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LIFE CYCLE ASSESSMENT

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11.1 Introduction to the methodology

The transition to a circular economy requires assessment tools to ensure that the new strategies put in place effectively contribute to reducing the environmental footprint (EF). The aim is to avoid what might be called "false good ideas." Numerous methods have been developed to assess the impact of an activity or product on the environment. Some focus on greenhouse gas (GHG) emissions only, such as Bilan Carbone in France (Guignard, 2017), the Greenhouse Gas Protocol (Ranganathan et al., 2004), and ISO 14067 (ISO, 2018) at international level. However, focusing solely on the "carbon footprint" (a shorthand often used to express GHG emissions in the form of CO_2 equivalent) is likely to lead to technological developments that will have a major impact in categories of impact other than climate change alone (eutrophication, toxicity, acidification depletion of resources, etc.). Considering only climate change is often referred to the so-called "carbon reduction tunnel vision" that should be avoided in a holistic approach (Savasta-Kennedy, 2014). The associated risks are not only limited to a transfer between impact categories, but also between stages in the life cycle. For example, a reduction in impact at the use phase may prove problematic at the production stage (via the raw materials required) or at the end of life (complex waste to treat/recycle/ dispose of).

In addition, the need to communicate and the desire of many companies and organizations to promote their environmental performance have led to a profusion of expressions and claims that can be likened to greenwashing. How credible are claims such as "CO_2 neutral" or "net zero emissions?" The calculation methodology, the life-cycle stage under consideration, and even the existence of a third-party review is not always specified. In the context of the Greenhouse Gas Protocol, for example, zero GHG emission can be achieved in what is known as scope 1, by replacing domestic production of heat or electricity with purchases. The associated GHG emissions will then be included in "scope 2." This kind of strategy does nothing to solve the problem of global warming. Fortunately, in Europe, as a result of the Green Claims Directive (European Commission, 2023), claims of this kind will have to be backed up by scientific evidence and verified by third-party bodies, on pain of sanctions. In this context, life cycle assessment (LCA) is a key tool to measure the environmental performance of a product, and is promoted by the EU, namely through the environmental footprint method (European Commission, 2024).

It must be reminded that the so called embedded GHG emissions are sometimes forgotten. Indeed, when for example speaking about green electricity produced by PV panels with no direct GHG emissions, there are well indirect GHG emissions associated with the production of all the required components and with the supply chain. Besides developing CO_2 capture strategies, the main challenge remains finding way to reduce the use of fossil resources, along all value chains.

LCA presents the dual advantage of being quantitative and multi-criteria, including a range of impacts such as global resource depletion, water use, eutrophication, acidification, photochemical ozone formation, etc. In addition, when a LCA is carried out according to product category rules (PCR), the results can be presented in the form of environmental product declarations (EPD) (ISO, 2006a). EPDs are also known as ecoprofiles. These documents, which usually require to be reviewed by a third party ("critical review" process), enable objective communication of environmental performance, in compliance with the Green Claims directive. Environmental communication based on LCA is particularly widespread in the construction materials sector, with the existence of online platforms, accessible free of charge, bringing together EPDs. These include INIES[1] in France, IBU[2] in Germany, and BEPD[3] in Belgium, for instance. All these EPDs follow a common framework described in the EN15804+A2 (European Standard, 2020). A more general library is the one of Environdec[4] covering a large variety of sectors. More generally, the European Commission proposed the Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) methods as a common way of measuring

[1] https://www.base-inies.fr/iniesV4/dist/consultation.html

[2] https://ibu-epd.com/en/published-epds/

[3] https://www.health.belgium.be/en/database-environmental-product-declarations-epd

[4] https://www.environdec.com/library

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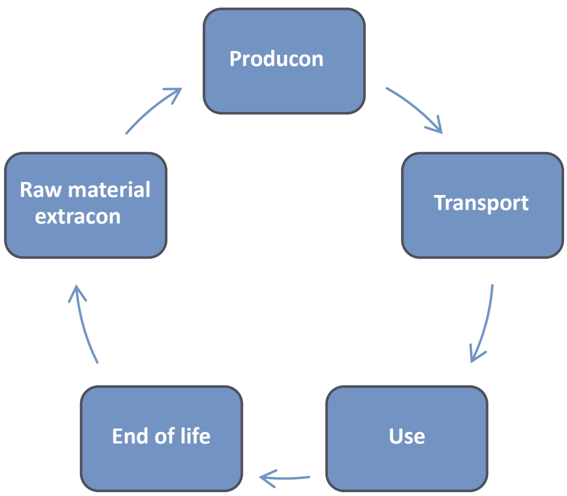
environmental performance (European Commission, 2021). The PEF and OEF are EU recommended LCA based methods to quantify the environmental impacts of products (goods or services) and organizations. The previously mentioned EN15804+A2 was updated in compliance with the PEF method.

When speaking about circularity, it has also to be mentioned that there exist an increasing number of research works aiming at clarifying the concept and developing circularity indexes, some based on LCA. However, this is out of the context of this chapter. We refer the readers to the works of Cilleruelo Palomero et al. (2024), Corona et al. (2019), Kadawo et al. (2023), Kirchherr et al. (2017, 2023), Luthin et al. (2024), and Rigamonti and Mancini (2021).

Figure 11.1 *Life cycle of product.*



11.1.1 Definition

LCA is a method standardized by ISO 14040 and 14044 (ISO, 2006b; ISO, 2006c). It deals with potential environmental aspects and impacts throughout a product's life cycle. This cycle begins with the acquisition of raw materials and ends at the end of the product's life, passing through the stages of production, use, transport and recycling. The term "product" can define both a product in the physical sense and a process or service. Fig. 11.1 represents a simplified and ideal life cycle for which all the content can be recycled at the end of its life. This method can be applied from cradle to grave, cradle to gate (factory) or cradle to cradle in a circular economy vision.

In the context of moving toward a circular economy, LCA makes it possible to objectively assess the environmental benefits of newly developed production or recycling schemes, whether in terms of the use of primary materials or the current management of the end-of life phase. More broadly, from an eco-design perspective, the LCA can be used to check the relevance of alternative solutions or proposed improvements to minimize the EF. A complete LCA can be used to determine the tipping point for a technology, by assessing the lifespan required to achieve an effective benefit, i.e., in the context of green electricity production. Besides being used as an eco-design, LCA can be used for an objective communication about the environmental performances, as explained before, following the establishment of EPDs relying on LCA.

In recent years, the inclusion of LCA in research projects conducted in partnership with industry has become widespread, whether it is at European, national or regional levels. The aims are many: to support the research and development process, to establish the environmental profile of the developed solution (product, process), and if relevant, to compare it with the conventional equivalent that already exists. In recent years, a shift has occurred, with LCA studies moving from being a constraint to an opportunity for manufacturers, who have learned to measure the potentialities of the method. This will be illustrated in the second part of this chapter by several case studies from research projects that are underway or have recently been completed.

It has to be said that there are two main types of LCA: attributional LCA which assesses the global impact share of a product's life cycle, and consequential LCA, which evaluates the consequential impact of a decision (usually represented by changes in demand for a product). In a recent review paper, Thomas Schaubroeck (2023) discussed the relevance of attributional and consequential LCA for society and decision support. As mentioned in his conclusions, even if the consequential approach is currently the preferred method from an ideological viewpoint, from a pragmatic perspective, the attributional approach is still often the main recommended method in standards for science-based targets, and the one used in the case studies of this chapter.

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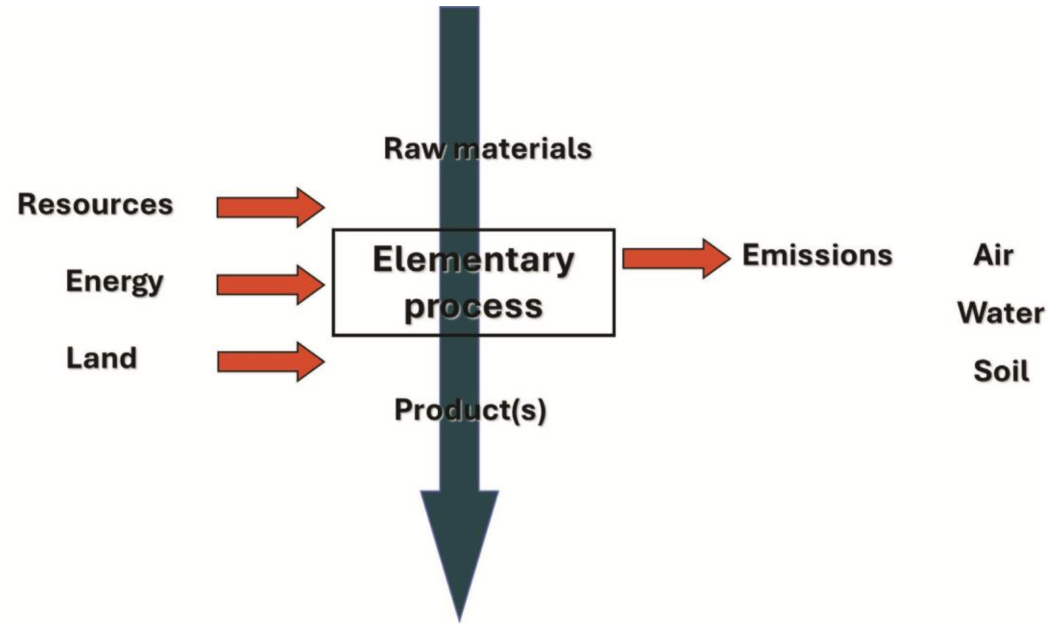
11.2 Four stages for a LCA

According to ISO standards, there are four stages to carry out a LCA. These are: describing the goal and scope of the study, collecting the data for the inventory, assessing the impacts, and finally interpreting the results. All these stages are interdependent, and the process is iterative: changes can be made over time to ensure consistency between the different stages and to refine the results. Within the EU, there are also recommendations in order to harmonize the way of making a LCA. The first reference document was the ILCD Handbook (Wolf et al., 2012) published in 2012 by the Joint Research Center. More recently extended guidelines have been released as outputs of the PEF initiative that started in 2011 and was already mentioned (European Commission. Joint Research Centre, 2022).

Goal and scope

Any LCA study has to specify what the goal and scope are. The goal must indicate the intended application of the LCA, the reasons for carrying out the study and the target audience. The goal of the study must therefore be precisely defined and not be limited to simply wanting to know the strengths or weaknesses of a product. Precision is necessary to make the right methodological choices later on. The goal can be expressed by a question such as: "What are the possibilities for improvement in the life cycle of the product under study?" or "Which life cycle activities contribute most to the environmental impact of the product under study?" The goal can also simply be to realize a LCA in view of environmental communication.

Figure 11.2 *Life cycle inventory principle.*



The scope of the study must clearly describe elements such as the product system to be studied, the function, the functional unit, the system boundaries, the allocation rules, the methodology, and so on. The function is linked to the performance characteristics of the system under study. The functional unit is defined as the reference unit to which the flows included in the processes must be related. It is used to standardize calculations and material and energy balances. The so-called reference flows are the quantities of materials or energy that are needed to fulfill the functional unit (in regard with potential losses, lifetime, reuse, etc.). The boundaries of the system determine the elementary processes that are considered in the study. An elementary process can be seen as a stage in the life cycle obtained by its decomposition in small building blocks for which the input and output data can be directly quantified.

Life cycle inventory

Once the goal and scope of the study have been defined, the boundaries of the system and the data to be collected are known. This is the most time-consuming stage, as it requires the collection of all the environmentally relevant flows involved in the elementary processes of the system under study (Fig. 11.2). The inventory therefore

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consists of carrying out material and energy balances of all the incoming and outgoing flows for each elementary process, as well as land use.

The most common data sources to compile the inventory are direct observations, LCA databases, theoretical models and experts' opinion. Direct measurements are called primary data and represent specific activities or set of activities. All other types of sources provide secondary data and are often referred to as generic data. Being closer to real conditions, primary data are preferred to build the inventory, especially for describing the foreground processes, or the portion of the system typical of the product described. Generic databases (secondary data) are a comprehensive collection of verified life cycle inventory (LCI) datasets of processes and products. They are mostly used to model background processes, that are the portion of the system that reflects industrial economy as a whole, such as energy and fuels supply, and is not under the direct control of the product manufacturer. In practice commercial (Ecoinvent, Gabi, …) or freely available (Agribalyse) databases can be found.

It should be noted that the situation becomes more complex when a process results in several co-products, i.e., multi-functional systems. Allocation rules must be used to share the inventory, and associated impacts, between the products. ISO 14044 defines a decision hierarchy, in descending order being subdivision and system expansion, allocation based on relevant underlying physical relationships (mass and energy), allocation based on other relationships (e.g., economic), or for chemicals based on stoichiometric distribution of elements.

Regarding the inventory, some hypotheses have also to be made in the case of recycling processes. Should the associated burdens or benefits be attributed to the provider of the endof-life product, or to the user of recycled materials, or shared between both? There is no single answer (Allacker et al., 2017) as it can depend on the PCR or standards that are to be followed. Also known as the 100:0 approach, the recycled content, or cut-off, approach states that the primary user carries the environmental impacts of the production process (following the "polluter pays" principle). If the material is then recycled at the end-of-life, the primary user does not receive the environmental benefit for the provision of these recycled materials to the secondary user. Instead, the secondary user receives the material without the environmental burdens of its primary production process and carries only the environmental impacts of the recycling processes. In the avoided burden approach, also known as the 0:100 approach, it is assumed that the recycled material (secondary material) replaces a quantity of virgin material in the secondary life cycle. Within this approach, the benefits of recycling are credited to the manufacturing of the primary product. Following the PEF and OEF framework (European Commission. Joint Research Centre, 2022), the Circular Footprint Formula (CFF) is the method to be used to address reused and recycled content, as well as diverse end-of-life scenarios in LCA. Depending on the supply and demand of the recycled material, the burdens of recycling are divided between the primary system and secondary system. The CFF includes the so-called "A factor," where an A factor of 1 would reflect the 100:0 approach (cut off), and an A factor of 0 would reflect the 0:100 approach (avoided burden). For PEF studies, the A factor shall always fall within the range of 0.2–0.8. A value of 0.2 indicates a low supply of recyclable materials and high market demand, while 0.8 indicates a high supply of recyclable materials and a low market demand. Specific values are provided for PEF studies, but if none are available, a default value of 0.5 is used.

Table 11.1: *Impact categories in the EF method.*

Category	Unit
Acidification	mol H^+ eq
Climate change	kg CO_2 eq
Ecotoxicity, freshwater	CTUe
Particulate matter	disease inc.
Eutrophication, marine	kg N eq
Eutrophication, freshwater	kg P eq
Eutrophication, terrestrial	mol N eq
Human toxicity, cancer	CTUh
Human toxicity, non-cancer	CTUh
Ionizing radiation	kBq U_{-235} eq
Land use	Pt
Ozone depletion	kg CFC_{11} eq
Photochemical ozone formation	kg NMVOC eq
Resource use, fossils	MJ
Resource use, minerals and metals	kg Sb eq
Water use	m^3 depriv.

From European Commission. Joint Research Centre (2022).

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In the EN15804+A2 (European Standard, 2020) relative to building materials, a cut-off approach has to be applied, meaning that if a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials, but these latter are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. One complex issue is the position of the cut-off point. Following EN15804+A2 (European Standard, 2020), the cut-off point between the primary and secondary system comes when the product reaches its end-of-waste state, i.e., when there is a market for the recovered product and when the recovered product fulfills technical and legislative requirements applicable to the product.

Life cycle impact assessment

Once the material and energy balance data has been obtained for each sub-process of the system under study, the environmental impact can be calculated. This involves describing the environmental consequences of the emissions and consumption obtained through the inventory. The ISO standards impose mandatory steps during this phase. These are the definition of impact categories, classification and characterization, which enables the environmental impact of each category to be calculated. Table 11.1 shows, e.g., the 16 impact categories evaluated by the EF method. Concerning impact categories, a distinction exists between midpoint and endpoint categories. Midpoint categories, also called problem oriented, focus on single environmental problems (e.g., climate change, acidification, and water use) while endpoint categories, or damage oriented, aggregate several the environmental impacts at a higher level, i.e., at the end of the cause-effect chain (e.g., human health, biodiversity, and resource scarcity) (Table 11.1).

Classification involves linking the substances emitted or consumed to environmental impacts (for example, all GHGs will be assigned to the climate change category). This step is now automatically realized in the background by LCA softwares based on the information included in databases or in the primary inventory data. Characterization is the first stage in obtaining a quantitative response. Impacts are calculated for each category using equivalent factors, known as characterization factors, defined when the cause-effect chains are modelled. For example, for climate change, the 100-year Global

Warming Potential values provided by the IPCC are used to obtain a response in kg of CO_2 equivalent, considering all the GHGs emitted.

There exist several impact assessment methods allowing to convert inventory data into environmental impacts. These impact assessment methods may differ by the geographical scope, the considered impact categories, the characterization factors used for a dedicated impact, the type of impacts (midpoint only, endpoint only, or both), … One can cite CML, ReCiPe, ILCD, Traci, … The EF one being now recommended at the EU level (European Commission. Joint Research Centre, 2022).

Optional steps including normalization, grouping and weighting steps can also be carried out after characterization. Normalization is the calculation of the relative magnitude of the category indicator results by using a reference system. One of the most used reference values is the per capita impacts of an average person in a given area over one year. Normalized results are dimensionless and allow to understand better which impact categories are more critical, showing the relative hierarchy between the categories. Weighting is the process of converting normalized results of the different impact categories into scores that can be aggregated into a single score. The weighing factors depend on the impact assessment methodology used. In the EF method, *they expressed relative importance of the impact categories, based on input from environmental experts and stakeholders* (European Commission. Joint Research Centre, 2018).

Conclusions and recommendations

ISO 14040 (ISO, 2006a) defines life cycle interpretation as the phase during which the results obtained from the inventory or impact analysis are combined consistently with the purpose and scope of the study to obtain adequate and relevant conclusions and recommendations. Three sub-steps are considered in the life cycle interpretation, namely the identification of significant issues, the verification of the study through completeness, consistency, sensitivity checks and uncertainty analyses, and finally the formulation of conclusions, limitations and recommendations related to the study.

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11.3 Case studies

In recent years, numerous research projects aimed at recycling various types of products have been launched, with a view to achieving circularity. LCA is generally used to support developments in an eco-design perspective and to quantify the associated environmental benefits at the end of the project. The next part of this chapter will present some results illustrating the interest of using LCA in this context.

The construction sector is particularly well represented. Indeed, at European level, it produces 36% (European Commission. Statistical Office of the European Union, 2020) of all waste generated. At the same time, and in line with the objectives of the European Green Deal (European Commission, 2019), huge efforts are made to reduce the environmental impacts, namely the GHG emissions associated to the use of cement and by extension concrete. After water, concrete is the most widely used substance on the planet (Gagg, 2014), with an average of 4 tons produced per inhabitant in 2020. This demand is constantly increasing with the development of our modern societies. Although its economic cost is relatively moderate, its environmental cost is substantial. Cement, used as a hydraulic binder in the production of concrete, is responsible for around 8% of global GHG emissions. In Europe, it is estimated that around 898 kg of CO_2 (equivalent) are emitted per ton of Portland cement produced (CEMBUREAU, 2015). These emissions come, on the one hand, from the decarbonation of limestone materials and, on the other, from the energy consumption required by kilns to reach clinkerization temperature. It takes 3 to 4 GJ of thermal energy to produce one ton of clinker, making the cement industry a major consumer of fossil resources despite the growing use of alternative fuels. The manufacture of cement and concrete also requires the consumption of non-renewable natural mineral resources, such as limestone, gravel and sand. It thus contributes to the depletion of these resources, and their the preservation is one of humanity's major challenges if we are to guarantee acceptable living conditions for future generations (Chen et al., 2010; Guo et al., 2018). This is why new types of cement including secondary materials (mostly waste such as ashes and blast furnace slags) are developed, and at the same time recycled concrete aggregates are used in new concrete formulations in substitution of natural aggregates (NAs) (Colangelo et al., 2020).

Concerning cements, there are different types, designated CEM I to CEM V, with a smaller or larger content of Portland cement and blast furnace slag, fly ash, or other secondary materials, as described in Table 11.2.

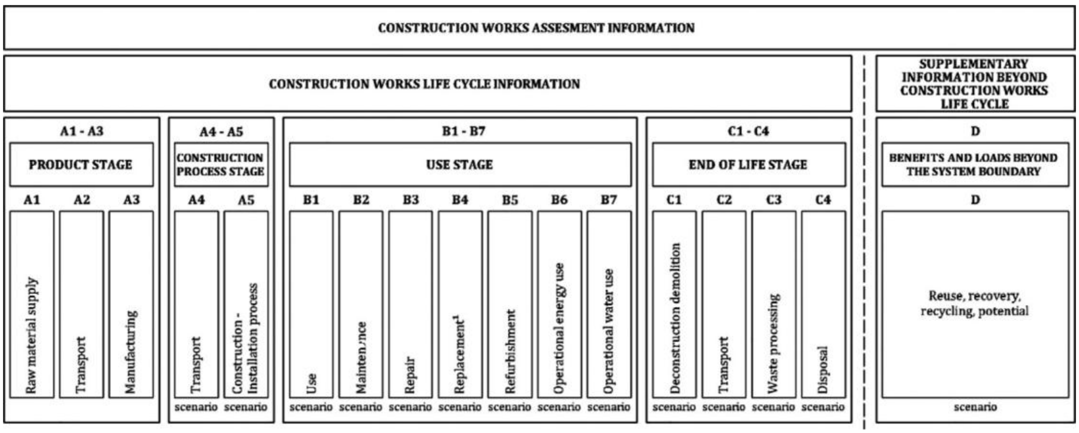
For confidentially reasons, formulations of products, as well of processes details are not provided in this chapter. More details about the inventories and the modelling can be obtained on request.

Table 11.2: *Categories of cement (European Standard, 2011).*

CEM I	**Portland cement with up to 5% other substances.**
CEM II	Portland-composite cement with a single secondary major constituent (e.g., shale, fly ash, blast furnace slag, pozzolana) and between 65% to 94% Portland cement.
CEM III	Blast furnace/Portland cement mixture in 3 classes: A, B, and C; the Portland content is, respectively, in the following ranges: 35%–64%, 20%–34%, 5%–19%.
CEM IV	Pozzolanic cements (45% to 89% Portland cement)
CEM V	Composite cements, with mixtures of Portland cement, blast furnace slag and pozzolans, in two classes: A and B. The Portland content is respectively in the following ranges: 40%–64%, 20%–39%.

From European Standard (2011).

Figure 11.3*. Life cycle steps following EN15804+A2.*



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11.3.1 VALDEM project

The VALDEM Interreg France-Wallonie-Vlaanderen project ran from 2016 to 2020. It brought together seven main partners[4] and aimed to develop integrated solutions for recovering material flows from demolition. During the project, a LCA study was carried out on recycling following the demolition of a Leroy Merlin shop in Douai (France). Two streams in particular were recovered: the 0–4 mm fraction and the 4–20 mm fraction. The 0–4 mm fraction was used mainly by Wasterial (France) to make slabs, by mixing it with a binder. A "cradle to gate" LCA (A1–A3) according to EN 15804+A1 (European Standard, 2012) was performed (Fig. 11.3). The first version of EN 15804 valid at the time of project required a specific version of the CML IA baseline method as impact assessment methodology.

The functional unit is the production of 1 m2 of tiles. The boundaries of the system include:

- Demolition (Douai and France) and on-site excavation of the slab, - crushing of concrete into recycled aggregate (RA) and their sieving (on site)
- Transporting the fine fraction of RA to Recynov's storage center in Santes, France, and their transport of RA to the Wasterial production site in Roubaix, France
- Direct transport of the large fraction (4-20 mm) of RA to the Eqiom concrete plants (Wambrechie to be reused in the new Leroy Merlin building in Tourcoing, and Roost for other uses)
- The binder and its transport from Italy (Milan region)
- Manufacture of the slabs

The reference year was 2019. The database used was Ecoinvent 3.5 (Wernet et al., 2016). Calculations were performed using Simapro 9.0.0.48 software (Pré-Sustainability, NL). The results are compared with the environmental impacts of NAs (gravel or sand: production

[4] NEO-ECO Recycling, CD2E, AMINES, INISMa, IMT Nord Europe, CD2E and ULiège.

and transport to the site of use, either Eqion concrete plant or distribution site of Recynov), and for the Wasterial tiles with those obtained for a conventional ceramic tile produced in Italy through an adaptation of a process of ecoivent, with the same function.

The 4–20 mm faction was partly incorporated into the concrete slabs used to build the chain's new shop in Tourcoing (France). The LCA study compared the use of these RAs with NAs for different locations of the concrete plant for the 4–20 mm fraction, or the distribution site for the fine fraction (and therefore different distances between the site and secondary use): Wambrechies and Roost (concrete plants), or Santes (Recynov distribution site). The functional unit was the production and transport of 1 ton of RA, and the comparison with the production and transport of NA. The NA traditionally used in the concrete plant comes from a Belgian quarry (primary data from concrete producer). The results show an environmental gain for the various indicators assessed, as illustrated in Fig. 11.4. The solid bars correspond to NAs, and the textured bars to RAs. The colors correspond to the different locations, according to their distance from the place of use. This highlights the importance of limiting the transportation distance of RA to keep an interest of using them from a climate change point of view. In this study, the gain between RA and NA corresponds to a distance of about 10 km. It means that there is some environmental benefit of using RA even if the "source" (the demolition site) is 10 km further than the quarry of NA.

Fig. 11.5 shows a characterization graph for seven indicators in the case of the use of the fine RA (0–4 mm) as filler in a composite tile. For each category, the scenario with the highest impact is set to 100% and the other scenario is represented in relative terms. The LCA results show that the environmental impact of the Wasterial slabs is lower overall than that of ceramic slabs that could be used for the same purpose. In particular, the climate change indicator is reduced by almost 50% (Table 11.3).

Figure 11.4. *Comparison of the environmental impact associated with the use of 1 tonne of natural aggregates (NA) or recycled aggregates (RA) - CML-IA 3.05 characterization.*

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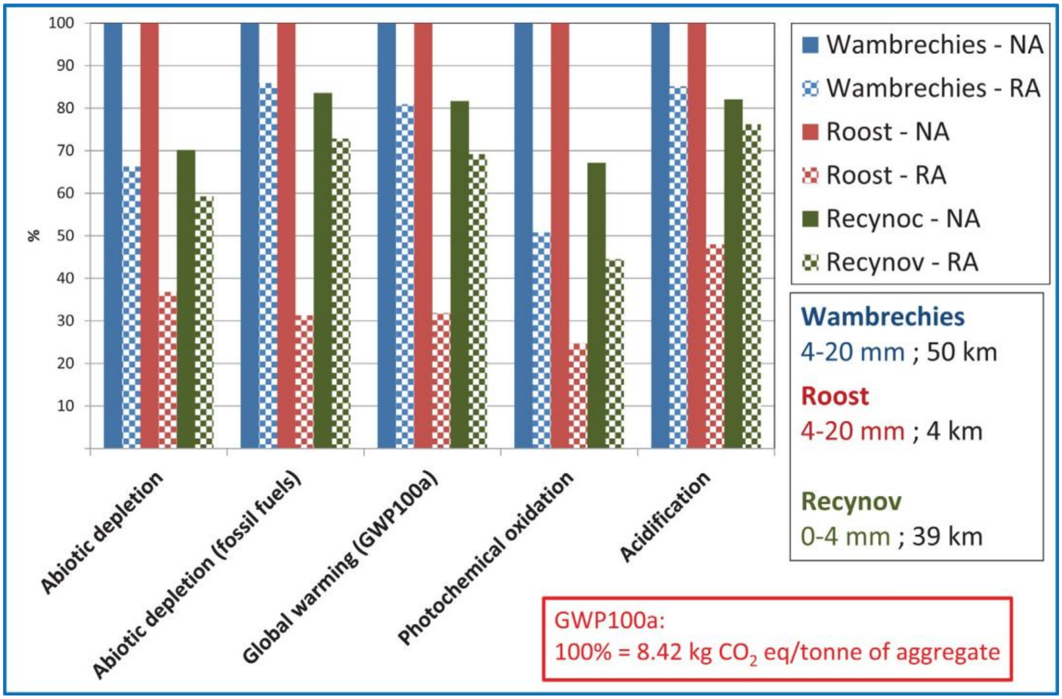

11.3.2 COSMOCEM project

The COSMOCEM project, funded by the Wallon Region through the GreenWin competitiveness cluster, is a 4-year project (2019–2024) involving seven partners.[5] Its aim is to "create reactive mineral additions for hydraulic binders by transforming Walloon waste flows that are little or not at all recycled using a new ecological activation process." The aim is to reduce the environmental impact of cement, a sector under particular pressure given the significant GHG emissions produced during clinker production.

The LCA results are presented in Fig. 11.6 as a single score according to EN15804+A2/normalization and weighting EF3.0, integrating all the environmental indicators. This score provides a summary of the effects of all the impact categories,

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[5] CBR, Duferco, SBMI, Tradecowall, CRIC, CTP, Lessine, and ULiège.

and a more global view than climate change only. The study was done with a functional unit corresponding to 1 ton of activated alternative materials (AMs), compared to pure clincker (used in CEM I) and to ground granulated blast furnace slags (GGBFS) (used in CEM III).

Figure 11.5. *Comparison of the impact of 1 m² of Wasterial tiles and Italian ceramic tiles - CML-IA 3.05 characterization.*

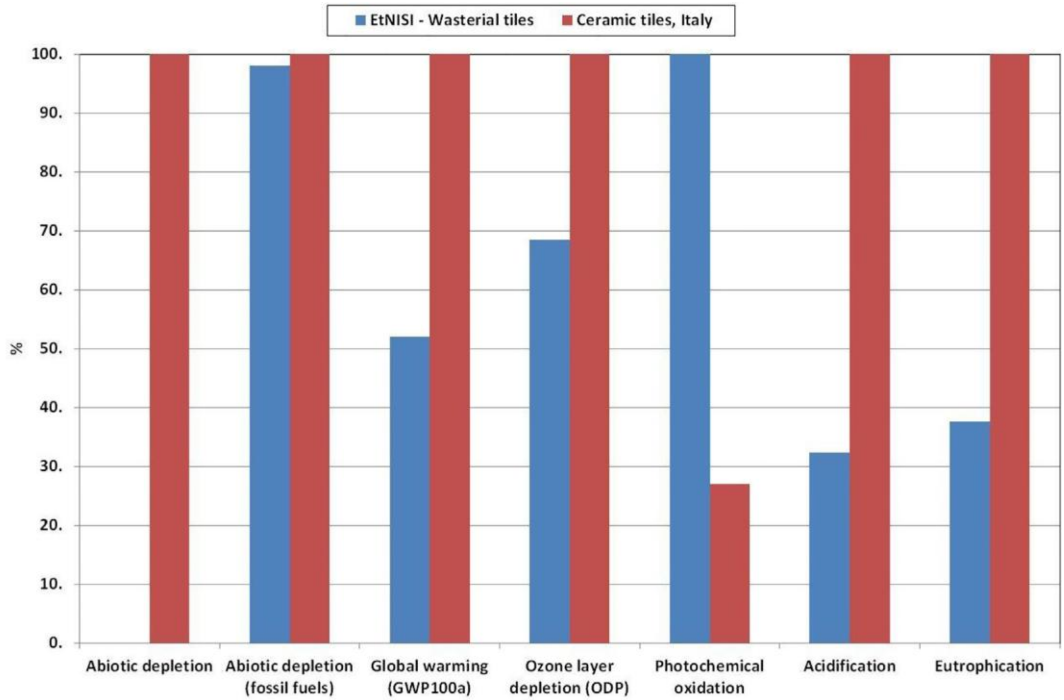

Table 11.3: *Comparison of the impact of 1 m² of Wasterial tiles and Italian ceramic tiles CML-IA 3.05 characterization.*

Impact category	Unit	Wasterial béton - 1 FU = 1 m²	Italian ceramic tile
Abiotic depletion	kg Sb eq	3.56E-07	8.50E-04
Abiotic depletion (fossil fuels)	MJ	183.14	186.80
Global warming (GWP100a)	kg CO_2 eq	6.93	13.30
Ozone layer depletion (ODP)	kg CFC-11 eq	1.16E-06	1.69E-06
Photochemical oxidation	kg C_2H_4 eq	1.26E-02	3.40E-03

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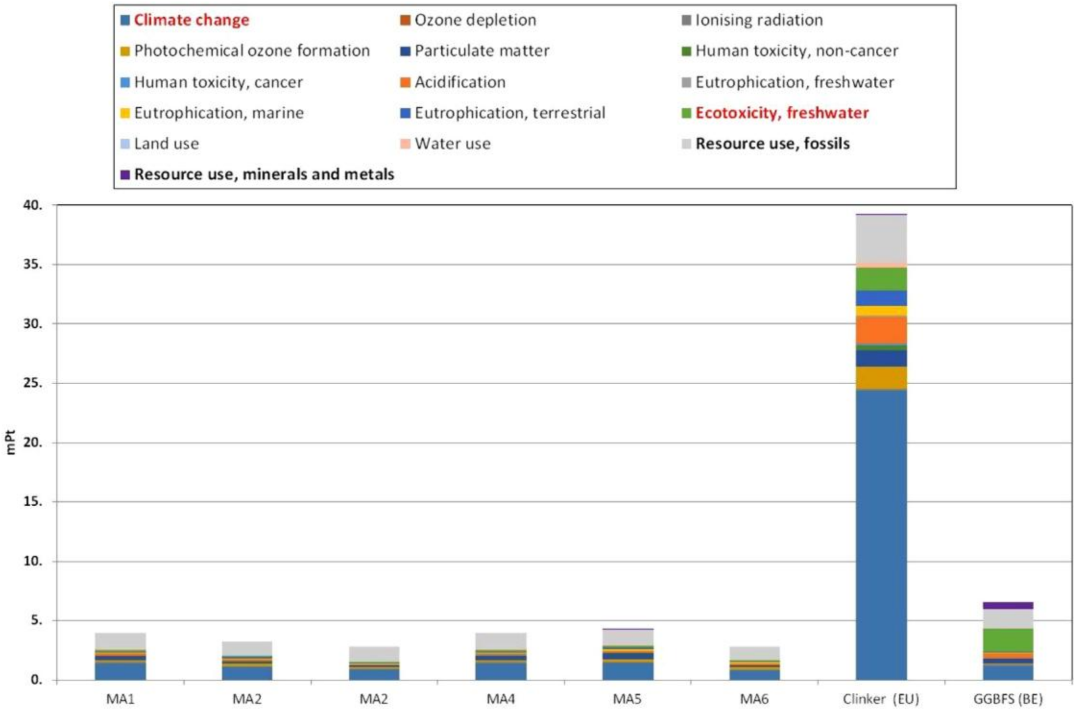
Acidification	kg SO_2 eq	2.37E-02	7.32E-02
Eutrophication	kg PO_4^{3-} eq	2.52E-03	6.68E-03

Figure 11.6. *Single score for various alternative materials (AM), compared with clinker and ground granulated blast furnace slag (GGBFS, ecoinvent process adapted for BE) - EN15804+A2 method / EF 3.0 normalization and weighting set.*



They show that the various AMs tested (called AM for the sake of confidentiality), including the steps involved in their preparation and activation, have a much lower environmental impact than clinker or (ground granulated) blast-furnace slag (GGBFS), the secondary materials already widely used in cement formulation.

For the climate change category, the value of the impact is respectively: average AM = 44.72 kg CO_2 eq/ton (min = 30.98 - max = 54.84), GGBFS = 45.29 kg CO_2 eq/ton, Clinker =

937.13 kg CO_2 eq/ton. The difference is not significant between the AM and the GGBFS but they both have a more than 20 times lower impact than the clinker.

The single score results are: average AM = 3.53 mPt/ton (min = 2.80 - max = 4.29), GGBFS = 6.51 mPt/ton, and Clinker = 39.31 mPt/ton. The AM single score is about 2 times lower than the one of the GGBFS, and more than 10 times lower than the clinker. It means that even if for the climate change category the AM and the GGBFS are similar, the last ones have a larger impact in other categories (in particular in freshwater ecotoxicity).

This example shows how important it is not to focus solely on climate change, but to include the other categories in the reflection, in order to avoid transferring the impact.

The challenge lies in the possible rates of incorporation and the final gains that will be obtained, for equivalent technical performance. Based on these encouraging results, a pilot scale production unit including the activation of AMs is currently under test phase.

11.3.3 MonoCrete project

The MonoCrete project [2], also funded by the Wallon Region through the GreenWin competitiveness cluster, was a 3-year project (2021–2024) involving five partners[6]. This project aimed to develop innovative solutions to reduce the environmental impact of road concrete. These solutions were threefold: (1) the development of a new CEM V cement incorporating fly ashes, (2) the formulation of road concrete based on this new cement and recycled concrete gravel from construction and demolition waste, and (3) the application of concrete in a thick single layer. Firstly, the incorporation of fly ash into cement is intended to replace clinker while reducing the use of blast-furnace slag, reserves of which are being depleted locally because of the reduction in metallurgical production. Secondly, the use of recycled concrete aggregate will both reduce the exploitation of natural gravel, conventionally used to make road concrete, and limit the environmental impact of managing this concrete waste. Finally, the road's thick single-layer design will increase its lifespan and facilitate the deconstruction and recycling phase at the end of its life. Results illustrated here focus on the development of new CEM V/A cements, in comparison CEM I and CEM III/A.

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[6] Eloy, Holcim, CRR, CRIC-OCCN, and ULiège.

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The cements are produced at the Holcim cement plant in Obourg (Belgium). CEM III/A incorporates granulated blast-furnace slag, and CEM V/A incorporates both "historic" (wet) fly ash and "fresh" (dry) fly ash from Walloon deposits. The motivation to use historic stocks of flashes comes from an expected reduction of fresh fly ashes on the market with the closure of coal power plants at midterm.[7] These components are transported by truck to the cement plant. Cement is produced by co-grinding with clinker (produced on the same site, from chalk) in ball mills.

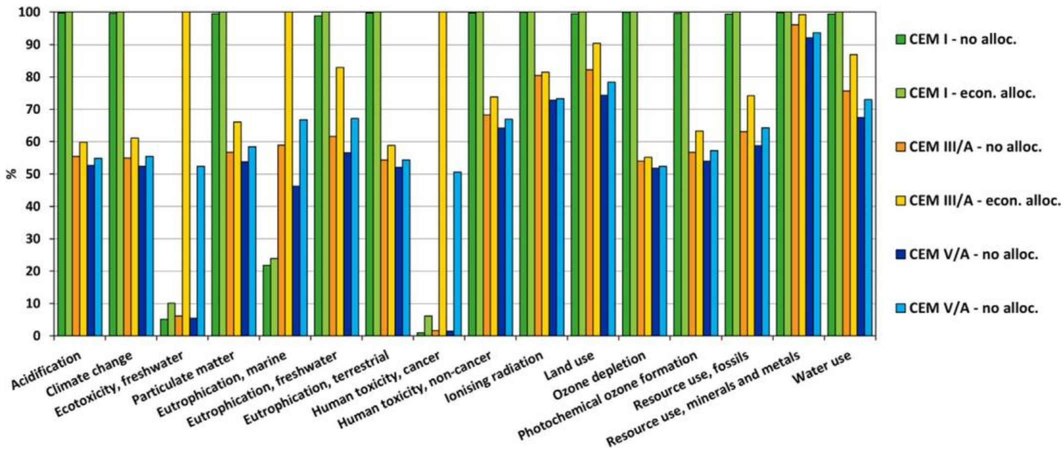
"Fresh" fly ash, which does not require drying or grinding, is injected directly into the separator. On the other hand, because of the presence of slag in Walloon "historic" fly ash, it has to pass through the cement mill. As it was not possible to set up a drying process for wet ashes as part of the project, they were mixed in equal proportions with "fresh" (dry) ash in order to limit the overall moisture content of these additions.

The functional unit was the production, from cradle to gate, of 1 ton of cement CEM I, CEM III/A, and CEM V/A, and their comparison. Simapro version 9.6 (Pré Consultants, 2022) associated to ecoinvent version 3.10 was used with the EN 15804+A2 (adapted) V1.00/EF 3.1 LCIA method.

Results presented in Fig. 11.7 show the environmental interest of using CEM III/a and CEM V/a as their impacts are significantly lower that CEM I. However, results obtained for CEM III/a and CEM V/a cannot be considered as different (considering uncertainties in the background data and characterization factors).

Figure 11.7. *Comparison of the impact of the production of 1 ton of different types of cement, with and without economic allocation – EN 15804 + A2 (adapted) V1.00 / EF 3.1 LCIA method – Characterization graph.*

[7] However, the conflict in Ukraine and its impact on energy prices has led to a reverse trend and increased use of coal/lignite in various European countries.



In the cut-off approach, both fly ashes and blast furnace slags are considered free of burdens, only their treatment before their addition are considered. However, in France, negotiations between the steel and the cement sectors have resulted in an economic allocation of 1.4% of the impact of cast iron production, to be attributed to the slags (AFNOR editions, 2022). To do this, data from the ecoinvent inventory "Pig iron {RER}| pig iron production | Cut-off, U" was used to calculate the allocation of impacts. The quantity of slag generated during pig iron production is estimated at 279 kg of slag per ton of pig iron, to which 1.4% of the impacts have been allocated. These impacts were then added to the impacts of the slag treatments (drying and co-grinding). Fig. 11.7 also shows the effect of applying this economic allocation when performing the LCA. The results obtained with economic allocation are always higher than their equivalent without economic allocation. In particular, when focusing on climate change, the impact remains lower for CEM III/A and CEM V/A in comparison to with CEM I, confirming the interest of substituting clinker by secondary materials. However, looking at other indicators, such as human toxicity – cancer, one can observed that the results are much higher when applying economic allocation. This is illustrated by single scores presented in Fig. 11.8. When considering all impact categories with their respective normalization and weighting factors, it appears that CEM III/A cement become less favorable for the environment than CEM I when economic allocation is applied. These results depend on the level of clinker substitution by slags, and the background modelling of pig iron and must be considered as an example. This highlights again the importance of keeping a holistic approach.

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Figure 11.8. *Comparison of the impact of the production of 1 ton of different types of cement, with and without economic allocation – EN 15804 + A2 (adapted) V1.00 / EF 3.1 LCIA method – Single score.*

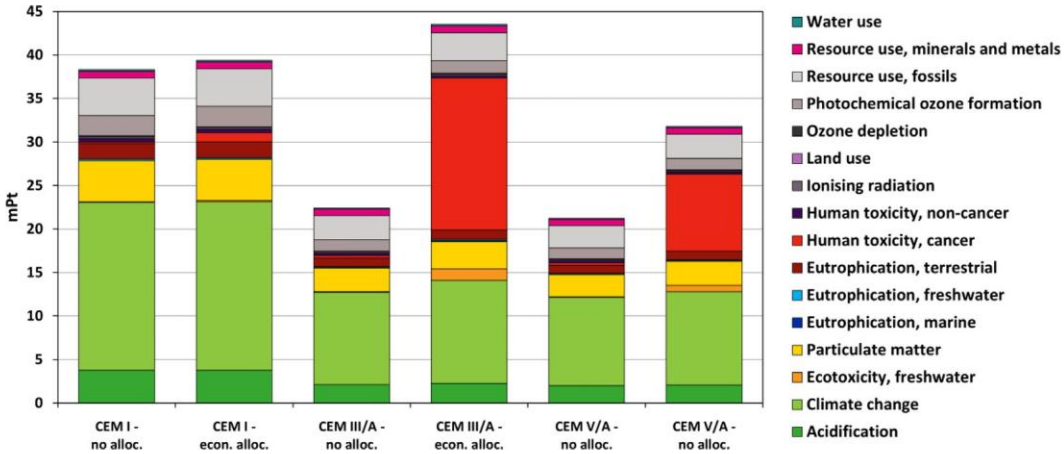
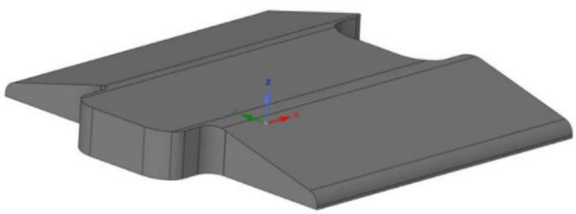


Figure 11.9. *Digital prototype of the retarder modelled by A-csys (credit L. Renson).*



11.3.4 AD-CORSSI project

The AD-CORSSI project aims to improve the thermosetting plastics recycling process by developing a specific application, i.e., the production of an industrial speed bump shown in Fig. 11.9. It brings together five partners[8] and started in 2021 for a period of 3 years.

[8] Reprocover, A-Csys, GDTech, Sirris, and ULiège.

The project has also been funded by the Walloon region through GreenWin competitiveness cluster.

The functional unit is defined as the production of a 25 kg speed bump. On a mass basis, the speed bump includes 80% of recycled plastics and 20% of recycled glass fibers. Three types of plastic are considered:

- Kunstof Recycling Nederland polypropylene (PP KRN)
- Off-white polypropylene (color selection close to white)
- Use of mixed polyethylene (PE mix), made up of over 70% PE.

The study is made from cradle to factory gate. Following the EN 15804+A2, only the treatments applied to the recycled materials are considered. The system boundaries include these treatments (washing, grinding, and sieving), all the transportation (considering supplier locations), heating, mixing, and pressing in the mold. Some developments are still ongoing, but first results shown in Fig. 11.10 indicate that using PE mix or PP KRN is more interesting from an environmental point of view that using off-white PP. Moreover, the environmental impacts are far below the conventional concrete speed bumps.

Figure 11.10. *Comparison of the impact of the production of 1 speed bump for three types of recycled plastics – EF3.1 (adapted) V1.00 - Characterization.*

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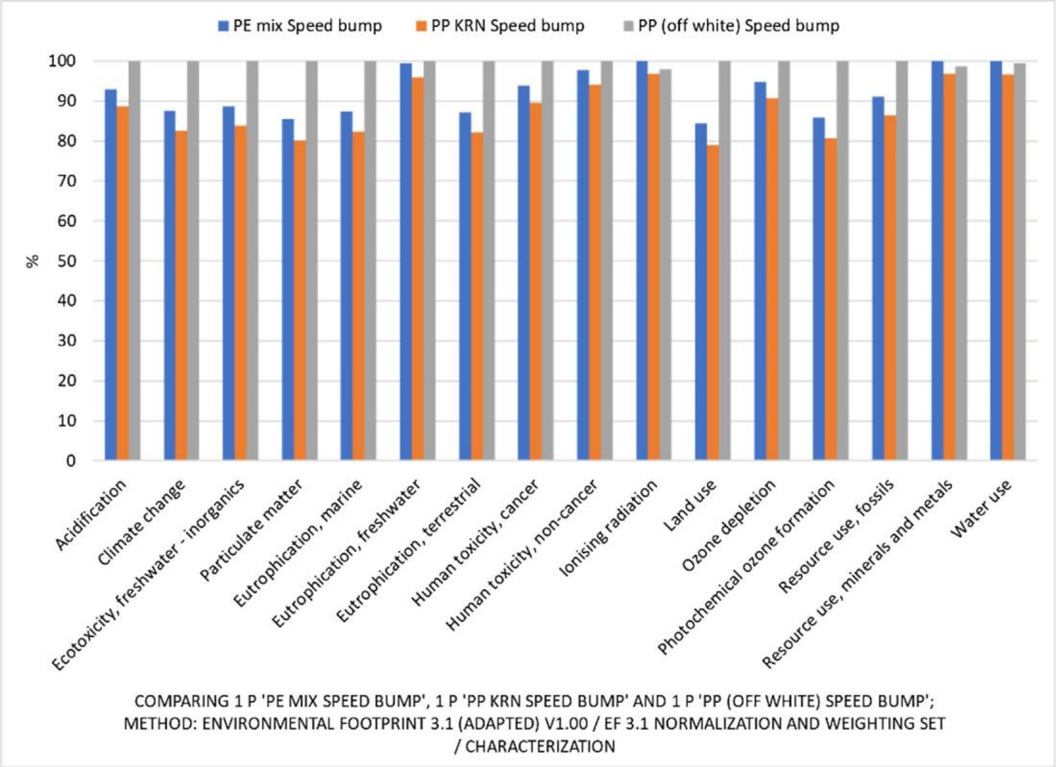

11.4 Conclusions

LCA has become the must-have method for assessing the environmental impact of a product or process. Consequently, LCA is increasingly used in research and development projects, with a view to eco-design. The case studies presented in this chapter illustrate some strengths, among others:

- LCA results can highlight alternatives to be preferred
- LCA can detect any transfer of impacts
- LCA can draw attention to the key parameters for ensuring that the implementation of a recycling process remains worthwhile

- With deeper analysis, LCA can be used to suggest changes to production methods, reagents, energy carriers, supplier locations, transportation methods

However, this methodology remains complex to implement and requires a certain level of knowledge of impact assessment tools and methodologies. There is still a risk of misinterpretation and shortcuts, and a critical eye is needed when LCA results are presented. This is why training remains a key issue in this field, both in student courses and in continuing education for companies.

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