods used, dimensions of sustainability covered, goal and scope, etc. Impact categories used and reported are also quite similar. Multiple impact categories are typically calculated and reported (such as GWP, AP, EP, PED etc.), while decision-making within the companies is typically done on a reduced number of (assumed) most relevant impact categories.

![Figure 3. Example of a detergent’s complete life cycle with collaboration along the supply chain and key sectors/stakeholders involved.](image-url)
In order to understand critical issues for the collaboration along the supply chain, an in-depth analysis has been conducted for sectors A (chemistry and fast-moving consumer goods (FMCGs)), B (metals and automotive) and C (waste), see Figure 4. By choosing sector A and B, important sectors of the European process industry are analysed. Furthermore, they represent typical examples of industrial collaboration along the value chains. Sector C complements both sectors A and B, since waste treatment is the final management step that should already be accounted for in process design and development. Whereas automotive products, analysed in sector B, have comparably long use phases and special waste collection systems, sector A is characterised by short life cycles and different collection systems after the use phase. An evaluation of these three process branches provides a comprehensive overview of industrial value chains in the European process industry.

Figure 4. Industrial value chains in the European process industry analysed concerning current implementation of sustainability assessment.
Sector A
Chemistry and FMCGs

The sector Chemistry and FMCGs is characterized by an important diversity in terms of products, applications and feedstock origins. Nevertheless, an overall good degree of consistency is observed amongst practitioners in terms of the choice of system boundaries, functional unit, impact categories reported and the consideration of the End-of-Life (EoL) stage. It should be mentioned that weighting impacts is not common in the sector, and that usually multiple impact categories are being reported. Industrial LCA practitioners pay a lot of attention to the maturity level of the LCIA methods and the robustness of the output, since the results may be communicated publicly in a B2B or B2C context.

Collaboration between parties in the sector is evident. The “Life Cycle Metrics for Chemical Products” guidelines of WBCSD (2014) is a recent document gaining increasing recognition as a useful application-oriented guide/roadmap for LCAs carried out in the sector. In addition, it is already an established practice within the chemical industry to release agreed average LCI datasets of important commercial products for use by industry and other practitioners. Examples include datasets of plastics (‘Ecoprofiles’) by the association of European plastics manufacturers ‘PlasticsEurope’, or for surfactants with their precursors by the industrial association ERASM (www.erasm.org). Nevertheless, a large number of chemicals and product categories still lack LCI or LCIA studies, or suffer from major differences in assumptions between practitioners.

Where major differences exist in Sector A, they are often related to specific LCIA methods and/or allocation assumptions. Examples are the assessment of the emissions from land use change, and the consideration of biogenic carbon for renewable-based feedstocks (see Section 3.3.).

Another important bottleneck is the assessment of toxicity, and which method to choose and trust for the needs of the industry. The USEtox model developed with the UNEP/SETAC Life Cycle Initiative, currently positioned as the consensus model for toxicity in LCA, remains criticized. Other initiatives are currently emerging to develop tools more adapted to business needs, making a closer link with the eco-toxicological data generated by industry for REACH. For these reasons, (eco)toxicity scores from LCA methods are mostly excluded from the actual decision-making process in Sector A.

In the last years, the assessment of water in LCA and water footprint gained increasing interest. Practical difficulties are faced due to a lack of available information in databases, such as regionalized data and remaining inconsistencies in published data. Further efforts are consequently required before water footprint becomes a fully established method in Sector A (and elsewhere).

A detailed report about sector A can be found in background document "Sector report: chemistry and FMCGs".
Sector B
Metals and Automotive

In the supply chain of metals and automotive both industry sectors are active in sustainability assessments and close collaboration between them already exists. They are using the data for customer information on different levels. This is mainly B2B communication in the case of results transferred from metals to automotive customers, and B2C communication in the case of the automotive industry communicating to final customers.

Metals can be used in a variety of products (e.g. cars, bridges, beverage cans), thus defining appropriate and common rules for metals already shows a link between many industry sectors. This is also the reason why the use phase is usually not evaluated in metals studies. Only the production phase and the EoL stage get assessed, because these are the two stages for metal products, which are independent from the product use. The importance of the correct accounting of recycling is explained in the following section. Contrarily, automotive suppliers focus mainly on the use phase, due to the high impact of the use-phase emissions, which cause the other life cycle stages to fade into the background. Subsequently, the current EU regulation controls tailpipe emissions only. This situation will change in the future as with new light-weighting materials and further technological improvements the use-phase emissions can be reduced so that the share of other life cycle stages becomes significant. Therefore, only the correct choice of system boundaries will avoid burden shifting between different life-cycle stages. Further details can be found in the background document “Sector report: metals and automotive”.

In terms of LCI management, metals industries are collaborating within their own specific trade associations to collect data, which is further provided as industry averaged data (e.g. worldsteel, Copper Alliance, European Aluminium Association). The metal industry considers industry averaged datasets to be the most accurate representation of the current production and transformation practices. For example, steel is a globally traded commodity and using global average data is appropriate for many studies. These industry averaged datasets are externally reviewed. Furthermore, in a whitepaper on harmonisation of LCA methodology metals and mining companies defined and summarised common methodological approaches and overarching procedures. Although these collaborations exist, satisfactory agreements cannot be found for all situations. In the case of by-product allocation a “one approach fits all” solution has not been found, due to the complex situation of different metals.

Metals and automotive sector are currently focussing on the most scientifically accepted LCIA methods. Collaboration in the case of choosing the right impact categories to enable further uptake by the successor in the supply chain works well. This is the reason why results aggregated to one single score indicators are only seldom used. However in the final customer communication mainly GWP results are expressed.
Sector C
Waste

The practice of sustainability assessment in the Solid Waste Management (SWM) sector is highly driven by legislation (see background document "Sector report: waste"). In addition to compulsory studies that any large investment project has to conduct to evaluate their impact on the environment (mainly at a local level), and in which waste management projects can often be classified, the EC introduced several waste directives in which the calculation of sustainability indicators in order to choose the most sustainable option for waste management is encouraged. The Waste Framework directive had a substantial merit in the increase of LCA application in the SWM sector, and LCA is the most used method to assess the environmental sustainability of waste treatment systems and technologies today. Because of the wide range of products that can be obtained from waste (recycled materials, fertilizers, energy, etc.), as well as the dependency of sustainability results to local conditions, other methods than LCA are being extensively used by industry, the scientific community and decision makers. This is the case of material flow and energy analyses, risk assessment and, to a lesser extent, exergy and energy analyses as well as the Ecological Footprint method. These methods do not all follow a life cycle perspective.

The main common issue regarding the application of these methods today is the lack of specific data considered (e.g. waste composition). A consistent mass balance is rarely conducted, potentially leading to the study of unrealistic systems or the exclusion of some emissions from the scope of the study. Furthermore, in studies following a life cycle perspective, an agreement on how to deal with long-term emissions is missing. Moreover, in these studies, avoided processes are usually chosen as the average production mix, whereas in many cases the implementation of a new system has marginal consequences.

Some initiatives, mainly lead by academia, are taken to enhance the application and the outcomes of different sustainability assessment methods to SWM systems. The combination of methods covering different issues (e.g. LCA and risk assessment) has been tested by the scientific community but is still a field that requires further development. Waste specific LCA software tools such as EASETECH (Danish Technical University) or SWOLF (North Carolina State University) are being developed and provide waste specific processes and their associated databases. The Vienna University of Technology developed STAN, a software tool now recommended to perform material flow analysis in the Austrian standard ÖNorm S 2096, as well as the software BIOMA to automatically calculate several parameters of input waste of waste-to-energy plants based on mass balance.

Amongst the sectors investigated, the waste sector remains more unique/specific in the way a sustainability assessment is conducted. This is due to the facts that their processes typically have multi inputs and outputs; the assessment depends very much on regional and regulatory-specific boundary conditions and the logistics; and the economic and regulatory contexts are playing important roles.

In the three analysed sectors various specific open issues were identified. These findings explain the difficulties in cross-sectorial cooperation. Furthermore, differences between sectors in terms of methodological choices are observed, such as preferences in data sources used, allocation or recycling methods. Even more, approaches can also differ between companies of the same sector. These different choices may lead to inconsistencies when an overarching sustainability assessment is performed involving different actors and sectors. Data sharing often remains a problematic aspect for the inter- and intra-sectorial collaboration. Those specific challenges are described in more detail in Section 3.3.
According to the sector specific analysis there are several methodological challenges especially relevant for particular sectors. These challenges can become crucial points of discussion or major sources of inconsistencies and uncertainty when different actors or sectors are cooperating. Three of those issues are described in this Roadmap, as they have been identified as being currently the most relevant topics:
- Allocation of by-products
- Allocation at End-of-Life
- Assessment of renewable materials and biogenic carbon accounting

### Allocation of by-products

If more than one product is produced in a process, the environmental burdens have to be distributed over these products. The approach chosen for this allocation should follow the ISO 14044 allocation hierarchy. By-product allocation is a topic of discussion, as it can influence the overall results for a product heavily. To avoid double counting or neglecting burdens, it has to be ensured that environmental burdens are allocated consequently, not only within a sector or product, or life cycle stage, but along the whole value chain. This has to be ensured via transparent communication with/between suppliers, customers or other actors involved.

The allocation approach chosen should be based on the characteristic of the joint-production, i.e. it should be based on material-specific properties and processes in reality as precise as possible. The definition of the most appropriate allocation rule (e.g. allocation based on physical properties or monetary value of co-products) depends on the specific co-product(s), which should be clearly identified, and cannot be fixed on a general level.

As considering different allocation approaches can in some cases change the outcomes of an LCA study (especially when comparative assessments are done), an agreement has to be made within each sector for using the same approach and thus better harmonise published LCA studies. That is where the development of PCRs can be an option.

To allow a better data usage along the supply chain and improve consistency, the approach chosen and the influence of this choice on the final results (e.g. through a sensitivity analysis) should be reported in the documentation of data sets. For better consistency (at least for B2B communication) and to avoid misunderstandings, the environmental performance of a product shall be communicated together with that of the by-products. Further details can be found in the background document “Sector report: metals and automotive”.

### Allocation at End-of-Life (EoL)

In order to obtain the complete picture and to clearly evaluate the potential benefits of valorising waste, the EoL of products has to be evaluated. Specific recycling properties and recycling chains should be reflected by a recycling model.

ISO 14044 differentiates between the concepts of open and closed loop recycling. Closed loop recycling cannot only be fulfilled when a product is recycled...
back into the same product, but also when there is no change in the inherent properties of the material. This implies that the quality of the recycled material can be maintained. Objective modelling approaches reflecting the recycling reality are needed. Material specific properties and changes in quality should be reflected by the recycling approach.

New and more detailed models for the LCI of waste water treatment impacts are also being developed. The allocation of the benefits of recycling has a huge impact on the interpretation of the LCA profile for some products, such as metals. Modelling of the recycling at the EoL phase for materials can be distinguished by two main extreme approaches that have been highly discussed lately (Figure 5):

- Recycled content approach (“cut-off” or 100:0) – the product carries the full environmental burden of the production of its primary material (recycling at EoL does not offset the production of primary material);
- End-of-life recycling approach (“avoided burden” or 0:100) – the product gets a benefit, if a recyclable material is produced from the EoL product, i.e. it gets a credit.

The avoided burden approach allows for consideration of recycling rates and the ability to account for quality losses in recycling. In case of cross-sectorial collaboration, fair rules for the recycling and the associated credit/burden have to be agreed upon. The open communication of separate results for different stages will be the first step and can be helpful for the usage of the data further along the supply chain.

Further details can be found in the background document “Sector report: metals and automotive”.

The “Life Cycle Metrics for Chemical Products” guidelines of WBCSD mentions that a 50/50 allocation shall be used as a rough estimation for chemicals, as EoL does not play a major role for those. Nevertheless, in the metal sector, the recycling stage is relevant and the avoided burden approach is considered more suitable.
Assessment of renewable materials and biogenic carbon accounting

Renewable materials can be used in many applications such as automotive, cosmetics, food, fuels household products, etc. Nonetheless, methodological inconsistencies and data uncertainty, which still exist, become major challenges for cross-sectorial sustainability assessments. According to the ISO technical specification given in ISO/TS 14067, direct and indirect land use change (dLUC and iLUC) shall be considered. However, no recommendation is given about methods or data sources to be used for the assessment of emissions from LUC. More information can be found in the GHG Protocol\[44\]: emissions from dLUC shall be reported separately considering the total change in carbon stock during the last 20 years or within a single harvest period. This is the most common approach used today to assess LUC. Nevertheless, several sources of uncertainty remain. The main reason is the difficulty to have full transparency of the very complex supply chain of renewable feedstocks. For example, the location of the feedstock production is often not precisely known. Several parameters have consequently to be averaged at the country or regional level, which results in an increase of the uncertainty. However, freely available tools have been developed for estimating dLUC with low data availability and could help to enhance comparability over the supply chain even if uncertainty remains high. An agreement within and between sectors for using these specific tools (such as the one from PAS 2050-1\[45\]) is required for calculating emissions from dLUC, or using the same assumptions or datasets. The MEASURE team also encourages the further development of these tools to reduce uncertainty linked with the calculation of LUC. However, more detailed information or recommendations should be provided in the ISO standards. Compared to dLUC, iLUC is currently rarely assessed due to lack of agreement on the general method, complexity of the topic and low data availability. The consideration of biogenic carbon also represents a source of inconsistency along the value-chain. Biogenic carbon contained in bio-based materials shall be considered when calculating the GWP. The biogenic carbon embedded in a product is relevant for calculating cradle-to-gate GWP, whereas the biogenic carbon balance is neutral over the full life cycle (cradle-to-gra-

Uncertain parameters in the calculation of CO₂ emissions from dLUC

- Determination of the function of land prior a certain land use i.e. 20 years ago (grassland, forest land, agricultural land etc.);
- Estimation of the carbon stock for the several carbon pools identified such as above ground biomass, peatland etc..

Recommended tool for assessing dLUC:

“Land Use Change Assessment tool” from the PAS 2050-1 based on the GHG Protocol and FAOSTAT data.
Several possibilities exist to access the data on products and raw materials:

- Use of generic data from LCA databases;
- Direct sharing of primary (specific) data in a B2B context;
- Use of industry average datasets; and
- Direct data exchange with black-box datasets.

The purpose of the sustainability assessment influences the choice of the data sharing approach. For general screening studies public databases are sufficient sources of information, whereas detailed studies require specific and exact data, which can only seldom be found in databases. However, the different types of data and sources, as well as data documentation and uncertainty, are described herewith.

**Use of generic data from LCA databases**

Considering environmental LCA, at the moment, two main commercial databases with LCI datasets are commonly used by industry and governmental bodies: the GaBi database developed by thinkstep (formerly known as PE International) since the 1990s, and the ecoinvent database developed by ecoinvent partner institutes available from 2003. Apart from commercial databases, many industries (including the process industries evaluated in MEASURE) provide their data for free (see next sub-sections) and publish them via different platforms, including the European reference Life Cycle Database (ELCD), or are used only internally. Furthermore, a number of national life cycle inventory databases have been developed focused on national products, the most developed ones being probably from USA and Latin America.

As regards the social pillar, databases such as the ones existing for environmental LCA do not yet exist, since challenges still occur on two levels: data collection itself and linking social indicators and impacts to a product (which is rarely used), as social data is hard to gather and usually very country, sector, and even chain specific. The most commonly used social database is the Social Hotspot Database, (http://socialhotspot.org/) containing few datasets but only provides generic data and information on risks that social impact may occur in a certain country or sector. More information is given in the background document "Current state in LCSA".

**Direct sharing of primary data**

In the conducted surveys, a clear preference for direct industry collaboration along the value chain was expressed. The sufficiency and adequateness of public databases is becoming superseded by the need for more detailed and specific data (i.e., primary data). Personal contacts and the possibility of direct questions to the data owners tend to create a more collaborative spirit.

However, direct sharing of primary LCA data bears the risk of disclosing confidential information about the process design. Furthermore, data on materials or energy inputs are directly linked with costs, which can make companies reluctant to broadly share such data. Confidentiality and competition law issues can also be an obstacle for the direct sharing of LCA primary data.
Use of industry average data sets

As already mentioned, many industry sectors are collecting LCA data and provide them to the public as industry average data sets. They are an appropriate option to overcome confidentiality issues, and provide at least basic data to the practitioners.

The level of disclosure defines the provided level of detail within a LCI database. There are several options available for the publication of the data within a LCI database. In general, vertical averaging is preferred over horizontal averaging (Figure 6).

Direct data exchange with black box datasets

A data exchange solution, already widely used in industry, is data sharing via “black box” systems. For complex processes made of several process steps, aggregated data for the final product of the overall process is shared instead of information on the single sub-processes (Figure 7). Two possibilities exist to exchange aggregated data: either a life cycle inventory or only the LCIA results can be provided, e.g., only results on certain categories such as GWP, AP, PED, etc. In both situations, a “black box” dataset can be exchanged in a special format suitable for the software used.

Information on the inventory level offers the possibility to choose the impact categories freely and therefore,
helps the interpretation of received data. Nevertheless, it can lead to confidentiality issues for some specific cases (e.g., a flow "emissions of biogenic carbon" in the inventory is directly correlated to the yield of a fermentation process).

The possibility to interpret such a black box model afterwards is very limited. Therefore, it does not allow for making informed choices and the identification of possible environmental improvements.

In the case of communication of final impact results to other industry sectors, scientifically robust and accepted impact categories and assessment methods should be used. The identification of the most relevant impact categories for the collaborating sectors is a priority. This will facilitate the analysis of complex results to reveal solutions for improvements in products and processes. It is important to consider the relevance and possible impact of a particular data set in a study as different levels of detail might be necessary and suitable.

Figure 7. Level of aggregation of LCA data for B2B communication.
Data documentation in B2B communication

The current state of documentation in customer specific data, Environmental Product Declarations (EPD) and professional databases were found to be often non satisfactory. Relevant information about underlying allocations, energy systems, general assumptions and version changes are often not documented in an adequate manner. There is also a lack of general rules regarding data exchange across sectors and along value chains, about the documentation needed and how to safeguard correct results.

Data exchange via official databases or platforms can only work if the data submitted meet certain requirements. To give an example, for the Life Cycle Data Network, ILCD Entry-Level requirements exist.[46] Among other requirements, a documentation of the dataset has to be provided. Concerning the exchange of primary data over the supply chain or within sectors (B2B communication), no rules exist concerning the documentation required or the minimum level of data quality.

Without a well-documented dataset, no interpretation is possible and risks of misunderstanding or inconsistencies (such as double counting of credits) are high. MEASURE therefore recommends a documentation standard for information that shall be provided with LCA data. This information gives to the data recipient the possibility to understand and better analyse results, while the confidentiality of the data provider is ensured.

This topic is further detailed in the background document “Challenges of cross-sectorial sustainability assessment”.

Data uncertainty

Today, the importance of quantifying uncertainty of LCA results is widely acknowledged in industry and the scientific community. However, there is confusion among LCA practitioners on the terminology used to conduct this step of LCA, as the terms sensitivity, variability and uncertainty are often used for one another. Whereas sensitivity aims at quantifying the effects of the methodological and data choices on results or output variables, uncertainty reflects the lack of knowledge on input variables and its cumulative impact of the results. Sensitivity analysis is therefore more a tool to evaluate the parameters having the most impacts of the LCA results than a way to quantify the actu-
al uncertainty of the results. Uncertainty analysis by contrast can be used to estimate the confidence levels around a certain calculated value or to define, if calculated, values for different alternative scenarios or products that are likely to be significantly different from each other.

There are three main sources of the uncertainty of LCA results:

- **Data uncertainty**: it is quantified following three main approaches: scenario analysis, the Pedigree matrix approach and the statistical approach;
- **Uncertainty of methodological choices**: e.g. mass allocation vs. economic allocation, system expansion vs. allocation etc., is rarely considered in LCA studies. However, it is acknowledged that different methodological choices can change the conclusions of a study; and
- **Model uncertainty**: e.g. associated with the value of the characterization factors is rarely evaluated in LCA studies, too. Some attempts using different characterization factors or applying the Monte-Carlo methodology to characterization factors can be found in literature, but they are rather limited.

The practical implementation of uncertainty analysis is challenging as it can be very time consuming and a complex task for LCA practitioners who are often not familiar with methods such as Monte-Carlo analysis. As a preliminary step, sensitivity analysis should be used to identify the parameters having most impacts on the LCA results.

The consideration of uncertainty in LCA studies plays a key role when results are used for decision-making. Indeed, in some studies the result’s uncertainty is too high to enable taking a decision (e.g. LCA of renewable materials), whereas sometimes uncertainty is not properly calculated or not calculated at all and therefore the LCA results cannot be used. Therefore, better communication between decision makers and the LCA community could contribute in increasing the proportion of LCA results used in the decision making process by better defining the needs of the decision makers and focusing on the main parameters of interest.

More information concerning uncertainty issues can be found in the background documents "Current state in LCSA" and "Sector report: waste".
CHALLENGES FOR SUSTAINABLE PROCESS DESIGN AND INNOVATION IN INDUSTRY AND ACADEMIA
4 Challenges for Sustainable Process Design and Innovation in Industry and Academia
**KEY MESSAGES**

- Existing methods for sustainability assessment are not used to their full potential as decision-support and innovation-support tools towards more sustainable technological developments.
- SPIRE projects have to focus on the future impact potentials of new technologies and should be more intensely used to demonstrate the chances of coupling engineering, design, decision-making and LCT.

- Little harmonisation of life cycle approaches applied within European FP7 framework projects and in their reporting regarding green/sustainable outcomes was found.
- At present more substance is given to the environmental part of sustainability due to easily quantifiable targets. Quantitative targets are required for economic and social aims, formulated in the SPIRE roadmap.
- The rules for calculation of material and energy intensities from a life-cycle perspective are not yet defined, significantly hampering the practical use of resource efficiency indicators as well as a standardised reporting.

- A method to funnel R&D into innovation is needed for the success of the SPIRE objectives. Implementation of a target-oriented stage and gate process within publicly funded projects is strongly recommended.

**R&D NEEDS**

- Better access of ERP to the plant floor data, agreement on data exchange standards, and an integration of process models and LCA models into plant management is required.
- Robust statistical treatment and ‘big-data’ approaches to LCA methods are urgently needed to support decision making and optimisation in process design studies.
- Data-mining methods for generic LC inventories should be more applicable to support early stage R&D with simplified LCA.
- Agreed evaluation methods for resource efficiency evaluation of innovation projects are needed.
Besides new challenges in sustainability assessment in the case of cross-sectorial cooperation within process industries, the currently weak link between process design, engineering, plant management and sustainability assessment was found to be a critical obstacle to reach the SPIRE targets. SPIRE aims to achieve a rejuvenating of the European process industry by making it both more sustainable (doing more with less) and more competitive at the world level.\cite{2} Substantial funding shall encourage multi-sectorial cooperation of sectors within the process industry in a value chain in order to accelerate innovation. Innovations in one sector, that have proven to increase resource and energy efficiency, shall be adapted and transferred to other sectors, speeding up the innovation rate.\cite{21} Likewise, co-developing solutions for resource and energy efficiency within the sectors and across value chains through converging technologies is encouraged. Using modelling and automation techniques to design, optimise and monitor technical processes is seen as key for developing sustainable innovations. The heart of the SPIRE innovation plan is collaborative projects between industry and applied science teams in academia. To be successful against competitive proposals, project concepts need a certain technology readiness level, a reliable scale-up and demonstration plan and last but not least a clear vision of the extent a specific project will contribute to the SPIRE sustainability and resource efficiency goals. However, the huge potential of innovation management and "benign by design" approaches by coupling of (already available) techniques and information is far from being utilised in its full extent. Easy-to-use, simplified life-cycle based methods applied at different development stages and scales could guide innovation processes to a more sustainable future.\cite{46} Coupling sustainability assessment approaches with engineering software tools would allow for synergies and a holistic understanding of innovation potentials.\cite{49}

Also, a harmonisation of indicators and benchmarking is urgently needed for a sound comparison of emerging new technologies. The sustainability targets of the SPIRE community have to be translated into operational, broadly accepted and clearly defined indicators allowing a quantitative monitoring of the progress towards the challenging targets. The clear orientation on the future implementation, as well as on quantitative target values for sustainability, is in such an extent a new approach for European projects. However, a key lesson learned in earlier EU research and innovation programmes was that funding suffered from a lack of clarity of focus and a weak intervention logic.\cite{50} To give an example, the EU’s Seventh Framework Programme for Research (FP7) was compromised by a plethora of too general, higher-level EU objectives, lacking an explicit breakdown of those into intermediate and operational objectives. Instead, it was fragmented into comparatively stand-alone thematic priorities and was focused on single sectors and technologies rather than on the achievement of the objectives.\cite{52} Consequently, comprehensive interim evaluation of Horizon 2020 and its specific programmes as well as a full-scale ex-post evaluation, analysing, in depth, the rationale, the implementation and the impact of the activities, are envisaged. Thus, comparability and a harmonisation of assessment rules will become essential for the evaluation process of each project and also for the analysis of the SPIRE programme outcome as a whole. This is especially true for the envisioned achievements in terms of sustainability and resource efficiency, being central SPIRE aims (see also background document “Towards sustainability in SPIRE innovation projects”).
The challenge of orientation of R&D projects towards commercially successful outcomes could be addressed by introducing the widely industry-accepted stage-gate approaches (Figure 8). If stage and gate innovation management in industry is coupled with LCT, it usually starts with screening methods and ends with full LCA. Clear hurdles and a scoring system for each category considered are set in order to quantify if the solution developed will result in improvement or deterioration.

The approach allows pragmatically prioritising resources to ideas that show the most potential and killing poor performers. It typically includes risk and probability estimations to obtain those targets for internal control and decision-making. Within a given team, the stage and gate approach could be highly effectively used as a project planning and monitoring tool, to ensure successful delivery of the key objectives, against which project success will be evaluated. It can be supplemented by comparative cost evaluations in order to focus on developments with a higher industrial uptake. Consequently, the stage and gate approach should be used pragmatically to stop research activities that are less likely to contribute to the goals of the project within its lifetime. However, this requires some degree of flexibility in funding within the project and access to other sources of funding by the research groups.
To aid the pragmatic use of stage and gate approaches, it is suggested that multi-criteria decision methods (MCDM) should be integrated into the decision process to provide consistent and transparent decision making. Depending on the complexity of the decision being made, as well as the number and type of criteria being considered, the MCDM used could range from a simple scorecard, through analytical hierarchy process (AHP)\(^5\), to the more complex PROMETHEE\(^5\). Though the use of suitable MCDM techniques, process design teams will be able to consider better all aspects of sustainability for which data are available, equally across multiple development pathways. With a wide range of economic, environmental and social criteria that are often contradictory, being factors in the decision making process, a structured approach to decision making can improve the understanding, influences and outcomes of decision making.

The MCDM technique used should be able to grow and expand through the stage and gate process as additional data become available and the complexity of the data increases. The same approach, and much of the subjective judgements required, can be reused, not only progressively as the stage and gate process continues but horizontally across multiple developments. Techniques such as PROMETHEE that clearly separate and define the objective data and subjective judgements made by the decision maker can help to gain a better understanding of the problem faced. The increased transparency obtained by using such a structured decision process can also improve communication to and, importantly, acceptance of decisions by stakeholders, critical where multiple stakeholders are involved.

Sustainability assessments, that by definition incorporate a range of economic, environmental and social criteria, are ideally suited to MCDM techniques. Multi-tier approaches allow equal importance be maintained to economic, environmental and social aspects, whilst allowing different weighting of individual impacts within those broad categories. Mixtures of qualitative and quantitative data can be used alongside each other and transparency of the decision process benefits stakeholders and decision makers alike.

The possibilities and opportunities from data analysis in early stages of process or product design could be amplified by the use of data-mining tools for more extensive analysis. However, data-mining methods for generic life cycle inventories are still in their infancy. Further development is needed, before they might become useful in a broader extent.
In many industries, especially in the processing industries sector, process models are ubiquitous and their development is an essential part of process design, validation and commercialisation. Hence, the link of a process model with an LCA tool seems a logical and timely development. Such models provide not only complete material and energy balances for the process within its gate-to-gate boundaries, but also, depending on the level of sophistication of a model, may be predictive, enabling exploration of wide ranges of input parameters; enabling first principles design of new processes; and facilitating the development of control models. Most process simulation tools include reasonably sophisticated parameter sensitivity and model uncertainty analyses that are frequently lacking in commercial LCA tools.

The combination of process simulation and LCA tools allows optimisation of global material and energy fluxes through the overall integrated process system on the basis of detailed process models, and easy access to further optimisation criteria based on life cycle impacts of relevance to the specific product/process. Improvements in resource efficiency may be achieved through retrofitting existing processes with more advanced technologies, extending or optimising existing plants and developing new processes. Key tools that enable these tasks and which all exist are: material/energy flux analysis and integration, e.g. pinch-technology, process modelling and flow-sheet optimisation, global optimisation tools. For engineers, the addition of life-cycle impacts would be the new component in the conventional work-flow of process development and optimisation. In addition to process models and flow-sheet models, many industries use sophisticated data management systems that allow different levels of optimisation, from a single process, to company-wide inventory, to enterprise resource planning.

To facilitate access to data, and management of both data and models, integration of LCA and sustainability assessment into enterprise resource planning/management (ERP) systems is strongly encouraged. Customised ERP systems may use the primary process data,
bill of materials and supply chain data not only for their primary objectives of management, scheduling/forecasting and business intelligence, but also to link the primary data with the models of life cycle impacts. An ERP system may be capable of pulling the necessary primary data into a suite of process models, comprising input-output LCA model for the desired evaluation report, such as a specific process environmental impact report, or a product footprint report, see Figure 8.

The use of such sophisticated data management systems for the purpose of global optimisation of the material and energy efficiency of plants with additional environmental constraints is not an impossible task, but requires to interface resource management and planning tools with LCIA tools, global optimization tools and MCDM tools. The open issues in developing such an approach are data management within enterprises, enabling access of ERP to the plant floor data, data exchange standards, exchange of data along the supply chain avoiding commercial sensitivity, and the integration of process models and LCA models.
Standardisation of the LCT based assessment and reporting of project outcomes regarding the SPIRE sustainability criteria (fossil energy intensity, non-renewable primary raw material intensity and reduced CO$_2$ equivalent emissions) is an indispensable requirement. Otherwise, neither the comparative assessment of success in case of industrial uptake and implementation of the innovations developed in particular SPIRE projects, nor the evaluation of the impacts of SPIRE PPP activities as a whole will be possible in a reasonable manner.

In order to address the issue of standardisation of assessment and reporting with respect to the SPIRE sustainability targets, the recommended measures in Figure 10 should be followed by all SPIRE projects.
Figure 10: Recommended measures for sustainability assessment within SPIRE innovation projects. Baseline selection according to WBCSD.

**MINIMUM**

- Perform (simplified) LCT based assessments throughout the project to guide the development towards sustainable solutions.
- Perform comparative cradle-to-gate analyses additionally including recycling, reuse and waste treatment steps.
- As described in the WBCSD 2013 guideline.

**BEST PRACTICE**

- Manage and maximise the innovation potential using a stage and gate approach, MCDM and further advanced tools in combination with a LCT based assessment. Include comparative cost analyses to point out alternatives with a higher likeliness of industrial uptake.
- Consider potential social impacts.
- Perform comparative cradle-to-grave analyses.
- As defined in the specific SPIRE call or
  - Use the existing industrial production process alternative under redesign / optimisation.
- Perform sensitivity analyses by worst/best case scenarios for significant process steps/parameters.
- Undertake at least qualitative uncertainty considerations.
- Communicate assumptions, risks and probabilities.
- Report regarding the SPIRE sustainability goals in a transparent, comprehensible manner based on an ISO 14040/44 compliant assessment.
- Report the project outcomes using the recommended Life Cycle Metrics.
- Report the potential project impacts by theoretical industrial case scenarios based on reasonable business cases (market, uptake etc.) after 5 years.
- Take into account further resource efficiency and impact categories of interest in the specific case.
A more detailed description of the recommended procedure is given in the background document "Towards sustainability in SPIRE innovation projects".

To achieve the SPIRE goals, it is furthermore necessary to clearly define what is meant by RE, as described in Section 2.5. The SPIRE Roadmap\[3\] defines resources as “energy, raw materials and water” and calls for a life-cycle based calculation. However, some SPIRE calls require projects to achieve specific targets with regard to resource efficiency (e.g., increase of "the resource and energy efficiency for the process industries by at least 20 %"; SPIRE-3-2014). Others ask for a specific reduction in process energy intensity and material resource (e.g., SPIRE-1-2015), in both cases without defining the method or types of resource to be considered in the calculation. Thus, these calls leave the project developers free to choose the method to evaluate resource efficiency or intensity and do not allow comparability between projects from the same call.

Several European projects are currently dealing with the development of a suitable set of KPIs in order to evaluate resource efficiency. For a better estimation of resource efficiency within SPIRE innovation projects, a better definition of the terms/scale/assessment practices have to be agreed upon and clear guidance on how to calculate resource efficiency provided if resource efficiency targets are set.

Until a broad acceptance for one of those sets of KPIs currently under development in all SPIRE projects, and likewise in the scientific LCM community, could be gained, the use of established Life Cycle Metrics is recommended for the evaluation of the SPIRE PPP targets. The rules for calculation of these indicators are commonly agreed and thus easy to harmonise. They can be calculated with the software tools commonly used for LCA and based on existing LCI data. Further case specific methods should be used on a voluntary basis.

Although the SPIRE roadmap mentioned economic and social targets, no measurable goals are given. Consequently, those goals are less pronounced. While environmental LCA is a standardised method and LCC can be performed in a straightforward manner, SLCA still suffers lack of scientific consensus and definitions, including proper impact assessment and thus, broader practical implementation. To establish the approach as a useful and applicable tool in research and innovation projects, further methodological improvements are needed.
### RECOMMENDED LIFE CYCLE METRICS FOR THE EVALUATION OF THE SPIRE PPP TARGETS

<table>
<thead>
<tr>
<th>Recommended metrics</th>
<th>SPIRE sustainability goal by 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative energy demand [MJ] according to VDI 4600 guideline expressed in:</td>
<td>A reduction in fossil energy intensity up to 30 % from current levels;</td>
</tr>
<tr>
<td>• Non-renewable energy demand</td>
<td></td>
</tr>
<tr>
<td>• Renewable energy demand</td>
<td></td>
</tr>
<tr>
<td>Total material consumption [kg] grouped in</td>
<td>A reduction of up to 20 % in non-renewable, primary raw material intensity compared to</td>
</tr>
<tr>
<td>• critical/non-critical[^56]</td>
<td>current levels;</td>
</tr>
<tr>
<td>• fossil/non-fossil</td>
<td></td>
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<tr>
<td>Global warming potential calculated via infrared radiative forcing (100 years) [kg CO₂-eq.], based on IPCC data, 2013</td>
<td>Efficiency improvement of CO₂ - equivalent footprints of up to 40 % compared to current levels.</td>
</tr>
</tbody>
</table>
Central to the MEASURE project has been a continuous consultation process with lead users of sustainability metrics in the European process industry. Through a combination of the project advisory board, stakeholder surveys, expert interviews and collaborative workshops, the MEASURE consortium aimed to identify the current state of sustainability assessment tools, techniques and approaches in different sectors of the process industries with a focus on life cycle tools and methods. Companies and organisations of different sizes and different sectors, national and EU regulators and standardisation bodies, NGOs, as well as academia were included within the consultation process. The initial stakeholder survey was undertaken in collaboration with the Horizon 2020 SPIRE projects SAMT and STYLE and received more than 120 feedbacks. The second stakeholder survey was undertaken by the MEASURE consortium, specifically focusing on the aims and objectives of MEASURE. Taking the format of a limited survey of identified experts working within the European process industry, the 50 questions of the survey considered a range of topics including the extent to which LCA is used; how supply chain data and interactions are handled; the use of sustainability assessments including social life cycle assessment and life cycle costing; decision
making with LCA; and its implementation from R&D up to full scale production. The survey received responses from 67 individuals working within a broad range of sectors within the process industry including: chemicals, consumer goods, waste, engineering, steel, pharmaceuticals, water, minerals and others. Most respondents were from a manufacturing or industrial in-house research background with consultancy, academia, contract research and industry associations also represented.

The MEASURE consortium has run three workshops (Belgium, United Kingdom and Germany) and a small number of expert interviews, where the views and opinions of stakeholders within the European process industry were elicited. The project also presented its intermediate results at the Life Cycle Management conference and the ACS Green Chemistry and Engineering conference in 2015. European and US experts were consulted during these conferences, respectively.

The outcomes from all aspects of the consultation process have been used to guide the MEASURE project and development of the MEASURE roadmap and background documents. Detailed information about the consultation process including analysis of the two stakeholder surveys can be found in the background document “MEASURE survey results.”
BACKGROUND DOCUMENTS

Background documents with detailed information concerning the main topics addressed in the Roadmap will be available starting from 1. April 2016 on the MEASURE website:

http://www.spire2030.eu/measure/

Background documents comprise the following topics:

• MEASURE survey results
• Current state of LCSA
• Current state in resource efficiency evaluation
• Sector report: chemistry and FMCGs
• Sector report: metals and automotive
• Sector report: waste
• Challenges of cross-sectorial sustainability assessment
• Towards sustainability in SPIRE innovation projects
• Teaching materials
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AP</td>
<td>Acidification Potential</td>
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<tr>
<td>ADP</td>
<td>Abiotic Depletion Potential</td>
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<tr>
<td>B2B</td>
<td>Business-to-Business</td>
</tr>
<tr>
<td>B2C</td>
<td>Business-to-Consumer</td>
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<tr>
<td>CBA</td>
<td>Cost Benefit Analysis</td>
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<tr>
<td>CED</td>
<td>Cumulative Energy Demand</td>
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<tr>
<td>CSA</td>
<td>Coordination and Supporting Action</td>
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<tr>
<td>EC</td>
<td>European Commission</td>
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<tr>
<td>ELCD</td>
<td>European reference Life Cycle Database</td>
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<tr>
<td>EoL</td>
<td>End-of-Life</td>
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<tr>
<td>EP</td>
<td>Eutrophication Potential</td>
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<td>EPD</td>
<td>Environment Product Declaration</td>
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<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
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<td>EU</td>
<td>European Union</td>
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<tr>
<td>GHG</td>
<td>Green House Gas</td>
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<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
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<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardisation</td>
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<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
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<td>LCA</td>
<td>Life Cycle Assessment</td>
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<td>LCC</td>
<td>Life Cycle Costing</td>
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<td>LCI</td>
<td>Life Cycle Inventory</td>
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<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
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<td>LCM</td>
<td>Life Cycle Management</td>
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<td>LCSA</td>
<td>Life Cycle Sustainability Assessment</td>
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<tr>
<td>LCT</td>
<td>Life Cycle Thinking</td>
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<td>LUC</td>
<td>Land Use Change/</td>
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<td>dLUC</td>
<td>Direct Land Use Change</td>
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<tr>
<td>iLUC</td>
<td>Indirect Land Use Change</td>
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<tr>
<td>MCDM</td>
<td>Multi-Criteria Decision Methods</td>
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<td>PCR</td>
<td>Product Category Rules</td>
</tr>
<tr>
<td>PED</td>
<td>Primary Energy Demand</td>
</tr>
<tr>
<td>PEF</td>
<td>Product Environmental Footprint</td>
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<tr>
<td>PPP</td>
<td>Public Private Partnership</td>
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<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
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<tr>
<td>RE</td>
<td>Resource Efficiency</td>
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<tr>
<td>SLCA</td>
<td>Social Life Cycle Assessment</td>
</tr>
<tr>
<td>SME</td>
<td>Small and medium-sized enterprise</td>
</tr>
<tr>
<td>SPIRE</td>
<td>Sustainable Process Industry through Resource and Energy Efficiency</td>
</tr>
<tr>
<td>SWM</td>
<td>Solid Waste Management</td>
</tr>
<tr>
<td>UNEP/SETAC</td>
<td>United Nations Environmental Programme/Society of Environmental Toxicology and Chemistry</td>
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<tr>
<td>WBCSD</td>
<td>World Business Council for Sustainable Development</td>
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</tbody>
</table>
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ACKNOWLEDGEMENT
The MEASURE team kindly acknowledge the valuable support of the Advisory Board members:

M. Gernus, J. Warsen, Volkswagen AG
S. Andrae, EXCO GmbH
I. Erdelmeier, Tetrahedron
I. Chaput, RDC Environment
S. Coles, KTN Ltd.
M.E. Monell, LEITAT Technology Center
D. Holtmann, DECHEMA Forschungsinstitut
S. Walraedt, essenscia
D. Brown, lChemE
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5. Procter & Gamble Services Company NV, Global Product Stewardship
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