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**Life Cycle Analysis and Life Cycle Impact
Assessment methodologies: A state of the art**

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Glossary

LCA	Life Cycle Analysis, or can be called also Life Cycle Assessment.
LCIA methodology	Life Cycle Impact Assessment methodologies, or can be called also impact assessment methodologies.
LCI results	Life Cycle Inventory results, or can be called also inventory results.
Impact categories (midpoint categories)	The environmental categories through which a substance emissions and releases to the environment are modelled up to the changes in the natural environmental aspects.
Damage categories (endpoint categories)	The environmental categories through which a substance emissions and releases to the environment are modelled up to the damage effect on the environmental aspects. Damage categories can be called impact categories as well, depending on the required study. However, the terminologies of impact categories and damage categories have to be clearly defined within a specific study.
Areas of protection (AoP)	The areas of environment which are supposed to be protected against the harmful emissions and releases. In some methodologies they are considered the same as the endpoint damage categories. However, a distinction can be made between endpoint damage categories and Areas of Protection, that is, an AoP is a type of endpoints which represents a social value and concern, such as: human health, natural environment, natural resources, and man-made environment; While an endpoint damage category is a variable of that social concern, such that, they are considered as a quantifiable representation of the AoP.
Midpoint modelling	A technique of modelling the impact of a certain substance on the environment up to the changes in the natural environmental aspects.

Endpoint modelling	A technique of modelling the impact of a certain substance on the environment up to the damage effect on the environmental aspects.
ISO	International Organization for Standardization.
Characterization	A step within the Impact Assessment phase of an LCA study. The relative contribution of each input and output within the product system is assigned to impact categories and converted into indicators that represent the corresponding potential impacts on the environment. The results obtained in the classification phase are multiplied by the characterization factors of each substance within each impact category.
Normalization	A step that comes after the characterization step within an Impact Assessment phase of an LCA study. The sum of each category indicator result is divided by a reference value. Thus, normalization is expressed in a way that allows the impact indicators to be compared to each other.
weighing	Weighting is the process of converting the results of the normalised indicators of the different impact categories using numerical factors (weighting factors) based on subjective valuations. These weighing factors are dependent on the incorporation of social, political and ethical factors. The results obtained in the normalization phase are multiplied by the weighting factors of each substance within each impact category. The main three steps of the Impact Assessment (Characterization, normalization and weighting) affect the regional validity of each methodology, or in another words, the spatial differentiation issue.

Spatial differentiation	<p>Spatial differentiation means that the different models and criteria used in the impact assessment step for characterization, normalization and weighting within each LCIA methodology are dependent on regions. For this reason, some LCIA methodologies have more than one version that considers spatial differentiation (such as the EDIP 2003 methodology). Spatial differentiation can be done on the level of continents and countries. In an LCIA methodology, when the environmental models are developed according to a certain region, then the regional validity of the methodology with its impact and damage categories becomes within the corresponding region that the methodology was developed for. However, some categories are of a global concern, not only of a regional concern, such as ozone layer depletion, climate change and resources.</p>
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Abstract

Life Cycle Analysis (LCA) is a comprehensive method for assessing the environmental impact of a product or an activity over its entire life cycle. The purpose of conducting LCA studies varies from one application to another. Different applications use LCA for different purposes. In general, the main aim of using LCA is to reduce the environmental impact of products through guiding the decision making process towards more sustainable solutions. The most critical phase in an LCA study is the Life Cycle Impact Assessment (LCIA) where the Life Cycle Inventory (LCI) results of the considered substances related to the study of a certain system are transformed into understandable impact categories that represent the impact on the environment. Several LCIA methodologies have been developed with different approaches towards dealing with modeling the emissions effect on the environment. In this research work, a general structure clarifying the steps that shall be followed in order to conduct an LCA study effectively is presented. These steps are based on the ISO 14040 standard framework. In addition, a survey is done on the most widely used LCIA methodologies. Recommendations about possible developments and suggestions for further research work regarding the use of LCA and LCIA methodologies are discussed as well.

Key words: Life Cycle Analysis (LCA), Life Cycle Impact Assessment (LCIA) methodologies, environmental impact, impact categories.

1. Introduction

The energy consumption world wide by different applications is growing rapidly, which consequently results in generation of significant quantities of wastes and emissions to the environment. Besides, it is expected that the world energy demand will increase by up to 71% between 2003 and 2030. Therefore, it was essential to take vital steps by the governmental authorities around the world to take the initiative and apply the necessary practices and regulations to reduce the energy consumption and therefore the impact on the environment. For example, at the present time, the energy performance of buildings directive includes environmental information about reduction of CO₂ emissions, and other regulations concerning the necessity to reduce the energy consumption, and concentrate on renewable energy resources as well as the efficient management of the demand side [1, 2].

Within the life cycle of a certain product, there is a consecutive order of life cycle stages, generally in most cases, these life cycle stages (phases) can be divided into three: The manufacturing phase (extraction of raw materials, handling and processing), the operation phase (normal use and utilization of product according to its intended purpose), and the disposal phase (end of life of product by final disposal or recycling). Each one of these phases consumes a certain amount of energy, minerals, water, etc.that subsequently induces a harmful impact on the environment. This impact on the environment can mainly affect three areas of protection: natural environment (Eco system), human health and natural resources [3].

For many years, reducing the environmental impacts focused on the treatment of wastes during the production processes in order to reduce the pollution to water, land and air.

However, this does not necessarily take into consideration the full potential negative impact on the environment that is associated with the Eco system, human health and the consumption of materials and resources. Besides, it does not account for the shifting of burdens, which means that reducing the impact in a certain life cycle stage can create an increase in the impact in another corresponding life cycle stage. So, solutions may not be optimized enough and may even be counter productive leading to opposite results [4].

Therefore, from the need to reduce the energy consumption and the impact on the environment throughout all the life cycle stages of products, and from the need to avoid the shifting of burdens, the concepts of Life Cycle Analysis (LCA) and Life Cycle thinking (LCT) have emerged.

Many definitions can be found for LCA in literature. In the Society of Environmental Toxicology and Chemistry (SETAC) [5] LCA is defined as an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying 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 activities, encompassing extracting and processing materials; manufacturing, transporting and distribution; use, reuse, maintenance; recycling and final disposal.

Another definition for LCA can be found in ISO14040 which describes LCA as a technique for assessing the environmental aspects and potential impacts associated with a product by: compiling an inventory of relevant inputs and outputs of a product system,

evaluating the potential environmental impacts associated with those inputs and outputs and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study [6].

The term “life cycle” refers to the major activities in the course of the product’s life span, starting with the raw material extraction and manufacturing, including the use, maintenance, and ending with the final disposal.

Thus, the aim of Life Cycle Analysis studies is to identify potential improvement opportunities of products or processes from the perspective of lower environmental impacts and reduced use of resources across all life cycle stages while avoiding the shifting of burdens. This means that LCA is acting at minimising the impacts at one stage of the life cycle while helping to avoid an increment of the impact elsewhere in another stage within the life cycle. For example, saving energy during the operation phase of a product, while avoiding the increase of the embodied energy needed during the manufacturing phase to provide the corresponding energy saving.

In brief, LCA evaluates all the stages of a product life cycle regarding their impact on the environment, these stages are dependent on each other, which means that one operation leads to the next. In another words, besides helping in avoiding the shifting of burdens from one stage to another, LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle. Thus, LCA is a comprehensive tool that can help different applications to cope with the current energy and environmental performance needs.

In many applications, the framework of applying LCA is dealing with a "Cradle to Grave concept" which means that it deals with the product life cycle from the manufacturing phase (cradle) moving through the operational phase, and finally to the disposal phase (grave). There are other principles which deal with "Cradle to Cradle concept" which is a specific kind of cradle to grave assessment, where the end-of-life disposal step for a product is a recycling process or in other words, an input for a new process. This kind of approach will lead to an open loop study where the waste or disposed materials will be used as raw materials for a new process [3].

2. Objectives

In this work, the meaning of LCA and how to implement it effectively through an organized order will be discussed. To conduct an LCA study effectively, some steps shall be followed. These steps are presented according to the recommendations provided by the ISO standards [6-9]. Within this framework, four steps are incorporated and defined: Definition of goal and scope, inventory analysis, impact assessment and interpretation of results. The impact assessment step (LCIA step) is the most data intensive and complex one. It is considered as the most critical step within an LCA, as it deals with a significant amount of data that result from the LCI analysis. In addition, within the LCIA step, the LCI analysis is interpreted into understandable environmental impacts recognized within certain impact categories that affect the environment through its different areas of protection. This transformation requires modeling the impact on the environment using different approaches that are dependent on comprehensive scientific background on the environmental mechanisms related to the environmental effects that may result from a certain release or emission. For this purpose, different methodologies

have been developed to study and simplify the process of the LCIA, and this will be the second objective of this research, which is to provide an overview of these methodologies.

3. Historical background

The starting of LCA studies was in the late 1960's by the USA department of energy. The first studies were conducted to investigate life cycle aspects of products and materials focusing on issues such as energy requirements and energy efficiency, some environmental releases were quantified and measured as well [10, 11].

Another initiative was taken by the Coca Cola Company [12] in 1969. It adopted a study which examined the resource consumption and environmental releases associated with beverage containers. Meanwhile, a similar approach of creating an inventory and studying its releases was developed under the name "Eco balance" in Europe, and it is known as "Resource and Environmental Profile Analysis" (REPA) in the USA [13].

Later on, in 1979, an inventory analysis about calculating the total energy used in the production of various types of beverage containers including glass, plastic, steel, and aluminum was done, and the hand book for industrial energy analysis was published [14], This kind of studies was extended thoroughly through the 70's with the beginning of the oil crisis in Europe and USA.

By the year 1988 when the solid waste became a global problem, LCA studies were widely investigated towards issuing the environmental problems and creating an inventory for the environmental releases, until an evolution was done by the SETAC [5]

where the use of LCA was moved from establishing inventory analysis to the impact assessment step.

Afterwards, in the beginning of the 90's, the pressure from the environmental organization and the need for the LCA tool to be widely recognized and standardized lead to the establishment of LCA standards by the International Organization for Standardization (ISO). A series of standards was developed including: Life Cycle Analysis principles and framework [6], standards for goal and scope definition and inventory analysis [7], standards for impact assessment [8] and standards for interpretation [9].

In 2002, the United Nations Environment Program (UNEP) [15] joined the Society of Environmental Toxicology and Chemistry (SETAC) to launch the Life Cycle initiative which is an international partnership that aims at putting life cycle thinking into practice and improving the supporting tools through better data and indicators [16].

Similar Projects such as the CASCADE project [10] were initiated also at the same time to establish the necessary standards for Life Cycle Analysis (LCA) data and to create an initial reference database.

At the current time, LCA is used in many applications in different sectors (industrial, buildings, agriculture, etc.). Many manufacturers in different industries, such as P&G [17], use LCA as a decision support tool to compare between their products of the same category according to their emissions and releases to the environment. Other

manufacturers such as Volvo have their own internal LCA software to evaluate and guide the performance of their products towards environmental sustainability [18].

4. The Purpose of using LCA

As detailed in section 1, the main need for establishing LCA studies emerged from the need to quantify the environmental releases of a product in order to identify possible improvement opportunities with respect to lower environmental impacts and reduced consumption of resources during the whole life cycle of that product. LCA can be used for several purposes, and each one may require a different level of details regarding the data collected. The data can be very detailed or simplified according to the purpose and application that the LCA tool is used for [19]. Some of the most utilized purposes for LCA are detailed in this section.

4.1. Product development

In case of product development using LCA, it is considered as a design for environment process. In the design stage of a product, there are many options for the choice of materials and resources. Using LCA in a product development is critical because any decision concerning the materials and resources will affect the following life cycle stages of the product [20]. Therefore, the earlier LCA is used efficiently in the design stage, the lower the impact will be on the environment.

In this case, the use of LCA may need extensive data collection and can be time consuming. However, simplifying LCA in this case can be useful [21], such that, the analysis and the focus can be on the materials and resources that probably affect the

environment significantly, and then seek alternative preliminary design solutions before proceeding in the development process.

4.2. Product Improvement

Improving an already made product or process can be easier regarding the data collection. When LCA is used as a product improvement tool, it is important only to focus on the materials and the resources that affect the product significantly.

By this way, several products can be compared with respect to each other from an environmental point of view, where the impact of each product is evaluated and compared to another one of the same category. Alternative solutions for the materials or the resources that cause higher impact in each life cycle phase (manufacturing, operation and disposal) are then incorporated and gathered, and the whole solution is reassessed [22].

4.3. Marketing

Marketing is the process of communicating a product features that coincide with the customer needs and expectations for certain level of quality requirements. As the level of environmental consciousness is increasing, more attention is being paid by the consumer to the environmental properties of goods and services. In case of conducting an LCA for the purpose of environmental marketing, the most relevant type of this kind of marketing is called environmental labelling (Eco labelling) [3]. Environmental labelling is considered as a proof that a certain product is environmentally friendly. When a product coincides with the Eco labelling criteria, it is given an Eco label and can therefore be attractive for marketing purposes, such that, environmentally friendly

products can be visible to the consumer. According to the EU Eco label regulation, LCA is required for the development of Eco-label criteria. The EU Eco labelling scheme has so far resulted in criteria for certain product groups: Washing machines, soil improvers, kitchen towels, laundry detergents, T-shirts and bed linen, paints and varnishes, dishwashers, ovens, toilet paper, light bulbs, televisions, cars, copying papers, refrigerators and freezers, water heaters, and air conditioning [3, 23, 24].

Another type of marketing purposes similar to the Eco label scheme is the environmental product declaration (EPD). EPD contains a variety of information about the components and environmental characteristics of a product based on LCA and in accordance to the ISO 14025 standard [25].

The general idea of EPD is to give a product a graphical presentation of a preset number of environmental impacts, for example, by using a bar diagram. This graphical presentation can therefore be interpreted easily by professional buyers and environmentally conscious consumers, but still may not be clear to general consumers. Although sometimes it is perceived that EPD is better than Eco labelling in enabling informed decisions instead of conferring judgments, the level of detail required to establish EPD is high compared to the Eco labelling scheme, which may be an obstacle towards its success and implementation [3, 26].

5. An example of an LCA application: The building sector

The building sector is responsible for about 40% of the energy demand worldwide, 32% of CO₂ emissions, and about 24% of raw materials extraction [21, 27]; these significant percentages make the use of LCA in the building sector a necessity to reduce the energy and other resources consumption and consequently reduce the impact on the environment.

Each of the previously mentioned purposes of the use of LCA can be directed to be used in different applications. For example, LCA can be applied in the building sector for the purpose of product development. So, in this case, the environmental limitations concerning the material selection and the building processes will be considered during the early design stages of the building. In case of product improvement, LCA can be applied and potential points of improvements can be addressed. For example, if a building is studied, its components (materials) that have the highest environmental impact can be identified and alternative solutions can be investigated.

Buildings can be awarded an Eco label as well according to the regulation of each region. An example for this is the European Eco label regulations [23].

Table 1 shows the possible uses of LCA during the design and construction of a building [21, 28].

Type of user	Stage of the process	Aim of using LCA at this stage
Consultants advising municipalities, urban designers	Preliminary phases	<ul style="list-style-type: none"> - Setting targets at municipal level. - Defining zones where residential/ office building is encouraged or prohibited. - Setting targets for development areas.
Property developers and clients	Preliminary phases	<ul style="list-style-type: none"> - Choosing a building site. - Sizing a project. - Setting environmental targets in a program.
Architects, Engineers and Consultants	<ul style="list-style-type: none"> - Early and detailed design (Product development) - Design of a renovation project (product improvement) 	Comparing design options (Geometry, orientation and technical choices)

Table 1. Possible uses of LCA in the construction sector [21]

6. General LCA Framework

In this section, some definitions and terminologies related to the LCA process in general are discussed.

According to the ISO 14040 recommendations [6], a frame work is given in order to conduct an LCA process. These recommendations can be summarized in the following four main steps:

- Definition of goal and scope
- Inventory analysis
- Impact assessment
- Interpretation of results.

These steps are demonstrated as shown in Figure 1. The double arrows between the phases indicate the interactive and iterative nature of LCA. For example, while doing

the impact assessment, it may appear that certain information is ambiguous or missing, which means that the inventory analysis must be improved. Another example is that during the interpretation phase, the interpreted results might be unclear or insufficient to fulfill the application requirements, and this means that the goal and scope definition may need to be revised and modified [3].

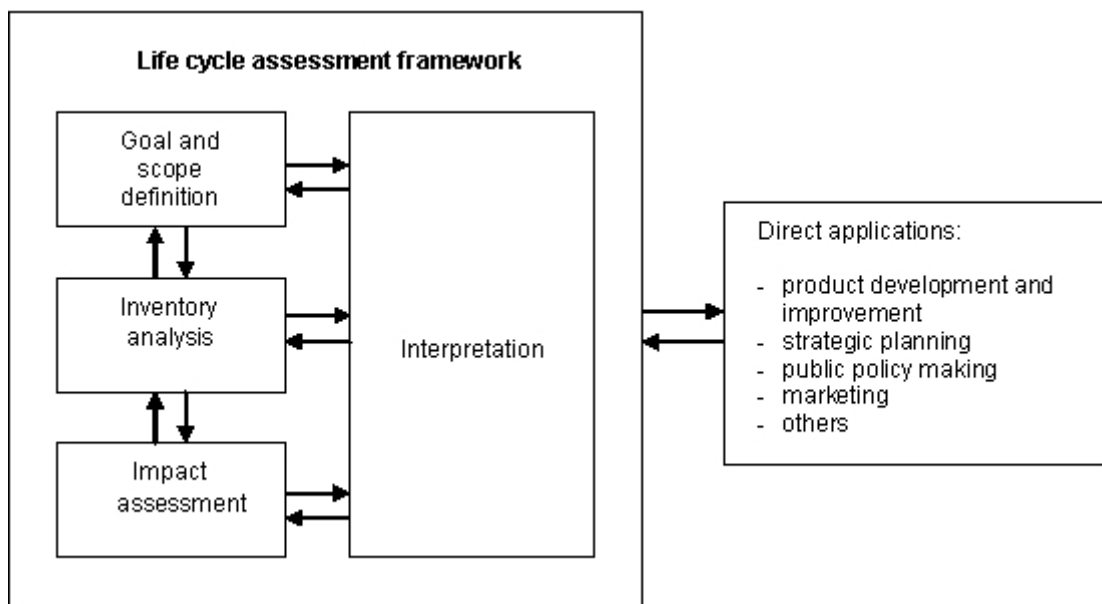


Figure 1. LCA frame work according to ISO 14040 standard [6]

These four phases (steps) that are required in order to conduct an LCA effectively are detailed in the ISO standard series [6-9], and are discussed in the following subsections.

6.1. Goal and scope definition

Goal and scope definition is the first step in a Life Cycle Analysis process where the product to be assessed is defined, as well as the context of the assessment to be made. This step is essential in the LCA process .It has a great influence on the impact

assessment step as many parameters are identified, such as the time and resources needed, the purpose of the study, the intended application, the system boundaries, the assessment methodology, and the general assumptions and limitations. Therefore, definition of the goal and scope will guide the entire LCA process to ensure that the most relevant results are achieved [7]. However, due to the iterative nature of LCA, changes may occur during the study in defining the goal and scope.

6.2. *Inventory analysis*

The result of the inventory analysis step is a list containing the quantities of the materials and energy consumed throughout the different stages of the life cycle of a product. Therefore, in the inventory analysis step, the related materials and energy flows of a product are explained in order to represent the product and its total inputs and outputs from and to the natural environment, respectively [7, 16, 29].

As shown in Figure 2, the LCI analysis is dependent on the types and quantities of natural resources (water, energy, etc.), the materials used in the production of the product, the transportation methods, the way in which the product is used during its lifespan, and how the product is finally disposed of. The consideration and effects of these factors can be different from one region to another. For example, a region may not have enough resources to produce a certain product, or another region has different technologies for the production of certain materials, or may be more dependent on renewable energy resources or fossil fuels. These differences may affect the assumptions and limitations of the required LCA study.

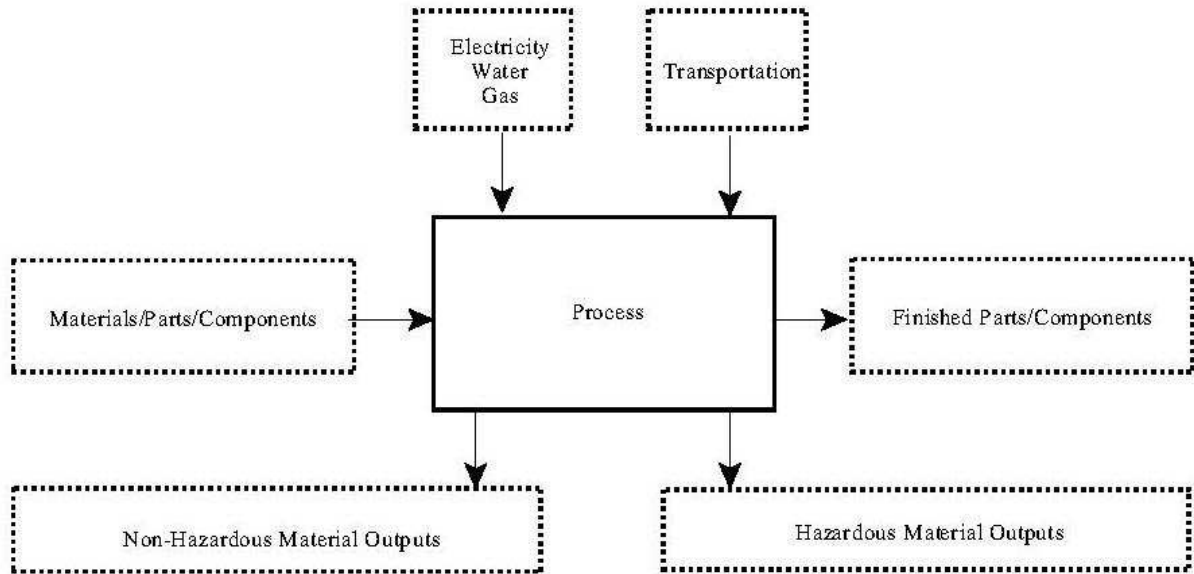


Figure 2. A flow diagram mapping the inputs and the outputs of the system in the inventory analysis step [16]

6.3. Impact assessment

This is the step where the LCI list that contains the corresponding materials and consumed energy quantities related to the studied product is interpreted and transformed into understandable impact indicators. These indicators express the severity of the contribution of the impact categories to the environmental load. These indicators are concluded through a series of steps recommended by the ISO standards 14042 [8], where some of these steps are obligatory and others are optional. The obligatory steps are: Definition and classification of impact categories, and characterization. The optional steps are normalization and weighting. The details of these steps are as follows:

6.3.1 Definition and classification of impact categories

The impact categories are defined and selected in order to describe the impacts caused by the emissions and the consumption of natural resources that are induced during the production, use and disposal of the considered product or process. In most LCIA Methodologies, the emissions and consumption of resources are attributable to three main areas of protection: Eco system quality, human health and natural resources. The three main areas of protection are preceded with several impact indicators that express the impact on the environment (midpoint and endpoint indicators).

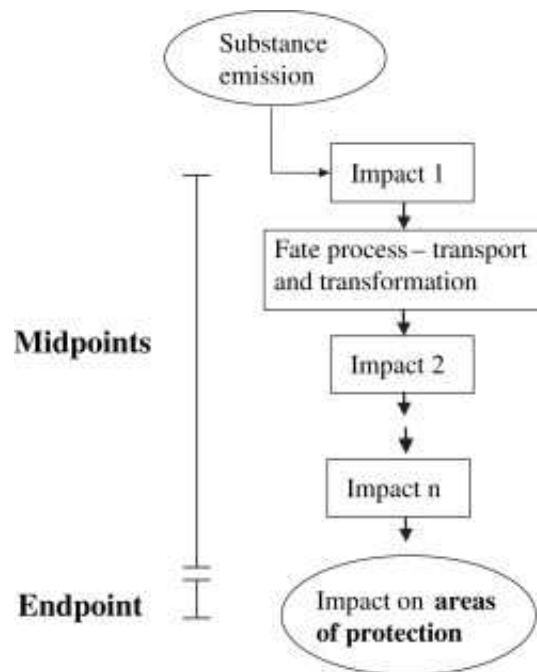


Figure 3. Shows a schematic presentation of the environmental impact assessment mechanism explaining the general modeling of a substance emission through a series of impacts leading to damages to the environmental areas of protection. The difference between midpoint and endpoint modeling along the mechanism is demonstrated [30]

Figure 3 above shows a schematic presentation of the environmental impact assessment mechanism explaining the general modeling of a substance emission through a series of impacts leading to damages to the environmental areas of protection. The difference between midpoint and endpoint modeling along the mechanism is demonstrated [30].

These types of modeling (midpoint and endpoint) represent the main difference between LCIA methodologies, beside other factors as well. The characteristics of each methodology will be discussed later in section 7.

6.3.2 Characterization

After the impact categories are selected and defined, the relative contribution of each input and output within the product system to the environmental load is assigned to these impact categories and converted into indicators that represent the corresponding potential impacts on the environment. This is done by multiplying the results of the inventory obtained in the classification phase by the characterization factors of each substance within each impact category as presented in equation (1).

$$\text{Category Indicator} = \sum_s \text{Characterisation Factor}(s) \times \text{Emission Inventory}(s) \quad (1)$$

where subscript s denotes the chemical.

The characterization factors of equation (1) linearly express the contribution of a unit mass (1 kg) of an emission to the environment. As an example, the relative contributions of different gases to climate change are commonly aggregated and compared in terms of carbon dioxide equivalents using Global Warming Potentials (GWP). A GWP_{500} of 100 implies that 1 kg of the substance has the same cumulative climate change effect as 100 kg of carbon dioxide during, in this case, a 500 year time period [31]. The characterization factors are calculated using quantitative models based on scientific analysis of the relevant environmental processes. Characterization models

can differ from one LCIA methodology to another. These differences can be attributed to the national differences in production processes or energy mixes. In addition, using different normalisation and weighting factors leads to further differences between the different LCIA methodologies. The normalization and weighing will be discussed in the following subsections.

6.3.3 Normalization

Normalization is an optional step according to the ISO 14040 standards [6]. However, normalization adds the benefits of placing the characterized impact indicator results in a broader context. It is expressed in a way that allows the impact indicators to be compared to each other, such that, the sum of each category indicator result is divided by a reference value according to equation (2) as follows:

$$N_k = S_k / R_k \quad (2)$$

Where k denotes the impact category, N is the normalized indicator, S is the category indicator from the characterization phase and R is the reference value, or the normalization factor.

The normalization factors are usually chosen to represent the real or potential magnitude of the corresponding impact category for a geographic area and over a certain time span. An example for a reference value is the annual national USA contribution to climate change in terms of GWPs. Other attributes that could be taken into account when choosing the reference value are the total emissions or resource use for a given area on a per capita basis, the ratio of one alternative to another (i.e. The baseline) and the highest value among all options [16, 31].

6.3.4 Weighting

Although weighting is also, like the normalization step, is considered as an optional step according to the ISO standards [6-9], both normalization and weighting are important when several solutions need to be clearly compared. Weighting is the process of converting the results of the normalised indicators of the different impact categories into other values using numerical factors (weighting factors) based on subjective valuations, that is, these weighting factors are dependent on the incorporation of social, political and ethical factors. The weighting process consists of multiplying the weighting factors by the result of the normalization for each impact category. Weighting is often applied in the form of linear weighting factors according to equation (3) as follows:

$$EI = \sum V_k N_k \text{ or } EI = \sum V_k S_k \quad (3)$$

Where EI is the overall environmental impact indicator, V_k is the weighting factor for impact category k, N is the normalized indicator and S is the category indicator from the characterization phase [31].

The weighting factors of each impact category represent the relative importance of each impact category to the environment. These factors are subjective and can vary according to the geographic area based on socioeconomic criteria. For example, the impact category "water consumption" can have significant importance in countries suffering from drought, where its relative importance in countries with plentiful water supplies is lower. Another example is the "respiratory effects" impact category which can have a great significance in areas which suffer from high rates of emissions that consequently affect the human health through the respiratory effects. A difference between the

normalization and weighting steps can be noticed, that is, normalisation provides a basis for comparing different types of environmental impact categories (all impacts get the same unit), while weighting assigns weights or relative values to the different impact categories based on their perceived importance or relevance [28]. Thus, although the weighting step is optional according to the ISO standards, its importance can be summarized in [3, 8]:

- Expressing the relative preference of an organization or group of stakeholders based on policies, goals or aims, and personal or group opinions or beliefs.
- To ensure that the process is visible, documentable, and reportable, and to verify that the relative importance of the results is based on the state of knowledge about these issues.

Weighting can be regarded as both qualitative and quantitative step that is not necessarily based on natural science but often on political or ethical values [3, 32].

Weighting methods have been developed by different institutions based on different principles [3, 31-33]. Some of them are as follows:

- Proxy approach: In this approach one or several quantitative measures are stated to be indicative for the total environmental impact. An Example on using this approach is energy consumption, material displacement and space consumption.
- Monetarisatión: This is considered as a weighting method that is carried out through expressed preference, where people are asked about their preferences. For example, asking people about their willingness to pay for keeping the environment safe and preserved, or they would rather accept the environmental degradation. The monetarisatión method can also be described with the premises of utilitarianism (values are measured by the aggregation of human preferences).

Moreover, values of environmental quality can be substituted by other commodities.

- Distance to target: The weighing factors are related to a target. This target can be decided by national or local authorities, within a company, etc. Thus the target can be environmental standards, environmental quality targets, or political targets, where they can be used to calculate critical volumes for emissions to air, water, soil or work environment.
- Panel approach: In this method, a group of people are asked to give ranks to the different impact and damage categories. Thus the relative importance of the impact and damage categories is derived from a group of people through surveys. This group of people is preferable to be composed of scientific experts, governments or international bodies.

6.3.5 Interpretation of results

In this step, the impact assessment results are interpreted, and conclusions are established in order to guide the decision making process. The critical environmental issues are defined, and the significance of the relative contribution of a certain product components or processes to the environmental load is recognized. Depending on the need of the study, verification of results can be done through checking the data with respect to three perspectives [3, 9, 29] as follows:

- Completeness check: Ensure the completeness of the study, such that, the significant environmental issues previously identified represent the information from the different LCA phases adequately (inventory analysis and impact assessment) in accordance with the goal and scope defined.

- Sensitivity check: Check if the final results and the conclusions are affected by uncertainties in the data or the selected evaluation methods. Thus, the aim of the sensitivity check is to establish a required degree of confidence in the results of the study relative to its overall goal. This check is mostly used in order to test the assumptions made during the study. The sensitivity check can be done by making a kind of “what if” scenario, where the value of different input parameters is changed systematically. This can be done also by using simulations (e.g. Monte Carlo simulations).
- Consistency check: Evaluating the consistency of the methods, procedures and treatment of data used throughout the study, and check their coherency with the objective and scope of the study. The items that can be subject to the consistency check are: data source, data accuracy, geographical representation, and system boundaries and assumptions.

7. An overview on LCIA methodologies

LCIA step within an LCA study is the most critical step, as it deals with an intensive amount of data that are represented in the inventory analysis results. These inventory results are then transformed into understandable impact indicators within impact categories after passing through complex environmental modeling based on environmental and natural science (characterization and normalization) and considering political, social and ethical issues as well (weighting). Because of this complexity in the LCIA step, methodologies were developed simplify and optimize the LCIA process. The LCIA methodologies are tools developed to relate the LCI results to the associated environmental impacts, where the LCI results are classified within impact categories,

each with a category indicator. By this way, the development of LCIA methodologies facilitates comparisons and trade-off among different product alternatives, simplify the process for the LCA practitioners and enable bench marking as well.

Within the LCIA step, two approaches of characterization can take place along the impact pathway of an impact indicator: midpoint approach and endpoint approach. Characterization at midpoint level models the impact using an indicator located somewhere along the methodology mechanism but before the endpoint categories; while characterization at the endpoint level requires modeling all the way until the endpoint categories described by the areas of protection (In most methodologies, the main areas of protection are: Eco system quality, human health and resources).

Therefore, the category indicators can be located at a point between the life cycle inventory results and the category endpoints (where the environmental effect occurs) in the cause effect chain. Within this context, two main schools of methodologies have been developed [34]:

- a) Classical impact assessment methods (problem oriented methods): For example, CML and EDIP methods. These assessment methods limit the quantitative modeling to the early stages in the cause-effect chain and group LCI results into so-called midpoint categories, according to themes. These themes are common mechanisms or commonly accepted grouping for impact sub categories.
- b) Damage oriented methods: such as Eco-indicator 99 and EPS. This school of impact assessment models the cause-effect chain up to the endpoint, or in

other words, up to the damage related to the different environmental areas of protection considered.

Another clarification can be given in order to differentiate between the two approaches (midpoint and endpoint) as follows: In the midpoint approach, the cause-effect chain starts with a specific process or an activity which lead to emissions and consequently, primary changes in the environment appear. These primary changes often occur early in cause-effect chain and are often chemical and physical changes. For example, in case of studying the primary effects in the climate change, changes in concentrations of gases in the atmosphere or changes in infrared radiation are noticed. At this point, the LCI results represent contributions to different environmental problems such as global warming or stratospheric ozone depletion. This is called midpoint approach. Thus midpoint approach is also known as problem-oriented approach.

Later on, in the cause-effect chain, often biological changes occur that are represented in damages on Eco systems, human health and resources. For example, one of the damages to human health resulting from stratospheric ozone depletion would be an increase in skin cancer. This is called an endpoint approach. Therefore, an endpoint approach is known as damage-oriented approach. Figure 4 shows an example for the difference between midpoint and endpoint assessment approaches [35].

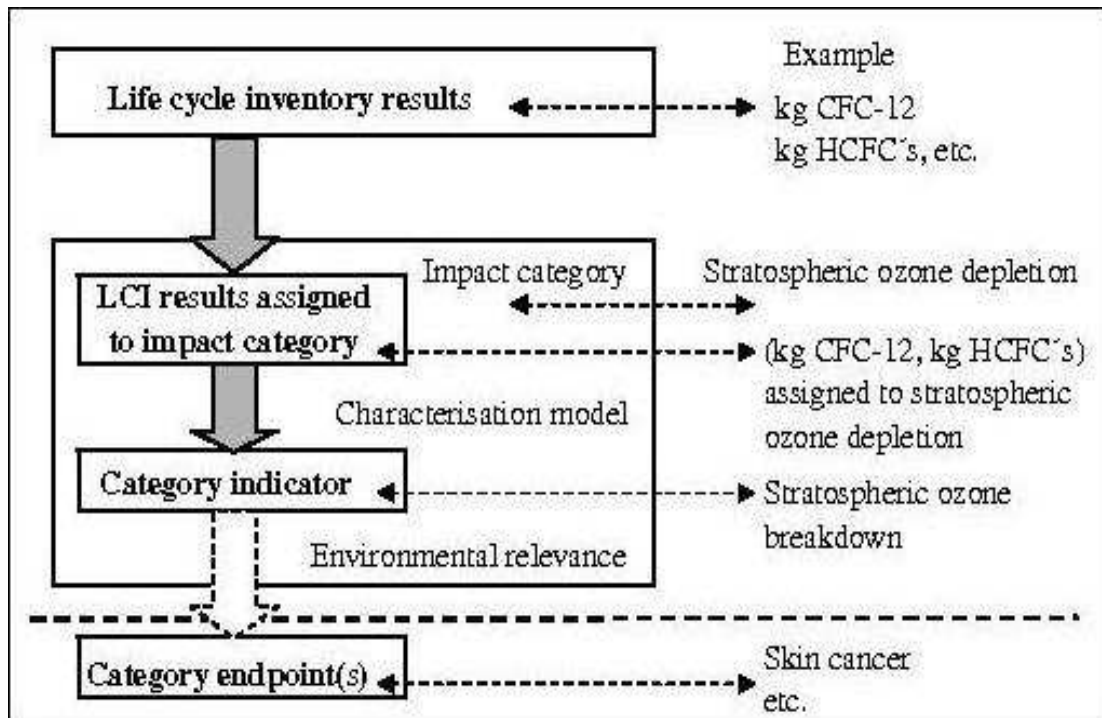


Figure 4. An example for the difference between midpoint and endpoint assessment approaches [35]

In brief, the methods that are based on early changes in the cause-effect chain are called midpoint methods, while endpoint or damage methods are those which are based on later changes in the environmental mechanism.

Recently, a life cycle partnership known as the Life Cycle Initiative [36] is launched between SETAC [5] and UNEP [15] after the recommendations given in the world summit on sustainable development in Johannesburg (2002) [37]. One among the objectives of this initiative is proposing a comprehensive LCIA tool that combines between both schools of LCIA methods (midpoint and endpoint). The Life Cycle Initiative suggests utilizing the advantages of both approaches. By a more precise and broadly agreed description of the main framework elements, the Life Cycle Initiative is expected to provide a common basis for the further development of consistent impact assessment methods that combines between both midpoint and endpoint approaches.

Such methods of this type were recently made available such as RECIPE, Impact 2002+ and the Japanese methodology LIME [38].

In addition to the differences between LCIA methodologies according to environmental modeling approach (midpoint and endpoint), there are other differences that can be noticed as well [39], such as:

- The number of impact categories covered by each methodology (midpoints and endpoint categories).
- The number of substances covered by each methodology.
- The corresponding criteria and models required for the characterization, normalization and weighting steps; which consequently affect the regional validity of the methodology, that is, a question may arise to specify if the methodology is developed based on the environmental background (Environmental profile) of a certain continent or a country (Spatial differentiation). Another inquiry that may arise is the temporal validity of the data used, which questions if the data used in the modeling are very old and does not suit the current environmental profile changes.

Some of these aspects will be mentioned in the section 7 within the description of each LCIA methodology.

Other types of LCIA methodologies, which are not categorized according to the modeling approach technique, have emerged. These methodologies are considered as specific LCIA methodologies that are concerned with the assessment of specific environmental areas or impact categories. Examples of these methods are: Cumulative

Energy Demand, Cumulative Exergy Demand and Ecological foot print. This type of methodologies will be covered in the following sections as well.

Table 2 to Table 5 show an overview of the widely used LCIA methodologies that are highlighted in this research. The modelling approach to which each methodology belongs (midpoint, endpoint, combined or other) and the corresponding impact categories are demonstrated.

Methodology	Impact categories (Midpoint categories)	Areas of protection
CML	<p>Obligatory impact categories: Depletion of abiotic resources, land competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, acidification and eutrophication.</p> <p>Optional impact categories: Loss of life support function, loss of biodiversity, freshwater sediment ecotoxicity, marine sediment ecotoxicity, impacts of ionizing radiation, malodorous air, noise, waste heat, casualties, lethal, non-lethal, depletion of biotic resources, desiccation and malodorous water</p>	Human health, natural environmental, man made environment, human resources
EDIP 2003	Global warming, ozone depletion, acidification, terrestrial eutrophication, aquatic eutrophication, photochemical ozone formation, human toxicity, ecotoxicity, and noise	Human health, Eco system and resources
TRACI	Ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health non cancer, human health criteria pollutants, eco-toxicity, and fossil fuel depletion	Human health, Eco system and resources

Table 2. An overview of the midpoint oriented LCIA methodologies studied

Thus, the types of LCIA methodologies that are discussed in the following sections can be summarized as follows:

- Midpoint approach methodologies.
- Endpoint approach methodologies.
- Combined midpoint and endpoint approach methodologies.
- Other LCA based methodologies.

Methodology	Damage categories (Endpoint categories)	Areas of protection
EI99	Climate change, ozone layer depletion, acidification, eutrophication, carcinogenic, respiratory effects, ionizing radiation, ecotoxicity, land-use, mineral resources, fossil resources	Human health, Eco system and resources
EPS 2000	Life expectancy, severe morbidity and suffering, morbidity, severe nuisance, nuisance crop production capacity, wood production capacity, fish and meat production capacity, base cation capacity, production capacity for water, share of species extinction, depletion of element reserves, depletion of fossil reserves (gas), depletion of fossil reserves (coal), depletion of fossil reserves (oil) and depletion of mineral reserves	Human health, Eco system production capacity, biodiversity and abiotic stock resources
Eco Scarcity	Ozone depletion, photochemical oxidant formation, respiratory effects, air emissions, surface water emissions, radioactive emissions, cancer caused by radio nuclides emitted to the sea , emissions to groundwater, emissions to soil, land filled municipal (reactive) wastes, hazardous wastes (stored underground), radioactive wastes , water consumption , gravel consumption , primary energy resources , endocrine disruptors ,and biodiversity losses (Damage categories are determined according to the political agenda of the corresponding country or region)	Human health, Eco system and resources
JEPIX	Ozone depletion, photochemical oxidant formation, respiratory effects, air emissions, surface water emissions, radioactive emissions, cancer caused by radio nuclides emitted to the sea , emissions to groundwater, emissions to soil, land filled municipal (reactive) wastes, hazardous wastes (stored underground), radioactive wastes , water consumption , gravel consumption , primary energy resources , endocrine disruptors ,and biodiversity losses (Damage categories are determined according to the political agenda of the corresponding country or region)	Human health, Eco system and resources

Table 3. An overview of the endpoint oriented LCIA methodologies studied

Each of these methodologies constitutes a database of substances and materials which are used in the LCA studies. Specific software tools are used to deal with the LCIA methodologies. Some of the most famous software tools are: Gabi [40], Sima pro [41], GEMIS [42], and BEES [43]. The use of such software tools requires much training and profound knowledge of LCA. However, in most cases, an LCA practitioner does not execute in details the impact assessment step (characterization, normalization and

weighing), as it is done efficiently with the help of the software tools and the associated

LCIA methodologies

Methodology	Impact categories (Midpoint categories)	Damage categories (Endpoint categories)	Areas of protection
RECIPE	Climate change, ozone depletion, terrestrial acidification , freshwater eutrophication , marine eutrophication , human toxicity, photochemical oxidant formation, particulate matter formation , terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation , urban land occupation, natural land transformation , water depletion , mineral resource depletion, fossil fuel depletion	damage to human health, damage to Ecosystem diversity and damage to resources availability	Human health, Eco system and resources
LIME	Ozone layer depletion, global warming, acidification, photochemical oxidant formation, regional air pollution, human-toxic chemical, eco- toxic chemical, eutrophication, land use, waste landfill, resource and consumption	Cataract, skin cancer, other cancer, respiratory disease, thermal stress, infectious disease, hypo alimentation, disaster causality, agricultural production, forestry production, fishery production, loss in land-use, energy consumption, user cost, terrestrial Eco system, aquatic Eco system	Human health, social welfare, net primary production and bio diversity.
IMPACT 2002+	Human toxicity , respiratory effects , ionizing radiation , ozone depletion , photochemical oxidant formation , aquatic ecotoxicity , terrestrial ecotoxicity , aquatic eutrophication , terrestrial eutrophication and acidification , land occupation , global warming , non renewable energy and mineral extraction	Damage to human health, damage to Eco system quality, damage to climate change and damage to resources	Human health, Eco system quality, climate change and resources
LUCAS	Climate change , ozone depletion , acidification , photochemical smog , respiratory effects , aquatic eutrophication , terrestrial eutrophication , ecotoxicity , human toxicity , land-use and abiotic resource depletion.	Under development	Human health, Eco system quality, and resources

Table 4. An overview of the combined (midpoint and endpoint) oriented LCIA methodologies studied

Methodology	Impact category
MEEup	Energy consumption, water consumption, materials in use, waste and to incinerator), hazardous waste generation, emissions to air and
BEES	Global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, smog, ecotoxicity, ozone depletion, and human health
Ecological footprint	Five types of direct land occupation are considered: cropland, pasture, forest, built-up area and hydropower area, and two indirect land occupations: fossil fuels and nuclear energy
USEtox	Ecotoxicity
EDP	Land occupation, land transformation and biodiversity.
IPCC	Climate change
CED	Fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for the nuclear and other renewable resources as well such as: biomass, water, wind, and solar energy
CExD	Fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for the nuclear and other renewable resources as well such as: biomass, water, wind, and solar energy. Non energetic resources such as water, minerals and metals.
Emergy	Renewable and non renewable resources, waste, soil loss, human labour, and water use
CExC	Fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for the nuclear and other renewable resources as well such as: biomass, water, wind, and solar energy
CEENE	Fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for the nuclear and other renewable resources as well such as: biomass, water, wind, and solar energy. Non energetic resources such as water, minerals and metals. And land use.

Table 5. An overview of the other based LCA methodologies studied

In general and depending on each methodology and the way by which the study is conducted (A basic level, or an advanced level using software tools), when evaluating the impact assessment of a certain product and its corresponding components, the evaluation of each impact category and the calculation of the final impact score points is given by equation (4):

$$IMP_j = \sum_k d_{k,j} \cdot LCI_k \quad (4)$$

Where IMP_j is the j impact category, $d_{k,j}$ is the coefficient of damage extracted from the corresponding LCIA methodology database and associated with the component k and impact j , and finally the LCI_k is the life cycle inventory entry (i.e. kg of polyurethane) [44, 45].

In the following subsections, the LCIA methodologies covered by this study are mentioned in details, highlighting the differences between them. The methodologies are divided according to their attribution to the different modelling approaches (midpoint, endpoint, combined or other) as mentioned previously.

7.1. Midpoint approach methodologies

7.1.1 CML

The CML is a midpoint oriented method that was first developed in 1992 by the Institute of Environmental Sciences of the University of Leiden (CML) [46]. The CML method groups the impact categories into two groups: Obligatory impact categories (base line impact categories) which are the impact categories used in most LCA studies, and additional impact categories which are operational impact categories that are dependent on the study requirements. The base line impact categories that are considered in this methodology are as follows: Depletion of abiotic resources, land competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, acidification and eutrophication. The optional impact categories that may be included in the study, or in another words dependent on the study requirements, can be one or more of the following: Loss of life support function, loss of biodiversity, fresh

water sediment ecotoxicity, marine sediment ecotoxicity, impacts of ionizing radiation, malodorous air, noise, waste heat, casualties, lethal, non-lethal, depletion of biotic resources, desiccation and malodorous water. Characterization is based on global and European average values. Normalization is done such that the baseline global normalization factors available are for the years 1990 and 1995 as aggregate annual world interventions or per capita as the annual interventions of an average world citizen. No weighting method is embedded into this methodology. The regional validity of the CML methodology impact categories is global, except for acidification and photo-oxidant formation, which are based on average European values [39, 47]. Figure 5 above shows the impact categories and path ways covered by the CML methodology.

7.1.2 EDIP 2003

The EDIP method (Environmental Design of Industrial Products) was developed in 1996 by Institute for Product development at the Danish Technical University [48] where the first methodology developed was EDIP 1997. This methodology is a midpoint oriented one. The impact categories considered in this context are: Global warming, ozone depletion, acidification, terrestrial eutrophication, aquatic eutrophication, photochemical ozone formation, human toxicity, ecotoxicity, and noise. Later on, some improvements concerning the characterization factors were done and introduced in EDIP 2003. These improvements are represented in developing the characterization factors of the EDIP 2003 in a site dependent and a site generic form, not only in a site generic form as in EDIP 1997. The difference between both forms of characterization is that the site generic form disregards the spatial variation in dispersion and distribution of the substance and exposure of the target.

Spatial differentiation means that the emissions and wastes generated by a specific process is not necessarily the same in each country. In the site dependent form of EDIP 2003, the emission takes place and covers site dependent dispersion, deposition, and Eco system sensitivity, such that, the characterization factors are spatially resolved at the level of countries. This allows the differences in impact from an emission when released in different countries to be a part of characterization, that is, the emissions in the conventional inventory table should be divided into emissions per country. However, some studies show that some impact categories do not result in significant differences in the results when considering the spatial difference in both approaches [39, 49]. Normalization factors for the world and Europe are available for the year 1995 as annual impact scores for an average citizen for all impact categories. Weighting is done using distance to political targets approach [50, 51]. The regional validity of the methodology impact categories is European, and is considered global as well for the impact categories that are not only of a regional concern, but of a global concern as well, such as global warming and ozone layer depletion.

7.1.3 TRACI

TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) is a midpoint oriented methodology developed by the environmental protection agency (EPA) in USA [52], with aim of assisting in the impact assessment of process designs and achieving pollution prevention. The midpoint impact categories selected for this methodology are: Ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health non cancer, human health criteria pollutants, eco-toxicity, and fossil fuel depletion. The impact categories were selected and characterized based on the assumptions made for the U.S. EPA Risk

Assessment Guidance for Superfund [53] and the U.S. EPA Exposure Factors Handbook [54-56]. The normalization factors are based on annual emissions and resources from US in the year 1999. No specific weighting is developed for this methodology; however, the authors suggest the panel approach for weighting [57]. The regional validity for the methodology impact categories is more suited to USA. However, as in the case of other methodologies, certain impact categories such as ozone layer depletion and global warming are considered as global impact categories.

7.2. Endpoint approach methodologies

7.2.1 Eco Indicator 99

The Eco indicator method is an endpoint oriented method that was first developed in 1995 under the Dutch NOH programme by PRé consultants [58] in a joint project with Philips Consumer Electronics [59], NedCar (Volvo/Mitsubishi) [60], Océ Copiers [61], Schuurink [62], CML Leiden [46], TU-Delft, IVAM-ER (Amsterdam)[63] and CE Delft [64]. Several improvements were made until another methodology was developed in 1999 (EI99). The improvements done in the EI99 are represented in providing better scientific basis for the damage models, such that the approach is more reliable. Besides, the indicator list is expanded, and the methodology is further improved for calculating the indicators [58, 65]. The environmental damage categories included are as follows: Climate change, ozone layer depletion, acidification, eutrophication, carcinogenic, respiratory effects, ionizing radiation, ecotoxicity, land use, mineral resources, and fossil resources. These categories are further aggregated into three areas of protection which are: Eco system quality, human health and natural resource. The calculation of

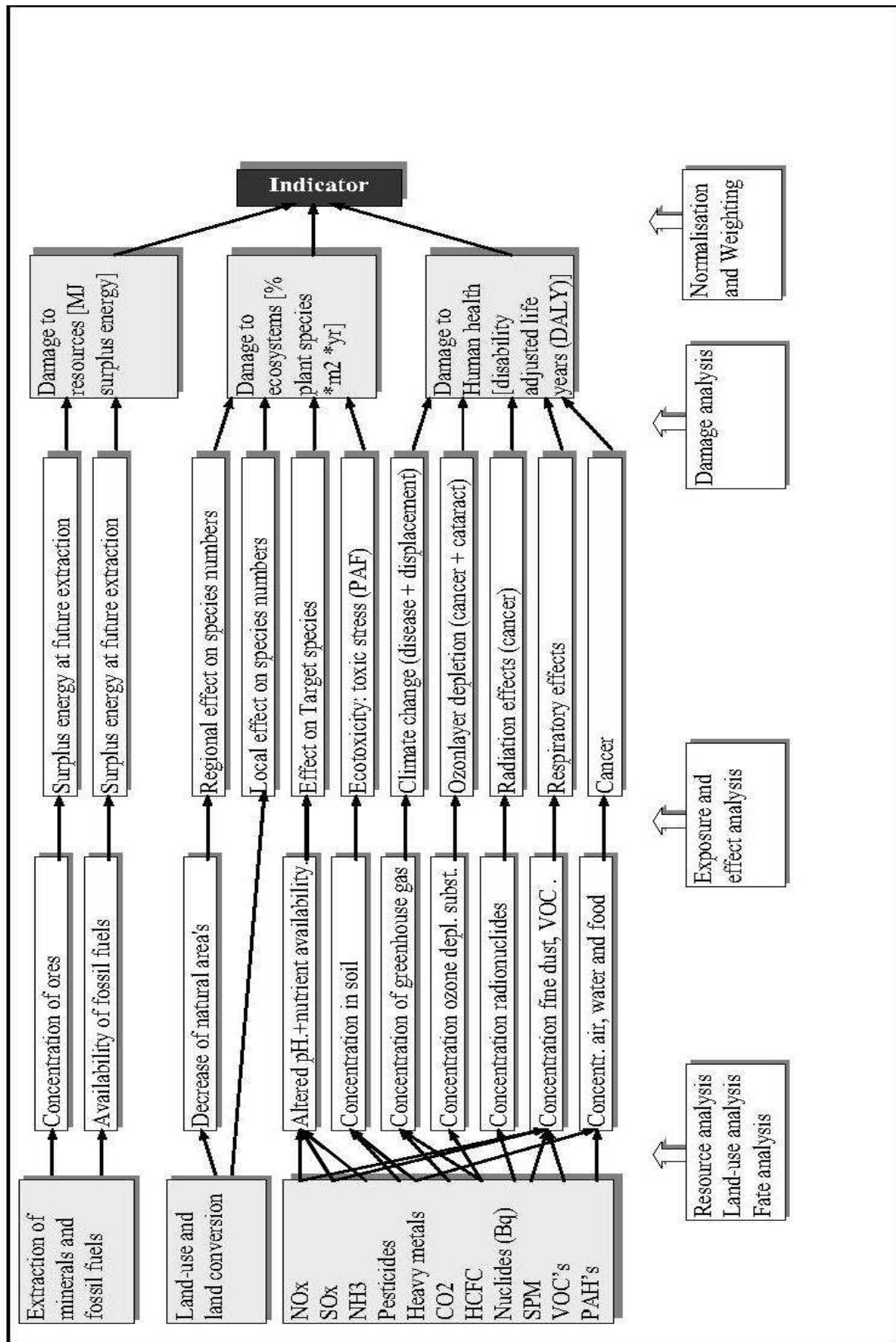


Figure 6. Impact categories and pathways covered by the Eco-indicator 99 methodology [39, 65]

characterization and normalization values have been carried out using the data on resource extraction and emissions which have been collected previously in a study carried out for the purpose of developing characterization and normalization values for the Dutch and the European territory. Those values are based on environmental interventions resulting from European production in 1990-1994. Weighting is done using the panel approach. In the EI99 methodology, the weighting approach is applied to three areas of protection. This is different from other methodologies where weighting is assigned for more than ten impact categories. Assigning the weights to the areas of protection is simpler than assigning the weights to the impact categories. Assigning the weights to the impact categories requires a great deal of knowledge on the mechanism of the effects, their probability and the way they cause the potential damage [39, 65, 66]. The regional validity of the methodology impact categories is European; certain categories are a part of global concern such as climate change, ozone layer depletion and resources. Figure 6 above shows the impact categories and pathways covered by the Eco Indicator 99 methodology.

7.2.2 EPS 2000

The EPS methodology (Environmental Priority Strategies in product design) was first developed in 1989 by a co-operation between Volvo [18], the Swedish Environmental Research Institute (IVL) [67], and the Swedish Federation of Industries (known now as Confederation of Swedish Enterprise since 2001) [68] with the aim of developing a tool that meets the efficient environmental requirements of product development process [58, 69]. The EPS is an endpoint oriented method. It considers the following damage categories: Life expectancy, severe morbidity and suffering, morbidity, severe nuisance, nuisance crop production capacity, wood production capacity, fish and meat production

capacity, base cation capacity, production capacity for water, share of species extinction, depletion of element reserves, depletion of fossil reserves (gas), depletion of fossil reserves (coal), depletion of fossil reserves (oil) and depletion of mineral reserves. It encompasses four areas of protection: Human health, Eco system production capacity, biodiversity and abiotic stock resources. Characterization among the environmental categories is done based on the precautionary principle using three methods: the empirical method, the equivalency method and the mechanistic methods considering the global conditions in the year 1990 [69, 70]. Normalization is not used in this method. Weighting is done based on monetisation methods (willingness to pay). The regional validity of the methodology impact categories is global except for the biodiversity damage category which is based on Swedish models. More information about the impact pathways can be found in [71].

7.2.3 Eco Scarcity method (Eco points)

The Eco scarcity method (or called Eco points method) was first introduced in 1990 and released in Switzerland in 1997. It is an endpoint methodology, where the endpoint categories are specified according to political targets. It covers the following damage categories: Ozone depletion, photochemical oxidant formation, respiratory effects, air emissions, surface water emissions, radioactive emissions, cancer caused by radio nuclides emitted to the sea, emissions to groundwater, emissions to soil, land filled municipal (reactive) wastes, hazardous wastes (stored underground), radioactive wastes, water consumption, gravel consumption, primary energy resources, endocrine disruptors, and biodiversity losses.

The damage categories covered are determined according to the political targets for a certain country or region. This provides the advantage that each country or region can

calculate its Eco points according to its legislations and political agenda. As an example, Japan has adopted the methodology while calculating their own endpoint indicators based on their national environmental situation and legislation. This led to the development of the JEPIX methodology [72] that will be discussed in the following subsection. Characterization and normalization are done based on Switzerland data from the year 2004. The data was updated later in a new version developed in 2006. These data are calculated from the present pollution level (current flows) and on the pollution considered as critical (critical flows). The latter ones are deduced from the scientifically supported goals of the Swiss environmental policy. Weighting is done using distance to target approach based on Switzerland environmental policy goals. The regional validity of the methodology is considered to be within Switzerland, as it was developed for Switzerland. However, as in case of other methodologies, some issues are of a global concern, such as ozone layer depletion and resources [73-75].

7.2.4 JEPIX

The JEPIX method (Japan Environmental Policy Priorities Index) is an LCIA methodology based on the Eco Scarcity methodology described previously. It was first developed in 2003 with the involvement of the Japan Environmental Ministry (MoE) [76], the Ministry for Economy Trade and Industry (METI) [77] and the Ministry for Education and Technology (MEXT) [78]. In conducting LCA studies and using LCIA methodologies, the Japanese companies were using European LCIA methodologies, and thus they were using the damage models related to Europe. So, The JEPIX methodology was released based on the Eco scarcity method but changing the political targets according to the Japanese political agenda and its environmental conditions. Thus, this makes the regional validity of the JEPIX methodology to be

within Japan. However, as in case of other methodologies, some issues are of a global concern, such as ozone layer depletion and resources [79-81].

7.3. Combined midpoint and endpoint approach

7.3.1 RECIPE

The Recipe methodology development was conducted by the cooperation of many developers working within the LCA field such as RIVM [82], CML [46], PRé Consultants [58], Radboud University Nijmegen [83] and CE Delft [64]. This methodology is considered as a follow up of the CML 2002 and the EI99 methodologies. The indicator scores are determined in a similar way as in the EI99 method. This method combines between both approaches of midpoint and endpoint modeling. Eighteen midpoint categories are addressed: Climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion, fossil fuel depletion.

At the endpoint level, three endpoint categories are considered, which in this case, are the same defined areas of environmental protection: damage to human health, damage to Eco system diversity and damage to resources availability. In the characterization and normalization steps, the year 2000 was chosen as a reference year, and information was gathered on the European level. However, concerning the midpoint normalization factors, some modifications were applied in the year 2010 [84-86]. The weighting in this method is carried out using the panel approach. The regional validity is for Europe.

However, as in the case of other methodologies, some issues are of a global concern, such as climate change, ozone layer depletion and resources. Figure 7 shows the impact categories and pathways covered by the ReCiPe methodology.

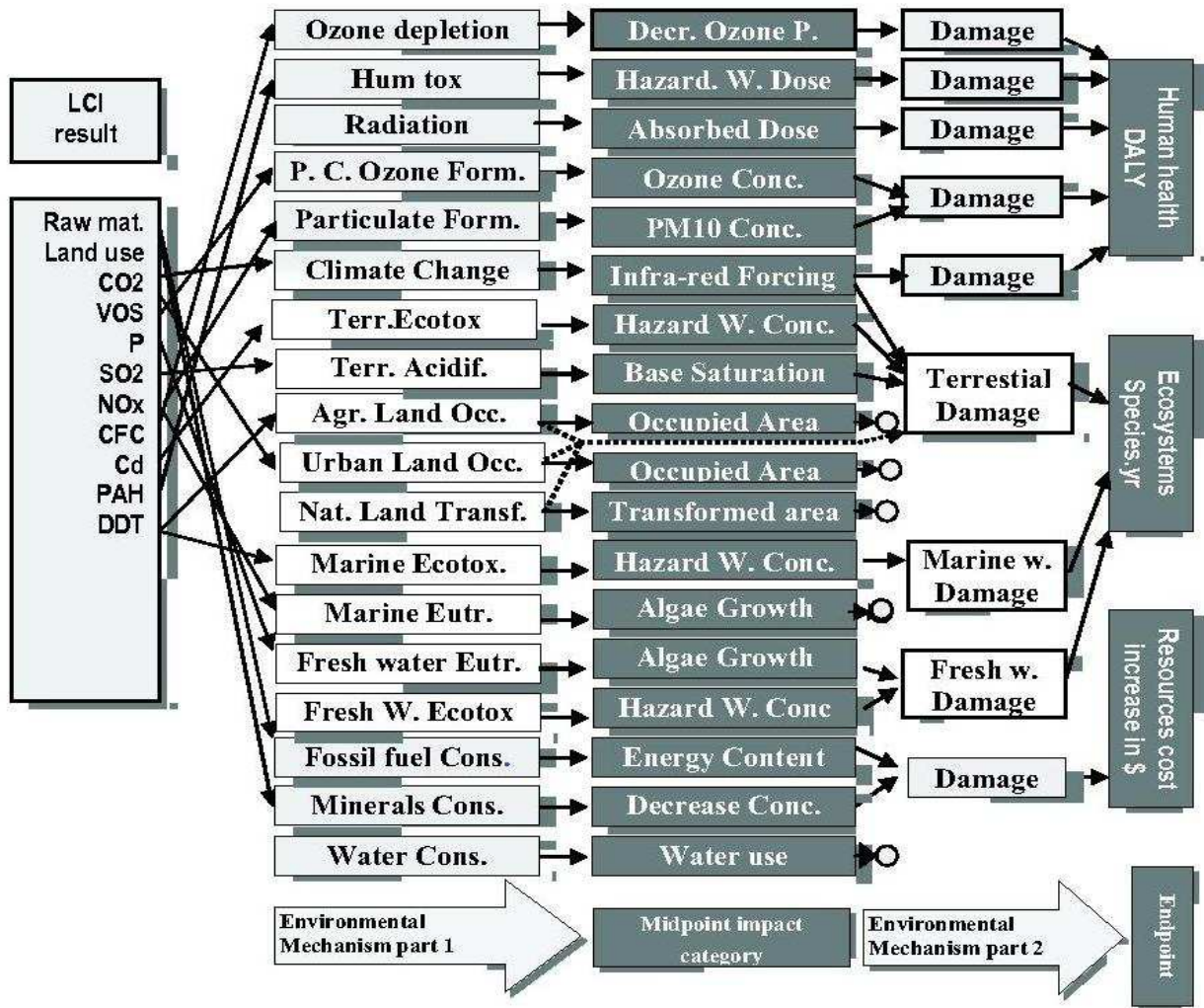


Figure 7. Impact categories and pathways covered by the ReCiPe methodology [85]

7.3.2 LIME

LIME was developed in Japan within the framework of an LCA national project funded by METI/NEDO [87-89]. The method was developed for quantifying the environmental impacts that are induced by the incidents of environmental loading in Japan. This

methodology is developed to combine between the two families of methodologies (midpoint and endpoint). Another version of this methodology, LIME 2, is developed where the uncertainties of all of the damage factors are measured and taken into consideration in order to improve the reliability of the result [90, 91]. This methodology includes the following midpoint impact categories: Ozone layer depletion, global warming, acidification, photochemical oxidant formation, regional air pollution, human-toxic chemical, eco-toxic chemical, eutrophication, land use, waste landfill, resource and consumption. The following endpoint damage categories are considered: Cataract, skin cancer, other cancer, respiratory disease, thermal stress, infectious disease, hypo-alimentation, disaster causality, agricultural production, forestry production, fishery production, loss in land-use, energy consumption, user cost, terrestrial Eco system, aquatic Eco system. Those endpoint damage categories are grouped into four safe guard objects (Areas of protection): Human health, social welfare, net primary production and bio diversity. The characterization factors are based on Japanese environmental profiles. The normalization values are calculated by summing products of annual environmental loading amounts and damage factors which express the potential damage of safeguard subject per unit environmental loading based on the Japanese environmental conditions. Weighting is done using monetisation methods (the amount of willingness to pay for a unit of damage to safeguard subject). As the methodology is developed for Japan, this makes its regional validity to be within Japan. However, as in case of other methodologies, some issue are of a global concern, such as ozone layer depletion and global warming [92, 93]. Figure 8 shows the impact categories and pathways covered by the LIME methodology.

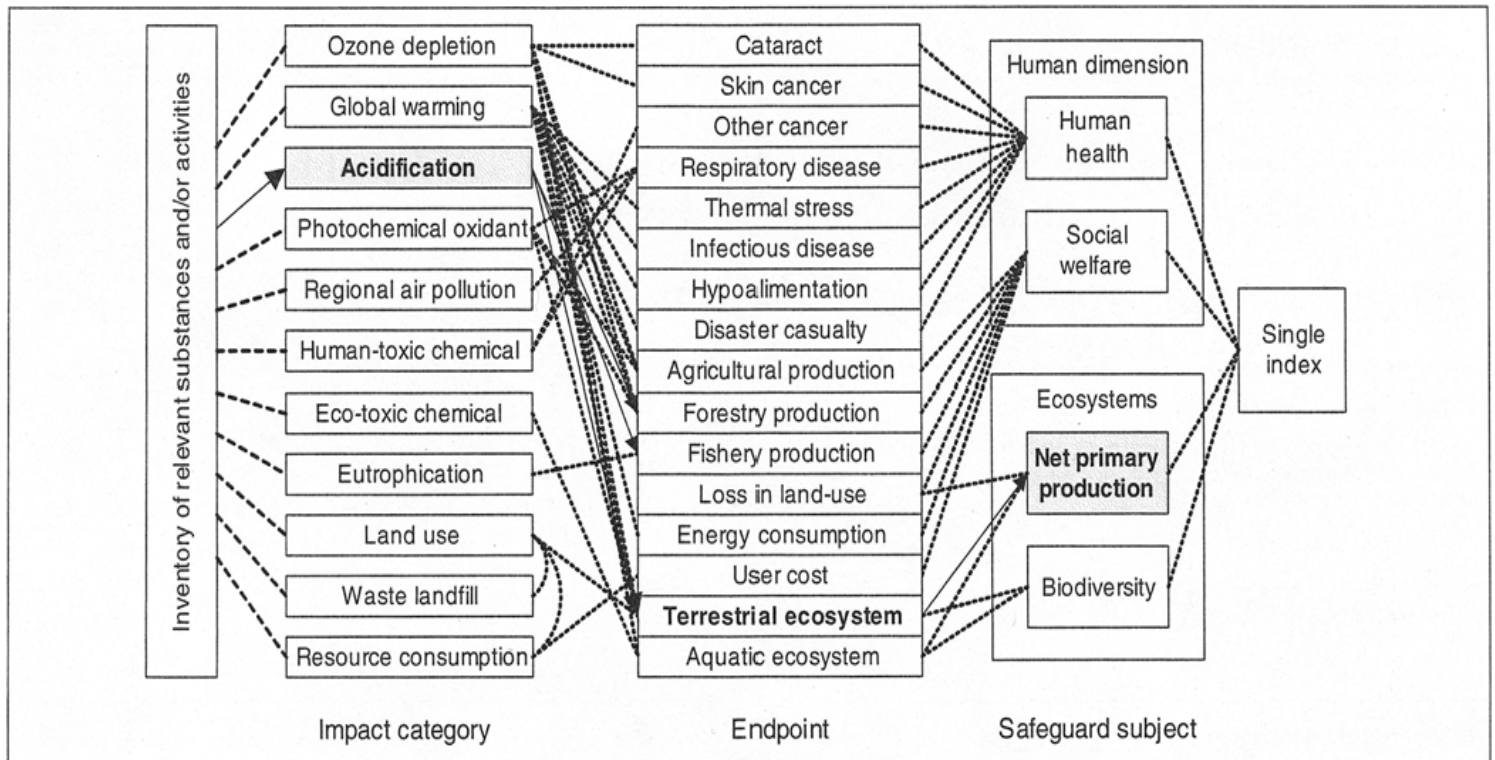


Figure 8. The impact categories and pathways covered by the LIME methodology [39, 89]

7.3.3 Impact 2002+

Impact 2002+ is a methodology that combines between the two schools of damage modelling (midpoint and endpoint oriented method). It was developed by the Swiss Federal Institute of Technology [94] and the federal polytechnic school of Lausanne (EPFL)-France [95]. The first version of the methodology was called Impact 2002. Later on, some modifications were introduced concerning the comparative assessment of some impact categories as well as developing public non-spatial, spatial European, and world versions of the environmental profile for other categories [34, 96, 97]. The methodology incorporates the following midpoint impact categories: Human toxicity, respiratory effects, ionizing radiation, ozone depletion, photochemical oxidant formation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic eutrophication, terrestrial eutrophication and acidification, land occupation, global warming, non

renewable energy and mineral extraction. Through the midpoint categories, the inventory results are linked to four endpoint damage categories, which in this case are also the environmental areas of protection: Human health, Eco system quality, climate change and resources. Characterization factors are adapted from other methodologies such as Impact 2002, Eco indicator 99 and CML. Normalisation factors are based on European average values as annual impact scores for an average citizen.

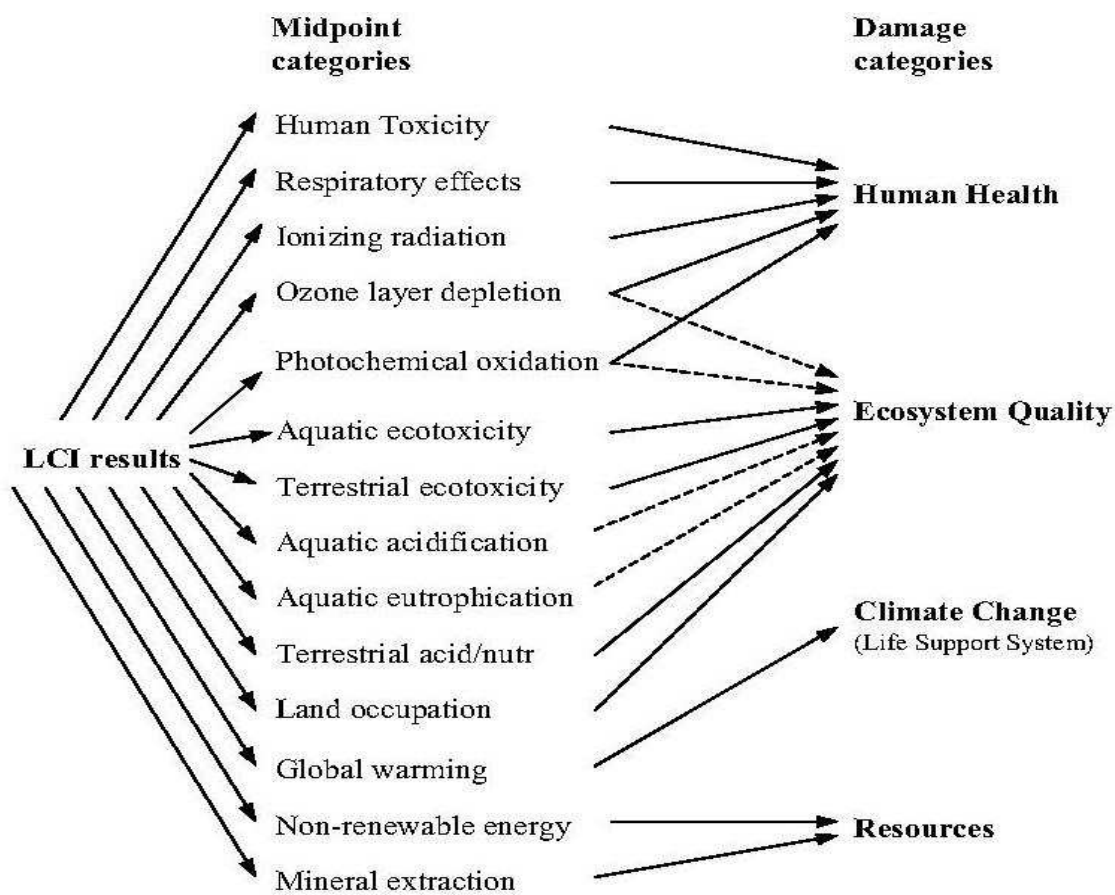


Figure 9. Impact categories and pathways covered by the Impact 2002+ methodology [39]

No specified weighting methodologies exist for this methodology. However, in case weighting is needed, the developers suggest considering the four damage categories (Human health, Eco system quality, climate change, and resources). One of the methods suggested to analyze the different weightings is the mixing triangle method which is a

simple decision support tool that is used to discuss the trade-off between impact categories. It illustrates evaluation issues, such as the weighting of different environmental effects when comparing product systems. The mixing triangle can only be used to compare three categories. Thus, in order to be able to apply this weighting method, two damage categories have to be summed (for example: climate change and resources, because of high correlations in most situations). The methodology has a European regional validity; certain issues are of a global concern such as ozone layer depletion and resources [39, 58, 98, 99]. Figure 9 above shows the impact categories and pathways covered by the Impact 2002+ method.

7.3.4 LUCAS

The LUCAS method (LCIA method Used for a CANadian-Specific context) is an LCIA methodology developed by CIRAIG [100]. Similar to the RECIPE, Impact 2002+ and LIME methods, it is considered as a method that mixes between both families of modeling (midpoint and endpoint). The reason behind developing this methodology is that the LCA studies in the Canadian industries have increased. These studies were using the widely known LCIA methodologies which are mostly based on average values for other regions than Canada (such as European average values). As the spatial differentiation in LCA have been growing as a trend for improving LCIA methodologies, the need to develop an LCIA methodology that is especially characterized for the Canadian territory has emerged and led to the development of the LUCAS methodology in 2005. The midpoints included in this method are: Climate change , ozone depletion , acidification , photochemical smog , respiratory effects , aquatic eutrophication , terrestrial eutrophication , ecotoxicity , human toxicity , land-use and abiotic resource depletion. As a first step, only midpoint characterization

models were selected, damage endpoint categories are in the framework of future development. The characterization factors were adapted from already existing methodologies such EDIP 2003, Impact 2002+ and TRACI. Some of these factors were introduced without change, and others are spatially characterized and differentiated to suit the Canadian region [39, 101]. The normalization factors are determined by the ratio of the impact per unit of emission divided by the total impact of all substances contributing to the specific impact category, per person, per year. The data used for calculating the normalization factors are based on information for populations and emissions provided by Statistics Canada (2004) [102] and Environment Canada (2002) [103]. Weighting is not used in this methodology. The regional validity is for Canada, as the methodology has been spatially differentiated for Canada. However, as in the case of other methodologies, some issues are of a global concern, not only regional, such as climate change, ozone layer depletion and resources

7.4. Other LCA based methodologies

7.4.1 MEEup

The MEEup methodology (Method for the Evaluation of Energy using Products) was developed by VHK consultants in Netherlands [104]. It is an especially oriented methodology that was established to evaluate the conformity level of energy using products with the criteria that make them eligible for implementing measures under the Eco design of energy using products directive 2005/32/EC [58, 105, 106].

The impact categories covered are: Energy consumption, water consumption, materials in use, waste generation (to landfill and to incinerator), hazardous waste generation, emissions to air and emissions to water. The impact categories are characterized based

on relevant EU and international legislation and treaties. Normalization and weighting are not specified for this methodology [39].

7.4.2 BEES

BEES (Building for Environmental and Economic Sustainability) is a software tool and a methodology developed by the National Institute of Standards and Technology (NIST) [107]. Unlike the other LCIA methodologies, this tool combines between the Life Cycle Impact Assessment (LCIA) and Life Cycle Costing (LCC).

In the LCIA part, the environmental impact of the studied product is evaluated. The following impact categories are considered: Global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, smog, ecotoxicity, ozone depletion, and human health. Characterization and normalisation are applied based on average USA values, such that within an impact category, each product performance measure is normalized by dividing by the highest measure of that category. Weighting can be done either by the user definition or by already existing weighting sets. These weighting sets are developed based on Environmental Protection Agency (EPA) science board advisory study, a Harvard university study and a set of equal weights.

In the LCC part, the economic performance is measured using the American Society for Testing and Materials (ASTM) standard Life Cycle Cost method [108], which covers the costs of initial investment, replacement, operation, maintenance and repair, and disposal. Environmental and economic performance results are combined into an overall performance measure using the ASTM standard for Multi-Attribute Decision Analysis [109]. This overall measure constitutes relative weights of environmental and economic performance. For example, according to the needed application, the results may be

preferred to be weighted such that it can be 50 percent/50 percent environmental/economic weighting importance, respectively [110, 111].

7.4.3 Ecological footprints

The Ecological Footprint has emerged as the world's premier measure of humanity's demand on nature, specifically on land use. It was first introduced in 1994, as a PhD dissertation of Mathis Wackernagel supervised by William Rees [37, 112, 113]. Unlike the previously mentioned assessment methods that focus on the direct and indirect resource inputs and emissions impact during the whole life cycle of products, the Ecological Foot print method is considered as a tool for the interpretation of product-specific life cycle resource. The Ecological Footprint measures the amount of biologically productive land and sea area that human activity requires to produce the resources it consumes and absorbs the waste it generates using prevailing technology and resource management. These measurements are then compared to land and sea area available. The Ecological Footprint has been commonly used to assess human pressure in a geographical context, for instance on the level of nations, regions or cities. In the analysis of the methodology, five types of direct land occupation are considered: cropland, pasture, forest, built-up area and hydropower area, and two indirect land occupations: fossil fuels and nuclear energy. All these seven factors are expressed in global hectares (standardization based on productivity), which are normalized to actual biological productive hectares available on earth [114, 115].

7.4.4 USEtox

The USEtox methodology is also a different kind of LCIA as it deals with the development of characterization models for human and ecotoxic impacts. USEtox was developed by the task force on ecotoxicity and human toxicity impacts within the framework of the SETAC/UNEP life cycle initiative project [47]. One among the objectives of this initiative is the improvement and the set up of recommended LCIA methodologies that are accessible world wide, the development of guidelines for the different impact categories and the development of consistent sets of characterization factors. Within this context, it was concluded that different LCIA methodologies does not have consistent toxicity characterization scores for substances, in addition to the limited number of covered substances. And as the toxicity indicators for human health effects and Eco system quality are necessary for LCIA and for comparative assessment and ranking of chemicals according to their hazardous characteristics, the USEtox methodology was developed to address these requirements. Future development and activities of the USEtox model includes user friendly programming of the characterization models, development of USEtox to accommodate metals better, full documentation of USEtox, and inclusion of terrestrial and marine ecotoxicity modelling [116, 117].

7.4.5 EDP

This methodology was developed by the Swiss Federal Institute of Technology (ETH) [94], Zürich. The Eco system Damage Potential (EDP) is an LCIA methodology that also deals with specific life cycle impact categories. It is specified for the development of generic characterization factors for land occupation, land transformation and biodiversity. A main advantage of this specific LCIA method is the possibility to

calculate the damages from complex series of land transformation, land occupation, and land restoration taking into account the virtual or factual restoration time of the land. This means that the damage of land transformation is largest for land use types which are difficult to restore and need extremely long to develop (e.g. thousand of years and more for primary forest) [118, 119].

7.4.6 IPCC

IPCC (Intergovernmental Panel on Climate Change) is a leading international body for the assessment of climate change. It was established by the United Nations Environment Programme (UNEP) [15] and the World Meteorological Organization (WMO) [120]. It reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. The IPCC methodology was first developed in 2001, and then some modifications in the characterization factors were done and another version was released in 2007. It is considered as specific LCIA methodology that deals with the climate change and assesses its impact on the different Eco system, resources and human health aspects through the development of characterization models. The climate change impact is characterized in terms of Global Warming Potential (GWP) within a time frame of 20, 100 and 500 years. Evaluation of future climate change impacts, adaptation, and vulnerability needs estimation studies about how future socio-economic and biophysical conditions will develop according to the expected climate change [99, 121, 122].

7.4.7 Cumulative Energy Demand

Cumulative energy demand (CED) is a parameter and a methodology used to quantify the direct and indirect energy use in units of MJ throughout the life cycle of a product or a process, including the energy consumed during the extraction, manufacturing and disposal of the materials. CED considers in its context the cumulative energy demand for fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for the nuclear and other renewable resources as well such as: biomass, water, wind, and solar energy. It represents the energy demand, valued as primary energy during the complete life cycle of products [123].

Cumulative energy demand has been used as a methodology to assess life cycle environmental impacts since the early seventies, but has also been criticized because it focuses on energy only. However, it is considered as an important energy parameter as it aggregates all forms of energy use over the whole life cycle (renewable and non renewable energy forms).

The importance of CED emerges from the fact of the dependency of the environmental impact on the energy demand during the entire life cycle of any product system. Then, it is suggested that the CED can be used as an indicator of environmental impacts, especially in the case of power producing systems. Thus, CED can be used as a complementary tool beside the other LCIA methodologies in order to provide the study with preliminary information about the critical part in the life cycle of a product or a process that consumes more energy [124-127].

7.4.8 Cumulative Exergy Demand

Exergy is an indicator and a specific LCIA methodology that evaluates the quality of energy resources. It quantifies the useful work that can be done by a certain quantity of energy. Exergy calculations are traditionally applied to assess energy efficiency of resources regarding the exergy losses. The indicator of Cumulative Exergy Demand (CExD) is introduced to assess the total exergy removal from nature in order to provide a product or a service.

The CExD is similar to the cumulative energy demand (CED) as they both assess the life cycle energy demand. However, CED is used to assess the energy demand of primary energy resources and the quality of energy is not taken into account. An advantage of the CExD is that it considers the quality of energy as it assesses the quality of energy resources. Moreover, CExD calculations include the exergy of different energy resources (renewable and non renewable) as well as non energetic resources (water, minerals and metals). This makes the CExD a more comprehensive energy indicator than the CED [128-130].

CExD has been used in research works in LCA to quantify the accumulated exergy consumption of a product or process from “cradle to grave”. Its significance emerges from its ability to analyze the cumulative exergy consumption of resources, which incorporates a quality measure of the resources as well. Thus, as the CED, it can be used as complementary tool beside the other LCIA methodologies [131-134].

7.4.9 Emergy Analysis

Emergy is defined as the total amount of one kind of energy that is directly or indirectly used in order to produce a product or a service. Emergy Analysis (EA) is a specific LCIA methodology concerning energy analysis. There is a different kind of emergy for each kind of available energy resource. For example: solar emergy is in units of solar emjoules, coal emergy in units of coal emjoules, and electrical emergy in units of electrical emjoules. Like energy, emergy is measured in relation to a reference level. In most applications, the measurements are expressed in the units of solar emergy [135, 136]. The main difference between Emergy Analysis (EA) and the previously mentioned energy oriented methods (CED and CExD) is that EA is a measure of the real wealth on earth in terms of the energy needed previously to make something. Emergy analysis allows the accounting for additional flows that influence sustainability, such as waste, soil loss, human labour, and water use. Thus, all previous available energy used to make something is considered in the calculation procedure, which means that the EA presents the energy memory of a product or a process represented by the final indicators [137, 138].

7.4.10 Cumulative Exergy Consumption

A more developed form of the Cumulative Exergy Demand (CExD) method is called the Cumulative Exergy Consumption (CExC). Such form expands the analysis to include two forms of analysis: Industrial Cumulative Exergy Consumption (ICEC) and Ecological Cumulative Exergy consumption (ECEC). Industrial Cumulative Exergy Consumption (ICEC) accounts for exergy consumption in industrial systems within their life cycle. Similar to CExD, its ability to measure the useful work of materials and energy flows allows the comparison across resources. It is considered to provide

information about short-term harm and within a local scale. Ecological Cumulative Exergy Consumption (ECEC) quantifies implications including the role of supporting Eco system services. ECEC considers longer term issues and the contribution from Eco systems processes. Moreover, ECEC also accounts for exergy consumption in labour and capital, exergy loss due to impact of emissions, and exergy consumed in Eco systems for creating the Eco system goods and services consumed by industrial activities [139].

7.4.11 CEENE

Cumulative Exergy Extraction from the Natural Environment (CEENE) is a methodology that is similar to the Cumulative Exergy Demand (CExD) that is specified for exergy analysis. CEENE is an extension for the CExD with some differences. CEENE is the same as CExD in evaluating energy resources and non energetic resources (water, minerals, and metals); But in addition to this, CEENE evaluates land use. Moreover, CEENE is expanded in concept, that is, CExD evaluates the exergy that is removed from nature and transferred into the technological system, while CEENE accounts for the total exergy that the natural system is deprived of. Thus, similar to the CExD, CEENE is a comprehensive tool to be used beside the Life Cycle Impact Assessment methods [140].

8. Conclusions and discussion

The research in this work demonstrates the concept and framework of Life Cycle Analysis. LCA follows organized steps in order to reach the required goal which is to be determined at the beginning of the studied project. In general, LCA can be used for

different purposes in different applications. LCA can be used for the purpose of product development, product improvement, Eco labelling and environmental product declaration. Those purposes can be applied in different applications, such as: The building sector, the industrial sector, agriculture, chemistry, etc.

A vital step in conducting an LCA is the LCIA. The comprehensiveness of this step is represented in transforming the LCI list into meaningful impact categories through complex environmental models. Many methodologies exist to perform LCIA in order to evaluate the impact assessment of products systems in a more simple way that can be easily understood and demonstrated. The methodologies are different in specific aspects, such as the number of impact categories covered, the number of substances covered, the environmental models developed for the characterization phase, and the normalization and weighting factors used. A main distinction between LCIA methodologies that differentiates between them significantly is the approach of modelling the substances within the associated data base within each methodology: Is it a midpoint or an endpoint modelling approach?

Many debates have been established to discuss the benefits and shortcomings of each approach [141-145], where it has been concluded that certain issues of uncertainties related to LCIA exist. Three types of uncertainties were recognized: Model uncertainty, parameter uncertainty and relevance of the results. Model uncertainty represents the accuracy of the model developed. Parameter uncertainty is the uncertainty associated with the input data and its quality, that is, whether it is measured or estimated, it has acceptable age, etc. The relevance of the results can be attributed to the importance of the conclusions according to the application required and according to the concerns of

the decision makers, the relevance of results is related also to what extent these results are based on the findings.

There is an overall belief that endpoint models are more relevant, as they are of direct relevance to a society's understanding for the final effects, such as measures of biodiversity changes and health effects; but at the same time they are considered to be less certain (i.e. higher model and parameter uncertainty). Midpoint modelling is conceived to be more certain, as the modelling is done at a point where the characterization factors could be adequately defined (i.e. lower model and parameter uncertainty) [143]. However, in many cases and depending on the application and the conducted study, midpoint categories are considered as less relevant to what the decision makers really want to know. So, a consistent framework combining both approaches can make use of the benefits of each one. The general idea of the combined approach is to align both of the midpoint and endpoint approaches. For example, in Figure 10, two environmental mechanisms are used in order to model the effect of climate change, starting from the LCI results and reaching to the midpoint and endpoint indicators. As mentioned previously and shown in Figure 10, the second part of the environmental mechanism contains more uncertainty. Thus, the idea of the combined approach is to take advantages of both approaches, that is, to align both indicators (midpoint and endpoint) along the same environmental mechanism, which is the aim of the methodologies that combines between both approaches such as the RECIPE methodology [85].

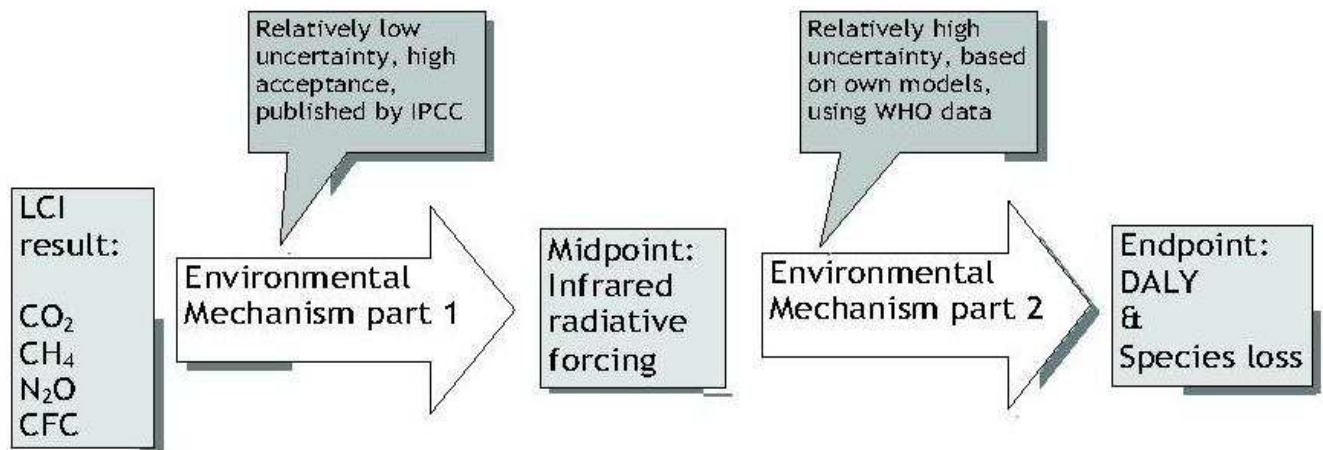


Figure 10. Modelling the climate change effect of the LCI results using two environmental mechanisms, reaching midpoint and endpoint indicators [85]

Another type of methodologies is recognized in this work which deals with specific impact categories (special purpose LCIA methodologies). For example, IPCC deals with climate change; as it assesses the most recent and up-to-date information and scientific findings related to climate change. Another methodology mentioned as well which is the Ecological foot print that focuses on the land use impact category. Energy and exergy assessment methodologies were discussed as well such as CED, CExD and CEENE. The exergy methods are believed to be a comprehensive measurement for the energy resources depletion on earth. Resource depletion can be expressed in terms of its concentration, as the human activities normally extract and use first the resources which have the highest concentration. The exergy value of resources includes the concentration factor, and hence the quality of a resource can be captured via its exergy value, which cannot be measured by mass and energy [146].

Thus, most of the LCIA methodologies can be used in different applications for different purposes. However, practitioners of LCA can make their choice for the LCIA methodology based on the following considerations:

- Since the main difference between LCIA methodologies lies in the distinct approaches in modelling the effect of emissions (midpoint and endpoint approaches), then a midpoint approach methodology can be chosen when the environmental effects are of interest to the reported results. Otherwise an endpoint approach methodology can be chosen as it is of more relevance to the final damages that occur to human health, Eco system and resources. The results presented by the latter approach are clearer and more understandable regarding the society's concern.

- Some of the LCIA methodologies were developed to be used within certain regions. For example, the LIME methodology was developed as an LCIA methodology specified for Japan, which makes the environmental mechanisms and models based on Japanese average values and data. This gives the LIME methodology a regional validity within Japan (except for the global issues such as ozone layer depletion, climate change and resources, they have global validity not only regional one, as they are problems of a global concern). Another example, an application in USA that needs to apply LCA may require choosing an LCIA methodology whose data and environmental models are developed according to USA environmental conditions (such as the TRACI methodology). This issue, which is called spatial differentiation, is regarded widely in some methodologies such as the EDIP 2003, where there are different versions of the same methodology considering spatial differentiation. Spatial differentiation can be done on continental or country levels. So, an LCA practitioner can make their choice of the LCIA methodology based on the region within which the intended application exists.

- The time horizon of the data should be adequate enough for the required application (i.e. assessing the data age which is an aspect of data quality issue).
- According to the application, the required impact categories have to be determined. Also, in case that certain impact category has to be neglected, this must be mentioned and documented in the scope of the project.

9. Ongoing projects

Similar to the SETAC/UNEP life cycle initiative project [36], other projects have emerged. The general aim of these projects is to improve several aspects of LCA. EULCIA (European Life Cycle Impact Assessment) is one of these projects. It has been initiated by the EU joint research centre in 2007 [58]. This project aims at developing and improving characterization factors for impact assessment modelling. Another project adopted by the EU joint research centre is the European platform on Life Cycle Assessment which is directed towards providing the necessary support to businesses and public authorities in the implementation of sustainable consumption and production. The support is provided through guidance based on consistent and quality assured life cycle data, methods and assessments [147]. LC-IMPACT, (which is an acronym for development and application of environmental Life Cycle Impact assessment Methods for imProved sustAinability Characterisation of Technologies) is a project that is considered as a follow up of the work done in the context of the life cycle initiative project of SETAC/UNEP and the European platform on Life Cycle Assessment project initiated by EU joint research centre. LC-IMPACT aims at the development of new LCIA methodologies that include uncommon impact categories (such as water exploitation, resource use, and noise). Other objectives of the project are to develop

spatially explicit characterization factors on a global scale for certain impact categories, and to quantify the uncertainty sources in the LCIA methodologies [148]. PROSUITE (PROspective SUstainability Assessment of TEchnologies) is a consortium project that includes about twenty six partners of different universities and companies specialized in LCA. It has been launched in 2009. This project aims at providing tools to assess the economic, environmental and social dimensions of technologies in a standardized and comprehensive way [149].

Application oriented projects can be found as well; an example is the ENSLIC project (ENergy Saving through promotion of Life Cycle assessment in buildings) which promotes the use of LCA in design for new buildings and refurbishments embedding the concepts of design for low energy consumption, integrated planning, and design for sustainability [28].

10. Recommendations

Other research ideas can be further investigated as follows:

- Spatial differentiation results can be tested through the assessment of a certain application using different methodologies. An example is the assessment of a certain product system using a well known methodology and then reassessing the same product using a methodology that considers spatial differentiation, and then, examine the differences in results.
- Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) together are complementary to each other in order to achieve a complete Life Cycle Management (LCM) system, which is the application of the Life Cycle Thinking

concept (LCT) in practice. Thus if both tools (LCA and LCC) are used in a certain study, a complete sustainable system can be reached.

- Several special LCIA methodologies were discussed such as CED, CExD and CEENE which are concerned with evaluating the energy demand and quality of the energy resources. Such tools and their corresponding characterization factors can be integrated into the other LCIA methodologies (midpoint, endpoint and combined) in order to reduce the uncertainty within the characterization models of specific impact and damage categories.
- Establishment of a common LCIA methodology by coordination between different LCA experts can lead to the development of a common worldwide used LCIA methodology. This can reduce the uncertainty of the differences between results from different LCIA methodologies.
- Several applications can be environmentally assessed using LCA. One of the important applications is the building sector. As mentioned previously in section 5, the building sector is responsible for about 40% of energy use world wide which consequently make it a big contributor to the harmful impact on the environment through different emissions and releases, in addition to other effects such as consumption of water resources, land occupation, etc. Researches have been done in order to reduce the energy consumption of buildings using insulating materials, phase change materials and different building materials. Although some types of these materials are proved to reduce the energy demand during the operation phase, they have high embodied energy that can cause high environmental impact during the manufacturing phase. This can be counterproductive in balancing the reduction of the environmental impact achieved due to energy savings gained during the operation phase. Thus, LCA

can help examining the environmental impact induced during the different life cycle stages of buildings and the environmental burdens that may be shifted from one phase to another. However, an LCA study can be limited to certain stages of a product due to time, resources or operating conditions constraints, and the study can still be useful. In other words, several variants of LCA, including cradle to grave, cradle to cradle or cradle to gate assessments can be applied. In addition, within the framework of achieving a sustainable Life Cycle Management (LCM) system, LCA and LCC studies can help reducing the impact on the environment with a balanced cost.

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