AQUABIOPRO-*FIT* at a glance

PART IV
Potential environmental impacts identification in side-streams valorization technologies

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Summary:	Part IV encompasses 2 courses presenting information about the identification of potential environmental impacts in technologies for valorization of side-streams.
	This part presents life cycle assessment (LCA) as a methodological tool for studying the environmental aspects and potential impacts of a product or service throughout its lifecycle, from the extraction of raw materials, production, its use, and eventually, its disposal and/or recycling. The evolution of LCA methodology is summarized, from the early 1960 to the recent emergence of hybrid LCA to gain benefits of process-based inventory analysis in the new production industries around the world, such as bio-based products. The four steps of the LCA methodology are outlined: Goal and scope definition; Life cycle inventory (LCI) analysis; Life cycle impact assessment (LCIA); Interpretation. Some limitations of LCA that stem from its holistic nature are described; it focuses on the physical characteristics of the industrial activities rather than on the secondary effects of technological development. However, the LCA is a useful methodology to make informed decisions because it allows the environmental impacts of different products and activities to be compared.
	The man object of the LCA is highlighted: the assessment of the potential human and ecological effects of energy, water, and materials used and discharged to the environment. The classification of different LCA methodologies depending on the final assessment goal is presented: i) environmental impact assessment and ii) assessment of damage. The most common impact categories used in LCA studies are outlined: Global Warming Potential, Acidification, Fresh water ecotoxicity, Cumulative Energy Demand, Abiotic resources depletion, and Eutrophication. Information about various LCA software tools available on the market is presented, among which the SimaPro and GaBi being the two most popular worldwide. Applying these tools, the results of the inventory analysis and impact assessment can be interpreted to select the product, process, or service with the best performance within the context of the goal and scope of a study. Particular attention is paid to the application of the LCA in biomass valorization technologies in the viewpoint of waste-to-energy transformation.

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Course 4.1: Understanding the main concepts of the LCA methodology

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4.1.1 Introduction

The life cycle assessment (LCA) is a methodological tool for studying the environmental aspects and potential impacts of a product or service throughout its lifecycle, from the extraction of raw materials, production, its use, and eventually, its disposal and/or recycling. The first official definition of an LCA was provided by the Society for Environmental Toxicology and Chemistry (Klöpffer 1997, 2006): *"Life Cycle Assessment is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and material uses and releases to the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, re-use, maintenance, recycling, and final disposal".*

Several tools to support decision-making have been developed in environmental management, such as: i) cumulative energy analysis (CERA); ii) environmental impact assessment (EIA); iii) environmental risk assessment (ERA); iv) input-output analysis (IOA); v) material flow accounting/substance flow analysis (MFA/SFA); vi) material intensity analysis (MIA). All these tools include the term life cycle in their definitions, however, the LCA differs because its principal goal is to reduce the use of resources and the volume of waste to optimize the environmental performance of the process being studied. The LCA is a useful methodology to make informed decisions because it allows the environmental impacts of different products and activities to be compared. The LCA is the most widely accepted methodology, it has been standardized and it is undergoing the process of harmonization (Hauschild, M.Z., Rosenbaum, R.K. and Olsen 2018; ISO 2006; Klöpffer, W. and Grahl, B. 2014).

4.1.2 LCA evolution

The LCA methodology has evolved during the previous decades (since early 1960); indeed, the life-cycle-oriented methods mentioned before heralded the current LCA technique. In the beginning, these sorts of assessments were known as Resource and Environmental Profile Analysis (REPA) or Ecobalances, until the 1990s when the LCA term became the norm (Hunt, Sellers, and Franklin 1992). As it can be observed in

Figure *4.1.1*, early methods are characterized as material and energy accounting and were inspired by material flow accounting, as they are mainly focused on inventorying energy and resource use (e.g. crude oil, steel, etc.), emissions and generation of solid waste, from each industrial process in the life cycle of product systems. During some years, the emphasis of these assessments was on the

generation of solid waste, which was considered problematic, mainly in the US, where landfilling was the dominant waste management practice. Similarly, at this stage, the methodology was initially employed to compare beverage packaging (McManus and Taylor 2015).
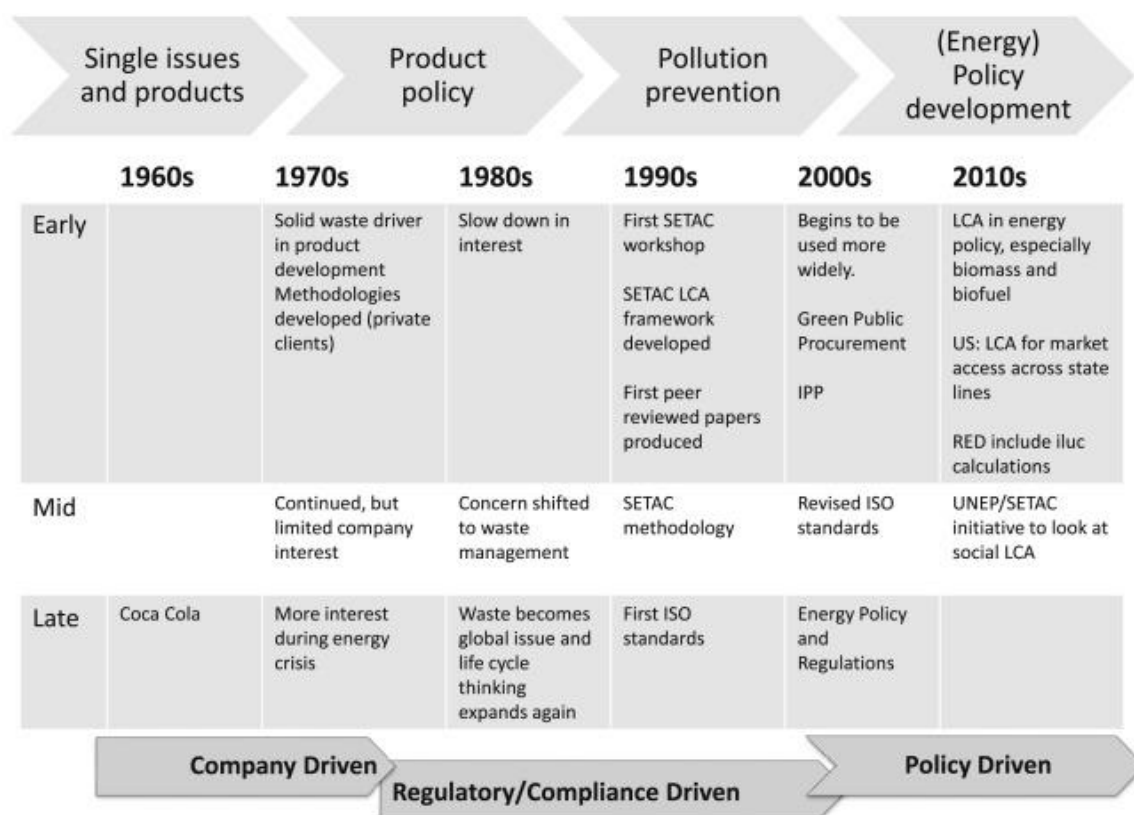

Figure 4.1.1 Trajectories and drivers in LCA development (from McManus & Taylor, 2015)*.

The second step of the evolution occurred when the analyses pass from a physical flow in a product life cycle (inventory results) to a potential environmental impact calculation. In brief, the list of resource used, and emissions are translated in a set of indicator scores for an assessed product, representing contributions to several impact categories, such as global warming, acidification, eutrophication, among others. Initial impact assessment methods are likely to represent impacts from emissions in the form of dilution volumes of air or water needed to dilute the emissions to safe levels or below regulatory thresholds, such as the Swiss Ecopoint method from the 1980s (Hauschild, M.Z., Rosenbaum, R.K. and Olsen 2018).

During the 1990s, the focus of the LCA was on pollution prevention (Fig. 4.2.2). In this regard, many impact assessment methods appeared, and the ambition was to quantify all relevant environmental impacts, independent of shifting public concerns, to avoid environmental burdens. The first impact assessment methodology that covers a wide-ranging set of midpoint impact categories was the CML92 (Heijungs et al., 1992)(Heijungs, R., Guinée, J.B., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wegener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., Duin, R.V. and De Goede 1992). Additionally, during the 1990s several life cycle inventory databases came out, covering various types of

industrial sectors. In the same decade, due to the increasing demand of modeling complex product systems and the management of multiple life cycle databases and impact assessment methodologies, some software such as SimaPro® and GaBi were launched (GaBi 2020; Pré 2020).

In 1998, the ISO standards related to LCA published the ISO 14040: 1998 standard, which establishes the principles and structure of this methodology. In subsequent years, other ISO standards related to LCA appear, including ISO 14041: 1999 (objective, scope and inventory analysis), ISO 14042: 2001 (evaluation of the impact of the life cycle) and ISO 14043: 2001 (interpretation of life cycle impact). These standards have been reviewed and replaced by ISO 14040: 2006 (principles and frame of reference) and by ISO 14044: 2006 (requirements and guidelines) (International Organization for Standardization 14044 2007)(International Organization for Standardization 14044 2007). In a relatively short time, life cycle analysis has become an essential methodology for analyzing the sustainability of products and processes, as evidenced by the growing number of scientific articles. Figure 4.1.2 shows the evolution of publication in this field (around 45,656 documents, until 2019).

In the last two decades, the impact assessment methods have continuously been refined and several methodologies have emerged and are frequently being updated, including mid- and endpoints. As the methodology has been evolved with the new production industries around the world, such as bio-based products, assessment indicators like water and land use have appeared as relevant impact categories in the 2000s and 2010s. Currently, the application of hybrid LCA has emerged to gain benefits of process-based inventory analysis (Hauschild, M.Z., Rosenbaum, R.K. and Olsen 2018).

For additional information related to the past, present and future of the LCA methodology, read Life Cycle Assessment: Past, Present, and Future.
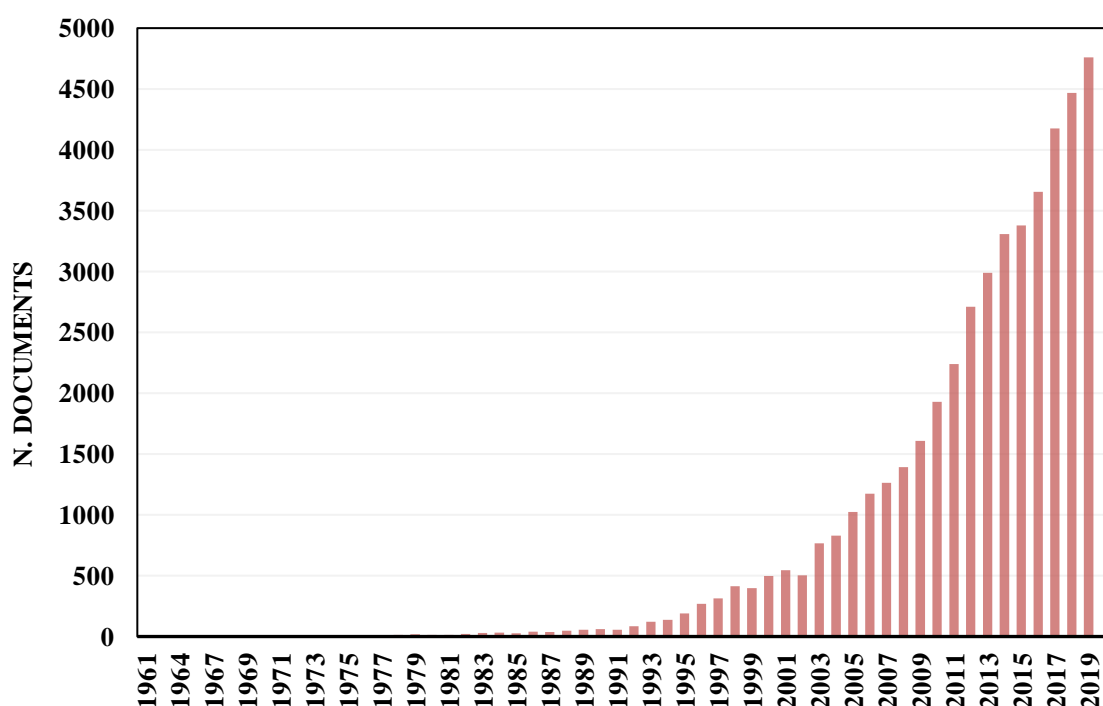

Figure 4.1.2 Number of publications in the SCOPUS database (keyword: life cycle assessment).

4.1.3   LCA methodology overview

The first structure of the LCA was attempt by the SETAC triangle, proposed in 1993 (Klöpffer, W. and Grahl, B. 2014) (Figure 4.1.3).

Figure 4.1.3 The SETAC-triangle in LCA guidelines (by Klöpffer, 1997)*.*

The phases proposed by SETAC are somehow maintained by the ISO (International Organization for Standardization 14044 2007), except for the Improvement Assessment, which was replaced by the Interpretation phase.

The structure of the international standard is depicted in Figure . According to the ISO, the LCA can be divided into four steps:

- Goal and scope definition;
- Life cycle inventory (LCI) analysis;
- Life cycle impact assessment (LCIA);
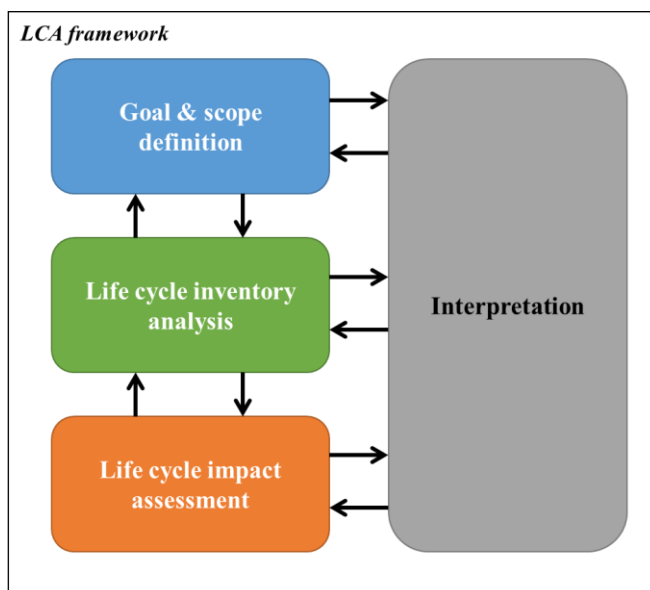- Interpretation.

Figure 4.1.4 General methodological framework of LCA (International Organization for Standardization 14044 2007)*.*

LCA standards ISO 14040 and 14044 belong to the ISO 14000 family concerning a variety of aspects related to environmental management (
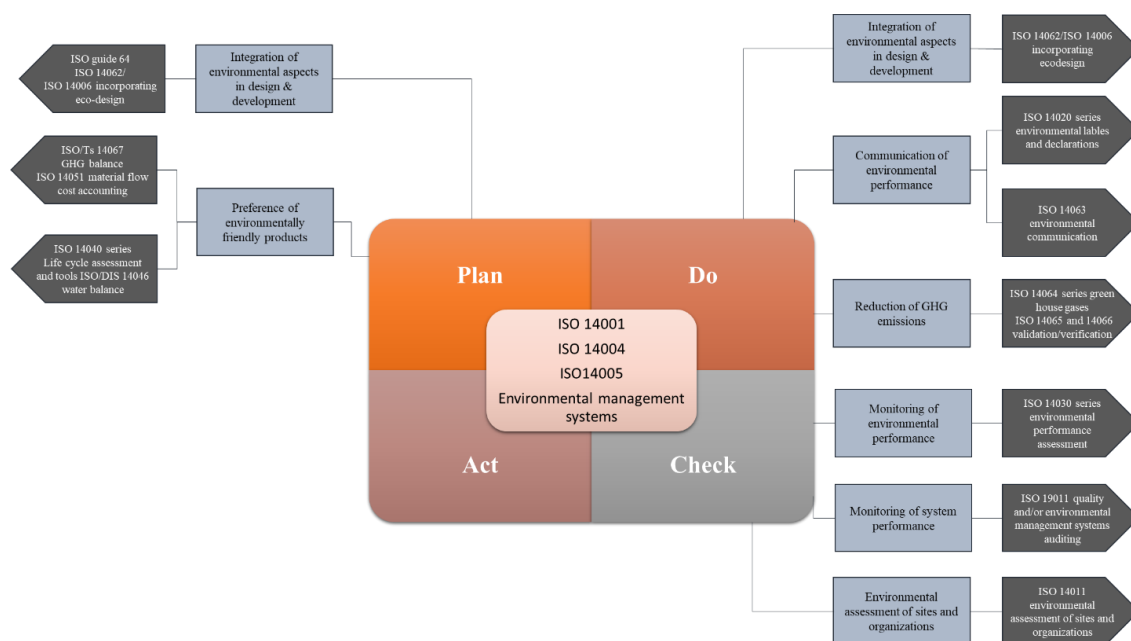Figure).

Figure 4.1.5 ISO 14000 model (based on (Klöpffer, W. and Grahl, B. 2014)*.*

The four steps included in the LCA methodology will be explained in detail below.

4.1.4 Methodology limitations and threats

The holistic nature of the LCAs is simultaneously a major advantage and disadvantage of employing this methodology. Some of the main LCA limitations and threats are listed below (Guinée et al. 2002) :

- LCA cannot address localized impacts. This methodology does not provide the framework for a full-fledged local risk assessment study.
- LCA model focuses on the physical characteristics of the industrial activities and some other processes but does not include the secondary effects of technological development.
- LCA regards all processes as linear, both in the economy and in the environment. Moreover, LCA focuses on the environmental aspects of products and does not take into account economic or social effects.
- Many databases are being developed in several countries, and the format for databases is being standardized, however, in practice, data are frequently obsolete, incomparable, or of unknown quality.
- The possibility of using different allocations, system boundaries, or recycling concepts can be reflected in data inconsistencies, as well as a double-counting or impacts omissions.

4.1.5   Goal and scope definition of the system under study

This stage defines and describes the product, process, service, or activity to be studied. Establishes the context in which the assessment will be conducted and identifies the boundaries and environmental effects to be evaluated. This section is key for the development of the study because it implies the definition of the functional unit and the system boundaries, which are linked to the entire analysis.

The goal definition is essential for all the other step in the LCA; therefore, some specific aspect must be considered and documented during this stage (ILCD, 2010):

- Reasons for performing the study and decision-context (why is the study carried out?);
- The target audience of the assessment results (what kind of questions are the study intended to answer?);
- Comparative studies to be disclosed to the public;
- Commissioner of the assessment and other relevant actors.

4.1.6   Functional Unit

The functional unit (FU) is defined as the quantification of the function(s) of the process under study and its primary purpose is to provide a reference related to input and output data (International Organization for Standardization 14044 2007). For comparative studies, the choice of the functional unit becomes critical and can have an important impact on the results obtained. For this reason, several works have performed their assessments by using more than one functional unit, in order to observe how the choice of the FU impacts the results (Batlle-Bayer et al. 2019; Haas, Wetterich, and Geier 2000; Kamali, Hewage, and Sadiq 2019; Prasad et al. 2020; Sonesson et al. 2019).

The functional unit defines the qualitative characteristics and calculates the quantitative aspects of the function, which usually entails responding to the following 5 questions: i) what?; ii) how much?; iii) for how long/how many times?; iv) where?; and v) how well? For instance, in the case of a comparative analysis of an outdoor paint, the functional unit can be defined as: the complete coverage of 1 m^2 primed outdoor wall for 10 years in France at 99.9 % opacity. It is relevant to mention that the FU must always include a specific function and in some cases is not linked to a physical quantity, such as 1 L, 1 kg or 1 MJ (Hauschild, M.Z., Rosenbaum, R.K. and Olsen 2018; ILCD 2010).

After the FU is defined, the reference flows can be determined. The reference flows are the number of products that are needed to perform the functional unit.

When some product system is analyzed, a multifunctional process can appear. In order to solve multifunctionality, ISO 14044 proposed a hierarchy of solutions (Figure). According to ISO 14044, the allocation must be avoided by:

- i)   dividing the unit process to be allocated into two or more sub-process and collecting input and output related to those subprocesses;
- ii)   expanding the product system to include the additional functions related to the co-products, considering the requirements for reuse and recycling.

If the allocation is not possible to be avoided, inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them. Finally, when physical relationship alone cannot be established, the inputs must be allocated between the products and functions in a way that reflects other relationships between them; therefore, inputs and outputs might be allocated between co-products in an economic proportion of the products, for instance (International Organization for Standardization 14044 2007)(International Organization for Standardization 14044 2007).

Additional examples of how to define the functional unit and reference flows can be found in [The product, functional unit and refence flows](#) (Weidema et al. 2004), [ILCD handbook](#) (ILCD 2010) and [Defining the FU.](#)

4.1.7 System boundaries

The system boundaries define what parts of the life cycle and which processes belong to the studied system. Therefore, the boundaries separate the analyzed system from the rest of the Technosphere (surrounding economy), as well as the interactions with the ecosphere (the environment). The definition of the system boundaries has a substantial effect on the LCA results because they establish the unit process from which the environmental impacts should be quantified. The system boundaries are represented in a chart that provides an overview of which parts of the analyzed product systems are included, and which are excluded from the study (Hauschild, M.Z., Rosenbaum, R.K. and Olsen 2018). Figure shows an example of system boundaries definition for a life cycle of a steel sheet used on roads.

Generally, system boundaries are defined concerning the following parameters (Li et al. 2014; Tillman et al. 1994):

- *Natural system*, which means, the border between the technical system and natural environment;
- *Geographical boundaries*, which means the area to which the system is limited;
- *Time boundaries* refer to the time perspective of the study, and, *Technical boundaries* relate to the activities that are considered in the study or to the life cycle of another product (if several systems share the same process, the environmental load will be shared between them).

Some recommendations about how to select the system boundaries in an LCA can be found in [A system boundary identification method for life cycle assessment](#) (Li et al. 2014).

Additional information related to the goal and scope definition step search in [Overview of Goal and Scope Definition in Life Cycle Assessment](#) (Curran 2017).
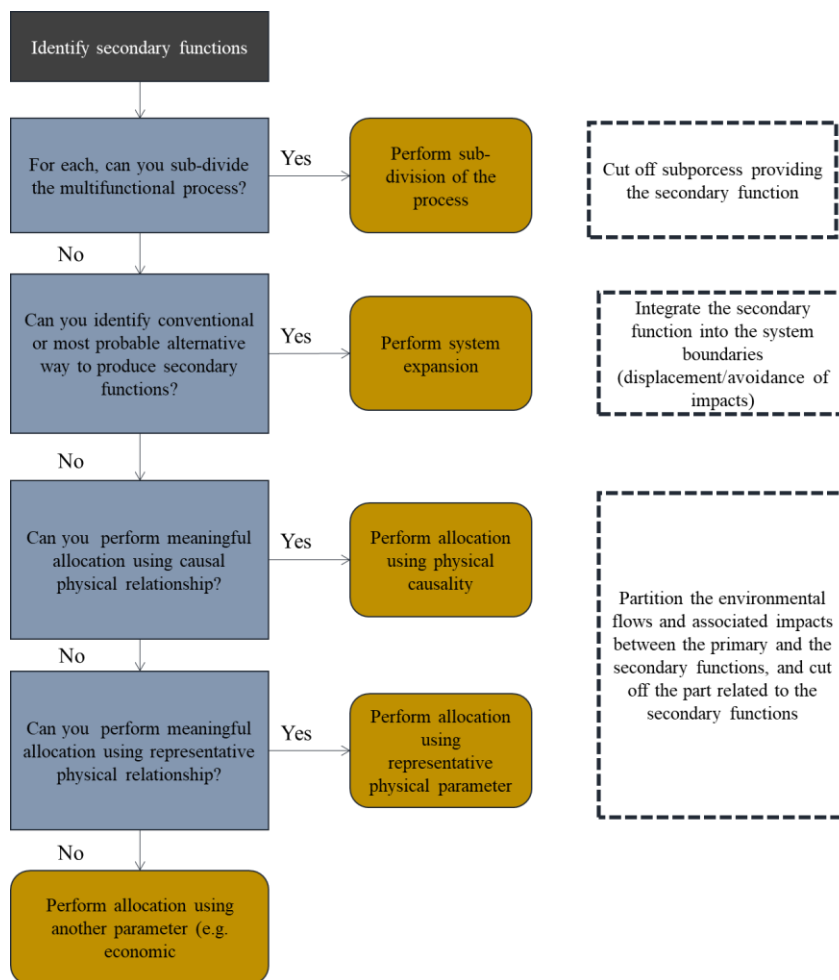
Figure 4.1.6 ISO hierarchy for solving multifunctionality presented in a decision tree.
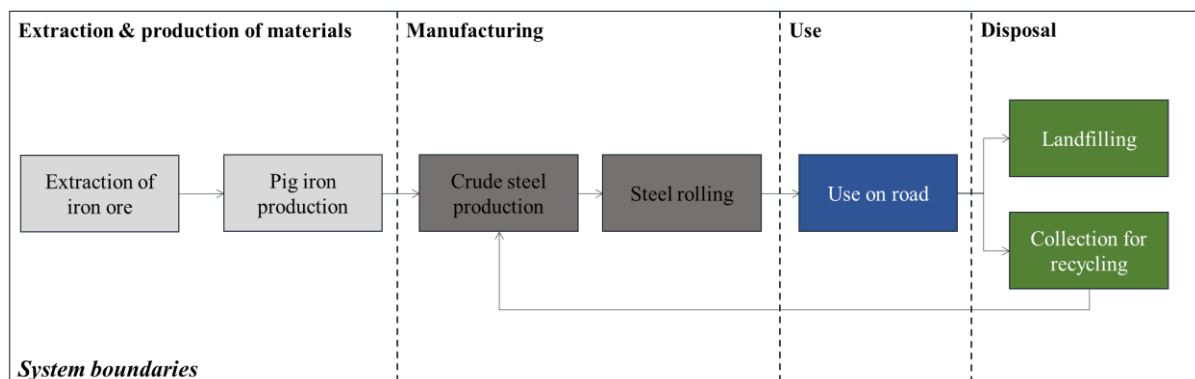
Figure 4.1.7 Example of system boundaries chart defined for the life cycle of a steel sheet used on roads (based on (Hauschild, M.Z., Rosenbaum, R.K. and Olsen 2018)*).*

4.1.8   Life cycle inventory analysis

This phase involves the identification, collection, and quantification of the data necessary to meet the defined goal and scope of the study. The level of detail of the inventory depends on the objectives outlined in the study. This phase is usually the most time and resource consuming step of an LCA (International Organization for Standardization 14044 2007) . This analysis is guided by the

goal and scope definition, and its core action is the collection and compilation of data on elementary flows from all processes in the studied product systems.

This step of the LCA is a technical, data-driven process to quantify energy and materials consumed, emissions to air and water, solid waste and any other discharged into the medium during the complete life cycle of a product, process, material, or activity. In a broad sense, inventory begins with raw materials and ends with the final management of product waste (International Organization for Standardization 14044 2007)(International Organization for Standardization 14044 2007).

According to (Fava, 1991) , the inventory analysis includes the following stages:

- Construction of the flow diagram according to the established system boundaries.
- Collection of data from all activities in the production system. It is necessary to establish the origin of these data: bibliographic and/or measurements *in-situ*.
- Calculation of environmental loads related to the functional unit.
- Normalization of the data in terms of units.
- Material balances, which allow the interrelation of inputs and outputs between the different subsystems.
- Quantification of the outflows from the system to nature or the Technosphere.
- Global inventory.
- Documentation of calculations.

Data acquisition can be divided into 4 main groups (Feijoo, et al., 2007)(Feijoo G., Hospido A., Gallego A., Rivela B. 2007):

- i)   direct measures;
- ii)   published documents;
- iii)   electronic sources, and;
- iv)   personal communications.

Among all these information sources, databases have been and continue to be one of the fundamental ways to find the inventory data needed to perform an LCA. There are different systematizations in the expression of data, but one of the most used is defined by the Society for the Promotion of Life Cycle Assessment Development (SPOLD), which indicates the reference of input and output data from or to nature and from or to the Technosphere.

Linked to data management, one of the main issues affecting the application of an LCA lies in the reliability of data on raw materials and emissions in the life cycle inventory. Therefore, a data quality classification is shown in Table 4.1..

Table 4.1.1 Data quality classification (Hauschild, M.Z., Rosenbaum, R.K. and Olsen 2018)*.*

Data specificity	Explanation
Very high	Measured directly at a specific site or scaled from measurements.
High	Derived from measurements at specific process site throughout the modeling.
Medium	Life cycle inventory data from database process, or data from literature specific to the actual process.

Low	Generic LCI database process, or data from literature (mixing of technologies in a country or region).
Very low	Judgment by experts or LCA practitioners.

Some examples of process-based LCI available databases are available in ecoinvent; ELCD; Agri-footprint; LCA Food; Swedish National LCA database; GaBi databases; LC-inventorires; NEEDS; NREL; ProBas; LCA Commons; Ökobaudat. Currently, the most comprehensive and widely used database is ecoinvent. The following link show an illustrative video related to the LCI data in LCA.

Some visual resources related to the LCA methodology are presented in Table 4.1.2.

Table 4.1.2 Visual resources related to LCA methodology.

Resource title	Link	Topic
Life Cycle Assessment – ICS 5: Global Disruption and Information Technology	https://youtu.be/zFaG4QZpzIs	LCA methodology
Life Cycle Analysis: A materials perspective	https://youtu.be/Z4LOqt7U-JE	LCA concept
GCSE Chemistry Life cycle assessment (AQA 9-1)	https://youtu.be/H1mJm1WxSgs	LCA methodology
What Is a Life Cycle Assessment?	https://youtu.be/3fdyubY_GBY	LCA concept
Webinar: An Introduction to LCA	https://youtu.be/a4ransnoCaY	LCA introduction
LCA methodology – Chalmers	https://youtu.be/tyZBfgIcacQ	LCA methodology
MIT ESD.S43 – Green Supply Chain Management	https://youtu.be/gpuvUU0Nl4k	LCA methodology
An Introduction to Life Cycle Assessment for Infrastructure	https://youtu.be/F-YERbH1giY	LCA introduction

4.1.9   References

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Course 4.2: Life cycle impact assessment, LCA assessment tools and their application

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4.2.1 Impact assessment categories selection

This step is devoted to the assessment of the potential human and ecological effects of energy, water, and materials used and discharged to the environment. In an impact assessment it is mandatory to do the following:

- Selection of impact categories, category indicators, and models.
- Classification, in which inputs and outputs identified in the inventory analysis are grouped into impact categories or indicators (i.e. CO_2, CH_4, and N_2O emissions are classified as contributing to the global warming potential category; NH_3 emissions, NOx and SOx, and other emissions contribute to acidification potential, and VOCs, CH_4, NOx, benzene, hexane among other substances contribute to the photochemical oxidation potential).
- Characterization, which involves the quantification of the potential contribution of the inputs and outputs to the environmental impacts, which allows them to be aggregated into a single value by weighting. The following are some examples: Global warming potential, expressed in kg equivalent of CO_2, receives contributions from CO_2, CH_4, N_2O and other emissions. Ammonia, H_2S, HCl, NOx and SOx and other emissions contribute to the acidification potential, which is calculated in kg equivalent of SO_2. VOCs, CH_4, NOx, benzene, hexane and other emissions contribute to the photochemical oxidation potential which is expressed as kg equivalent of C_2H_4.
- Normalization, which consists in the evaluation of the environmental profile generated in the previous steps, by establishing the weight of each category. This stage allows the dimensionless of the categories and the comparison between them. The value obtained in each category can be relativized concerning a reference quantity, which can be, for example, the value of that category in question for the whole world activity, or the country, or the region where the study was carried out.
- Weighting, where the environmental profile is reduced from a set of indicators to a single impact score, by using weighting factors based on subjective value judgments. The weighting between categories is a step with a certain degree of subjectivity and is rarely carried out in LCA studies.

The different life cycle impact assessment methodologies can be cluster into two main groups depending on the final assessment goal: i) environmental impact assessment: in here, some methodologies result in the definition of an environmental profile, by quantifying the environmental effect on various categories over the product, process or service analyzed. In contrast to the second group of methodologies, this reaches only to evaluates indirect or intermediate effects about the human being (i.e. midpoints); ii) assessment of damage: these methodologies analyze the ultimate effect (i.e. endpoints)

environmental impact, where they try to identify and define the damage caused to humans and natural systems.

According to (ISO, 2006b), the selection of the impact categories should consider the following aspects:

    i)   the categories are nor redundant and do not lead to double counting;

    ii)   they do not disguise significant impacts;

    iii)   they are complete, and; iv) they allow traceability.

On the other hand, other relevant questions to be addressed during the selection of LCIA methods are (Hauschild, M.Z., Rosenbaum, R.K. and Olsen 2018):

    i)   what kind of environmental issues are needed to be covered?;

    ii)   in which region the study is taking place?;

    iii)   are mid- or endpoints needed to be assessed, or both?;

    iv)   which elementary flows are needed to be characterized?;

    v)   how well is the method documented?;

    vi)   how practical will be to communicate the results?;

    vii)   when was the method published and have there been important scientific advances in the meantime?

Some of the available life cycle impact assessment methods in LCA software are: ReCiPe, CML, TRACI, EDIP, LIME, IMPACT 2002+, CED, among others.

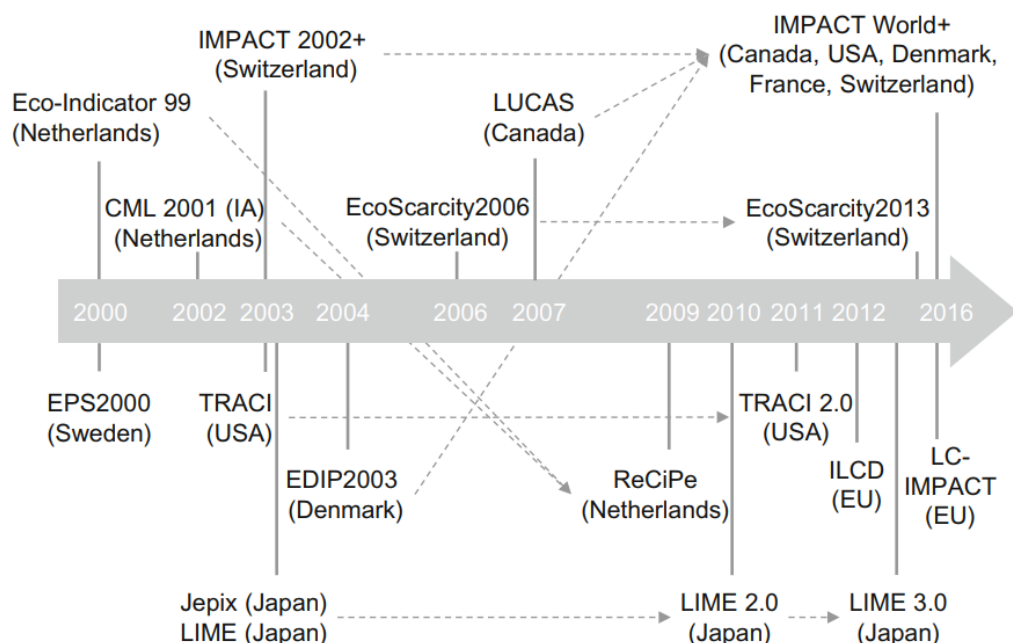Figure 4.2.1 shows the evolution of some LCAI methods around the world.

Figure 4.2.1 Life Cycle Impact Assessment methods published since 2000 (Rosenbaum 2017)*.*

Table 4.2.1 includes the most common impact categories used in LCA studies.

Table 4.2.1 Impact categories based in LCIA methods (Acero, Rodríguez, and Ciroth 2015; Hischier et al. 2010; ILCD 2010; Owsianiak et al. 2014)*.*

Impact category	Description
Global Warming Potential (GWP100)	It is related to emissions of greenhouse gases to the air. The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for the development of characterization factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100) in kg carbon dioxide/kg emission (in kg CO_2 eq.). The GWP is impacted mainly by greenhouse gases (carbon dioxide, CO_2, and methane, CH_4). It is calculated for a period of 100 years and it determines the contribution to global warming of a substance released into the atmosphere. IPCC 2007 GWP 100a methodology.
Acidification	It is caused by air emissions of NH_3, NO_2 and SOx. These acidic gases react with water in the atmosphere and form "acid rain". It causes a disturbance of varying degrees in ecosystems. It is measured by the Accumulated Exceedance (AE) in mol H+ eq/kg. CML 2001 methodology.
Fresh water ecotoxicity	It refers to the impact on freshwater ecosystems, as a result of emissions of toxic substances to air, water and soil. Ecotoxicity Potential are calculated with USES-LCA, describing fate, exposure and effects of toxic substances. Characterization factors are expressed as 1,4-dichlorobenzene eq/kg emission. CML 2001 methodology.
Cumulative Energy Demand (CED)	It quantifies the primary energy usage throughout the life cycle of a good or service. The method includes the direct and indirect uses of energy, but not the wastes used for energy purposes (Total CED). It is calculated as MJ. VDI 1997 method.
Abiotic resources depletion	It is related to the extraction of minerals and fossil fuels. The resource depletion factor is determined for each extraction of mineral or fossil fuel (the unit of reference is kg Sb eq) based on the concentration of the reserves and the decomposition index. The geographical scope of this indicator is global.
Eutrophication	It is expressed in kg of PO4- eq/kg of emission. Destination and exposure are not included, the time horizon is infinite, and the scale Geographic varies between local and continental scale.

Additional information related to the environmental impact categories selection can be accessed in Impact categories, normalisation and weighting in LCA (Heidi K. Stranddorf et al. 2005) and Impact categories overview and Environmental Profiles Methodology.
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4.2.2.   LCA tools for evaluation

Up to date, there are several LCA software that can be found in the market, such as [Gabi](#), [Umberto](#), [SimaPro](#), [Gemis](#), [OpenLCA](#), [One Click LCA](#), [BEES](#), [CCaLC2](#) or [Quantis Suite 2.0](#); being SimaPro and GaBi the two most popular worldwide. Among the alternatives available, some of them are free of costs, such as OpenLCA or CCaLC2. Similarly, there are some tools specialized only in carbon footprint calculations or devoted to the construction sector (e.g. One Click LCA).

In [life cycle assessment software](#) (Heijungs 2017) and [A Comparative Lca Software Study](#) (Ormazabal et al., 2014), you can find details on criteria for the evaluation of life cycle assessment software (Heijungs 2017)(Heijungs 2017) and a comparative LCA software study(Ormazabal, M., Jaca, C., & Puga-Leal 2014)(Ormazabal, M., Jaca, C., & Puga-Leal 2014).

Additionally, some illustrative videos regarding GaBi, SimaPro, OpenLCA, and One Click LCA software can be accessed: [GaBi](#), [SimaPro](#), [OpenLCA](#), and [One Click LCA](#).

4.2.3.   Interpretation of results

Interpretation involves the evaluation of the results of the inventory analysis and impact assessment to select the product, process, or service with the best performance within the context of the goal and scope of the study (International Organization for Standardization 14044 2007) (International Organization for Standardization 14044 2007)(International Organization for Standardization 14044 2007). In this phase, the findings obtained are presented synthetically, showing the critical sources of impacts and the possible options to reduce them. The interpretation is useful to indicate the results consistency according to all the aspects defined during the goal and scope stage. First of all, significant issues need to be identified (e.g. main process contributing most to the results). The interpretation requires consistency checks, ensuring that there is complete information. Sensitivity checks should be run. The uncertainty and accuracy of results are also addressed at this stage.

The interpretation proceeds in three main steps (International Organization for Standardization 14044 2007):
  i)   identification of significant issues;
  ii)   evaluation by completeness, sensitivity and consistency check; and,
  iii)   conclusions, limitations, and recommendations(International Organization for Standardization 14044 2007)(International Organization for Standardization 14044 2007).

4.2.4   Sensitivity analysis

The sensitivity analysis of a study defines the extent to which the variation of an input parameter or a choice leads to influence of the study result. In brief, an assessment model is sensitive toward a parameter if a minor change in this parameter will result in a large change in the model result, while a model is

insensitive concerning a parameter if any change in that parameter will have no (or negligible) effect on the model result. Sensitivity may be analyzed for both continuous and discrete input parameters, and it can also be evaluated for options heading to discrete sets of input values (Hauschild, M.Z., Rosenbaum, R.K., and Olsen, 2018; ILCD, 2010). According to Wei et al. (2015), sensitivity analysis is a substantial tool for evaluates the robustness of results and their sensitivity to uncertainty factors in LCA. It highlights the most important set of model parameters to determine whether data quality requires to be improved and to enhance interpretation of results.

On the other hand, a sensitivity check aims at identifying the crucial processes and most important elementary flows as those elements that contribute highly to the global impacts from the product system. A sensitivity check allows in an explanatory manner to determine and document the influence of the altered parameter on the final result. The results of the sensitivity analyses are: i) the adjusted parameter does not modify or insignificantly affects the results; ii) further detailed sensitivity analyses are needed; iii) the results are barely valid within margins, which requires to be considered within the conclusions (Klöpffer, W. and Grahl, B. 2014).

Additional information related to how to perform a proper sensitivity analysis can be found in Sensitivity analysis in life cycle assessment (Groen et al., 2014) and Methods for global sensitivity analysis in life cycle assessment (Groen et al., 2017).

4.2.5   LCA iterative approach

LCA steps are clearly ordered; however, LCA studies are iterative, which means that LCA operations are repeated, to approximate the results paying special attention to the most relevant processes, resources, and emissions. The most relevant processes will be identified taking into account partners' expertise and supported by the assessment run initially. The accuracy of this should be studied and then corrections may be made. It is a common practice carrying out one to three iterations before reaching the final results (Figure 4.2.2).
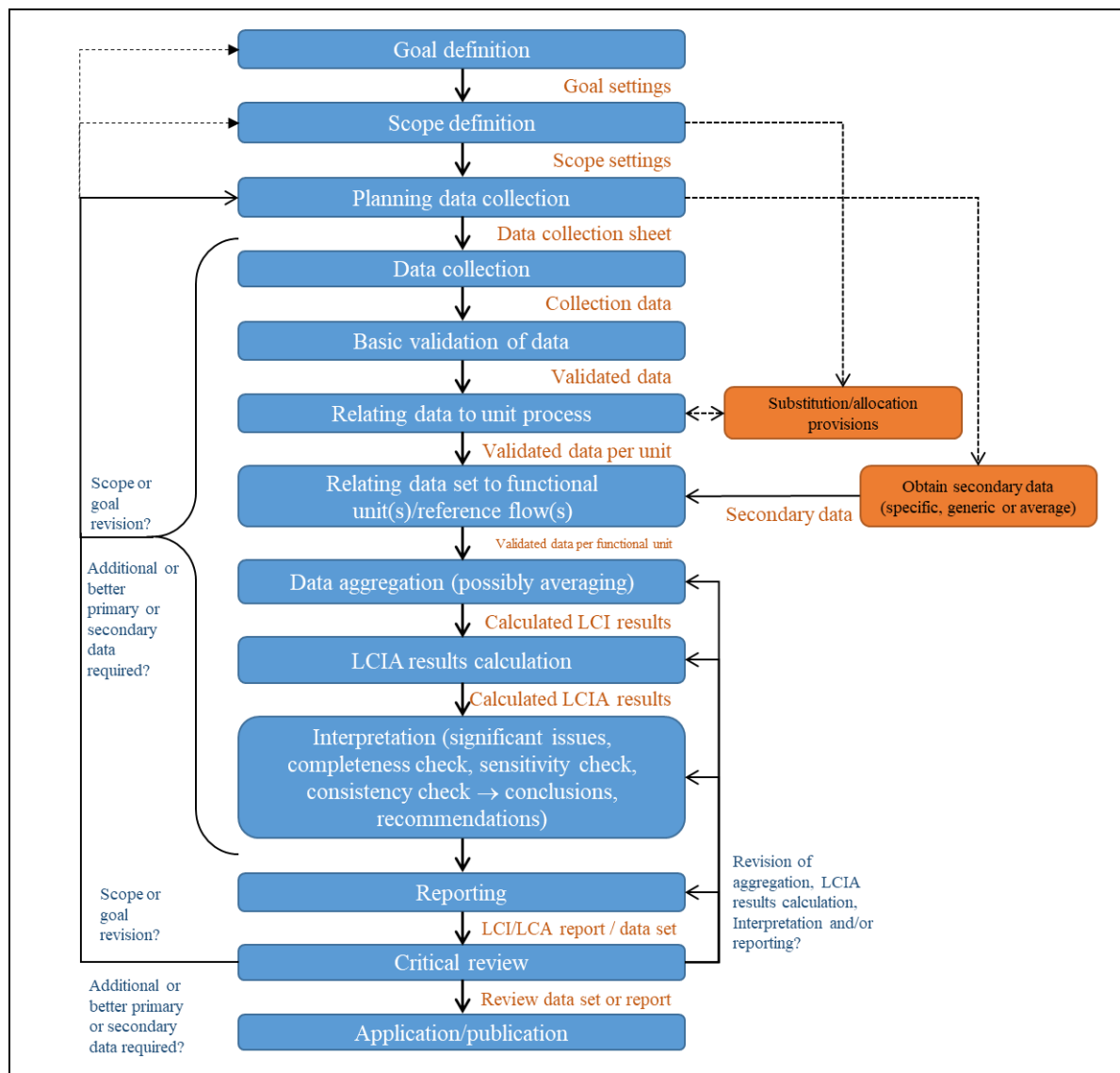
Figure 4.2.2 Details of the iterative LCA approach (ILCD 2010).

4.2.6   Importance of the LCA applied in the side-streams valorization technologies

As it was mentioned during the previous sections of this module, LCA is a powerful tool used for assessing the potential environmental impacts of a product, process or service, which has been applied in many industrial sectors including the biomass production and valorization of side-streams systems (one of the main topic of AQUABIOPRO-FIT project). In this regard, the following subsection will enlighten the work done related to the environmental determinations on waste biomass valorization, as well as the scientific issues related to the application of this methodology in that field.

4.2.7 Application of the LCA in biomass valorization technologies

One of the most studied topics over the biomass valorization from a life cycle assessment perspective is the waste-to-energy (WtE) approach. This topic appears as a relevant point because it addresses a critical issue related to the final disposal of wastes towards a circular economy of resources and energy recovery. WtE is part of the modern management of wastes and can reduce the dependence on fossil fuel, as well as the minimization of landfilling treatment. In this regard, thermal WtE technologies, such as pyrolysis and gasification are proposed as improved energy efficiency techniques, which also reduce environmental burdens compare to classical incineration processes (Panepinto et al. 2014; Zheng et al. 2016). Nevertheless, all these processes should need to be analyzed systematically and holistically, and it is here where the LCA appears as a tool to measure all inputs and outputs of materials and energy 'from cradle to grave', including all up- and downstream activities. According to (Zhou et al. 2018), who performed a review analysis of available LCA WtE technologies (i.e. landfill with energy recovery, incineration, pyrolysis, gasification and pyrolysis-gasification), stated that LCA is sufficiently developed and widely accepted for WtE environmental evaluation. In brief, the main conclusions found were:

i) The data inventory is every day more concrete and detailed from a mass and energy flows point of view;

ii) Sensitivity analyses are widely considered to decrease uncertainty;

iii) Allocation and characterization are grown into different methods;

iv) The environmental impact results of WtE techniques are lower than those of the conventional municipal solid waste treatment methods.

On the other hand, studies of biomass residues transformation into renewable energies are quite studied from an LCA standpoint. This is the case of the analysis made by Neri et al. (2016), who focused on the assessment of a small Italian municipality to treat wood residues to produce renewable energy. They evaluated the potential environmental impacts linked to resource depletion and human health within the whole biomass handling chain, from the wood collection, transportation, and utilization to produce wood chips. According to the results found, the global environmental impacts (e.g. GHG emissions and non-renewable fuel depletion) reduce if the district heating system in the municipality change from fossil resources to the waste biomass system; however, biomass combustion resulted in the worst effects in terms of toxic substances emitted. Furthermore, transportation contributes to the global impact by 98%, even if distances are limited to a 30 km roundtrip.

Another recent example of the LCA applied to biomass residues valorization can be found in the work done by Kopsahelis et al. (2019). They calculated the environmental impacts of end-of-life dairy products (EoL-DPs) managements throughout co-treatment with agro-industrial wastes (AgW) in a centralized biogas plant in Cyprus. They analyzed two scenarios:

i) EoL-DPs co-treatment with different AgW in one-stage mesophilic anaerobic digestion, and;

ii) The same amount of EoLDPs acidified before methanogenesis with AgW to improve biogas production. According to the LCA results, EoLDPs showed better environmental performance before acidification, compare to the direct co-digestion in a mesophilic digester.

Additionally, biogas production upon acidification, and energy yield, was higher compared to the case where no pretreatment was carried out. Nevertheless, further studies must be performed from an environmental point of view in order to extend the system boundaries of the analysis (i.e. they only analyze from a gate-to-gate approach).

Regarding environmental assessments applied to food waste valorization, it is possible to find several scientific references. For instance, Woon et al. (2016) evaluated the valorization of food for 3 types of energy use: i) electricity and heat; ii) city gas; and, iii) biogas fuel as petrol, diesel, and liquified petroleum gas substitute for vehicle use. They based this analysis on data extracted from reports of government and industrial sectors in Hong Kong. One of the main conclusions was that biogas fuel as a petrol substitute for vehicle use shows benefits over the other type of energy use regarding human health and ecosystems. Transforming 1080 tons per day of food waste into biogas vehicle fuel can reduce 1.9% of the GHG emissions in the transport sector in the Hong Kong context.

On the other hand, the waste valorization technologies applied to poultry production was also lately studied from an LCA perspective (Kanani et al. 2020). Poultry industry (including both meat and eggs), is considered one of the industries with the highest growth rates among livestock sectors in the following decades. Primary methods for handling these industry wastes are currently either landfill or rendering for spent hens and mortalities, a landfill for egg-shell sand direct land application of manure as organic fertilizer. This review study identified, categorized, and described current and emerging waste valorization technologies for livestock biomass and assesses their possible applicability for key poultry waste streams from a theoretic viewpoint. As an outcome, this review identified 4 well-developed technologies as potentially suitable for the valorization of key poultry waste streams: i) anaerobic co-digestion; ii) anaerobic mono-digestion (biological technologies); iii) pyrolysis; and; iv) gasification. From an LCA angle, the analyzed studies recommended to systematically calculate the potential net sustainability benefits and impacts of these technologies compared to conventional alternatives, as well as cost comparisons to assess their viability for commercial applications.

Waste biorefineries are also widely studied under a circular bioeconomy approach. Ahmad et al. (2020) performed a critical review of the state-of-the-art biorefinery opportunities beyond traditional methods as a solution in the grape wine industry. They analyzed the current challenges in this sector, such as waste minimization, stems, seed, pomace, wine lees, as well as the biosynthesis of different high-value bioproducts (e.g. phenolic compounds, hydroxybenzoic acids, hydroxycinnamic acids, lignocellulosic substrates, etc). The study was focused on the valorization of winery waste (i.e. solid, liquid, or gaseous) and the LCA was used to find a sustainable solution with value-added energy products in an integrated biorefinery approach, maintaining the environment and circular economy emphasis.

Finally, another interesting research paper linked to LCA applied to waste and biomass valorization was published by Bellon-Maurel et al. (2013). This scientific document summarizes the main issues encounter during the application of the LCA methodology in the before mentioned topic. They identified issues related to: i) *goal and scope*: the difficulty of choosing the functional unit due to the highly multifunctional nature of such systems, as well as the allocation selections and the need for spatial differentiation; ii) *inventory analysis*: the prickly issue of

modeling complex systems and properly estimating field emissions; iii) *impact assessment*: the lack of suitable impact categories in LCA (e.g. odor indicator); iv) *interpretation*: efforts must be set to facilitate the way actor can deal with multicriteria results in LCA.

Information about LCA applied to biomass valorization, as well as its limitations can be found in [What Scientific Issues in Life Cycle Assessment Applied to Waste and Biomass Valorization? Editorial](#) (Bellon-Maurel et al. 2013); [Simplified LCA & LCC of food waste valorisation](#) (Östergren et al., 2018) and [Environmental sustainability assessment of food waste valorization options](#) (Vandermeersch et al. 2014).

4.2.8   Carbon footprint calculation of a simple technology

Simplify calculation of the carbon footprint

The main objective of this section is to calculate the carbon footprint of a simple case study. The carbon footprint is calculated by summing the emissions resulting from every stage of a product or service's lifetime (e.g. material production, manufacturing, use phase, and end-of-life disposal). Throughout a product's lifetime, or lifecycle, different greenhouse gases (GHGs) may be emitted, such as methane and nitrous oxide, each with a greater or lesser ability to trap heat in the atmosphere. These differences are accounted for by calculating the global warming potential (GWP) of each gas in units of carbon dioxide equivalents (CO_2 eq.), giving carbon footprints a single unit for easy comparison (Jones and Kammen 2011).

The case study is described in the PPT file. The assessment was performed via CCaLC2 software. All the step linked on how to use the software, as well as how to carry out the calculation of the carbon footprint are also detailed in the PPT file.

Additional information about the CCaLC2 software can be access in [CCaLC2 © for Windows Manual (V1.1)](#) and [CCaLC2 overview: Main features and modelling (Webinar)](#).

Some visual resources related to the LCA methodology are presented in Table 4.2.2.

Table 4.2.2 Visual resources related to LCA application.

Resource title	Link	Topic
A Cradle to Grave Assessment of Bio-Jet Fuels Production	https://youtu.be/Lt58sBZM4dM	LCA applied to bio-based products

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