Impact assessment modelling of the matter-less stressors in the context of Life Cycle Assessment

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1

General introduction and research questions

1.1
The evolution of the Life Cycle Assessment framework and its health state in the years 2010's

Though its birth is disputed, it is with the publication of the book Silent Spring (Carson, 1962) that many identify the pivotal moment in the history of what we now call modern environmentalism. The book had the immediate cascade effect of increasing the interest of citizens, academics, and politicians alike in issues such as resource efficiency, energy efficiency, pollution control and solid waste management (Pepper, 2002). It is in this context that also corporations start to be interested in conducting studies to quantify resource requirements, emissions loadings and waste flows in their systems (Guinée et al., 2011). During the 1970s and 1980s unconcerted efforts to analyse company systems from a life cycle perspective took place in various parts of the world. The first forms of what we now call life cycle assessment (LCA) were used across the globe without a common framework. The lack of a common system of rules and methods invalidated at this stage much of the results that the first studies obtained (Guinée et al., 1993). It is in the 1990s that international efforts start to be united and the first publications put the basis for a scientific foundation of LCA.

Already back in 1996, Hunt and Franklin conclude a history of LCA with their appreciation of its growth from an "academic seed of an idea into a very popular analytical technique available to many" (Hunt and Franklin, 1996; p.7). The authors state to expect in the following years more challenges to come on methodological issues regarding the impact assessment, the analysis of data and the streamlining of methodologies (*ibidem*).

Almost twenty years have passed, and LCA is now in a rather mature phase of development. The complexity of the framework has increased probably at a faster pace than expected, thanks to a great number of academics from a multiplicity of disciplines that are daily involved in the development and improvement of the framework. Huijbregts (2013) points out that the last twenty years have been the years of the search for a consensus in the field of LCA. A plethora of researchers and scientists in the academia and in international organizations have worked to set the scientific basis for LCA, to standardize LCA practice, and to reach a scientific consensus, both in the form of guidelines and handbooks (e.g. Guinée et al., 2002; Curran, 2012), or textbooks (e.g. Bauman and Tillman, 2004).

The efforts towards the harmonization of LCA have flown into the operational ISO standard on how to perform LCA, which established a milestone in the history of LCA and provided a benchmark on which to compare new LCA studies and developments

(ISO 14040, 2006a; ISO 14044, 2006b). The availability of official LCA standards certainly contributed to increase the popularity of LCA, its acceptance and its use (Finkbeiner, 2013).

Today, LCA has grown to become the reference to evaluate the environmental performance of products and services. In every corner of the globe LCA is used by an active community of developers, practitioners, consultants and policy makers. Every month LCA courses are organized in every corner of the planet, and active discussions on the significance of methods and on the use of the tools are held in national and international LCA societies, on ad hoc fora, in workshops and meetings. Such a variety of stakeholders and users keeps LCA active and vital. Current efforts to develop tools for non-expert, open source software (see e.g. the open LCA initiative) and databases (e.g. the European reference Life Cycle Database) will likely further lower the barriers to the adoption of LCA.

The strive for a consensus, for an increased robustness, for better tools and for a more conscious diffusion of LCA is still ongoing. International initiatives and collaborative projects are tackling several aspects of LCA and are working on expanding its focus and further improving the methods and the significance of the results. With the classical attributional-LCA, the consequential LCA approach has been proposed as an alternative to respond to the necessity of quantifying the consequences determined by changes in certain product-systems (see e.g. Zamagni et al., 2012). Researchers have also been working on complementing LCA with the possibility of evaluating the projected financial consequences of a certain product-system, or of changes thereof, in the form of Life Cycle Costing (LCC; Asiedu and Gu, 1998; Epstein and Wisner, 2002; Heijungs et al., 2013). Many of the more recent developments now work on trying to incorporate in LCA the social impacts that may be determined by a certain product-system (Dreyer et al., 2010). New standards are expected to be published in the months to come to address the newest trends in LCA, particularly in the context of the footprinting family of tools (e.g. the water footprint; see Finkbeiner, 2013).

LCA is in continuous evolution, as are the impact assessment models that are used in the specific life cycle impact assessment (LCIA) phase. With the report on recommended practice for lifecycle impact assessment methods in a European context, the search for a consensus also extended to LCIA models (ILCD, 2011; Hauschild et al., 2013). In this context, the best practices in the field of LCA impact assessment models have been defined. The report identified gaps in the current LCIA methodologies and recommended to expand the framework to include a variety of new impacts, and to improve the existing knowledge of underdeveloped impacts. However, the way LCIA should further develop and the priorities that should be set for the future expansion of the framework have not yet been addressed by the international community. The importance of maintaining a link to the computational structure of LCA and the constituent phases of LCA seems to have been shifted to the background of the consensus-discourse. This dissertation focuses precisely on the way new impacts should be selected for inclusion in LCA, and, particularly, on how to deal methodologically with impacts that are not related to the release or transformation of matter.

1.2
Life Cycle Impact Assessment: methods and best practice

In the last decade, existing impact categories have been improved, refined and perfected. Models have been also made more representative in a spatial sense, meaning that modellers have worked on making the results that LCA provides as much as possible representative of any location of emission around the globe. The availability of a scientific foundation on which to base new developments, allowed LCA modellers, to develop a range of new environmental impact categories to be covered in LCIA.

Impact assessment methods (i.e. collections of characterization models for specific impact categories) have been the focus of a big share of the efforts of LCA interested academics in the last years, with a number of research groups focusing only on these aspects of LCA. As a result/consequently, Hauschild et al. (2013) identified 12 alternative LCIA methods, corresponding to a total of 91 different characterization models. Such number of characterization models, has not made easier the choice for the LCA practitioner of which impacts to consider in a LCA study. The most appropriate set of impacts to be considered in LCIA, in fact, is still under discussion (see ILCD, 2011). The ISO 14044 standard (ISO, 2006b) simply recommends that impact categories and characterization models should be "based on an international agreement or approved by a competent international body".

According to the LCA reference handbook of the Joint Research Center (ILCD, 2011), the modelling effort of experts should be further increased to include those impacts that are still underdeveloped or not yet modelled. The evolution of LCIA models did not develop equally for all impact categories. Certain impact categories have been only proposed in methodological papers, but not yet applied in case studies. According to the ILCD report (2011), some impacts that are still out of the LCA framework and not yet included in any of the most commonly used impact assessment methods would probably affect the results for a number of product systems. A full list of underdeveloped or undeveloped impacts has been drafted by the panel of expert of the ILCD report. Previously, also Bare and Gloria had already highlighted areas of improvements for characterization methods in a full taxonomy of LCIA (2008).

Impacts that have been classified as a potential candidate to be covered in LCA include, among others, the impacts from the cultivation of genetically modified organisms, odour, desiccation, accidents, salination, noise, light and non-ionizing radiation (ILCD, 2011; Sala et al., 2013). Reasons for the limited development or absence of these impacts from LCA are the lack of suitable and scientific sound models, the lack of inventory data, the level of uncertainty of the modelling process and the unsuitability to the computational structure of LCA. Nonetheless, the ILCD handbook (2011) recommends to have an open mind towards these underdeveloped matter-less impacts and to start to tackle their modelling.

1.3
Underdeveloped matter-less impacts and their inclusion in LCA

The ILCD handbook (2011) does not provide criteria of selection and optimisation to guide the developers of impact categories that have attracted a limited attention in LCA. Nevertheless, it seems clear that LCA should be expanded to become a holistic tool for the assessment of any product system, and for the characterization of any emission or use of resources.

Traditionally, only impacts that have a flow character have been systematically included in LCA databases and used in case studies and some recommend that only those should be adapted to the structure of LCA and to its computational rules (see e.g. Udo de Haes, 2006). LCA, in fact, has traditionally been considered "a quantitative environmental performance tool essentially based around mass and energy balances" (Azapagic and Clift, 1999; p.1510). LCA has been dealing with stressors with matter, thus both mass and volume, related to the classic emissions of substances/extraction of resources scheme.

In the last years, methodological developments in LCA expanded the boundaries of the concept of functional unit (ISO, 2006a), in order to include in the framework also impacts (and activities), for which the relationship to a functional unit is not mediated by the extraction/emission pattern. The experience of the past years has proven that impacts that are not following such pattern may also be tackled by LCA modellers. In particular, some of the developments that can be dealt with in LCA regard environmental stressors (i.e. pressures on the environment caused by human activities) that are matter-less. We define matter-less in this work of thesis those stressors that are not related to the extraction of matter, or to the release of a certain quantity of matter, thus are in this sense immaterial. Such stressors and the emissions that are related to them do not allow, strictly speaking, for a mass-balance. Matter-less stressors have received limited attention in LCA and are still outside case studies. The most discussed and investigated exception is certainly the category concerning land-use impacts (see e.g. Brandão and Milá i Canals, 2013).

The modelling of matter-less stressors does not necessarily require escaping the computational structure of LCA. However, more care needs to be taken in studying a way to inventory elementary flows in and out of the unit processes and to scale them to the final demand of the full product system considered in the life cycle, thus to its reference flow and functional unit. The LCI phase of LCA is, in fact, a fundamental aspect of the development of any characterization model (i.e. also for matter-less stressors), and one of the drivers for its success in the daily practice of users and for its inclusion in databases and software.

On the LCIA side, the principles on which characterization models are moulded typically are developed outside the field of LCA, and, therefore, may need to be adapted to the structure of LCA. Such a consideration counts both for classic stressors (e.g. toxic substances) as well as for matter-less impacts. All non-linearities need to be solved and characterization factors need to allow to be simply multiplied to the recorded inventory items to provide an impact score for the category under development. The need to adapt alien models to the LCA framework requires that such models have already found the consensus of experts in their specialist field of reference and that a sufficient body of scientific evidence (e.g. laboratory tests, future trends) is available for a new stressor. Such consideration should also deem whether a stressor is relevant for only human targets, or also for other areas of protection (i.e. entities that we want to protect: human health, biodiversity and ecosystem, resource productivity, or man-made environment; ISO, 2006; ILCD, 2010). A set of criteria of validity needs to be defined and applied in all cases, in which a new development is considered necessary in LCA.

1.4
A brief overview of the computational structure of the inventory and impact assessment phases of LCA

In both the case of matter-less and traditional mass-impacts, the rather specific computational structure of LCA defines a confined ground, within which a modeller builds a new characterization model for an impact category. The concept of the functional unit and the procedure of scaling through a factor to the final demand of the entire product system need to be taken into account in order for new models to be compatible to the existing LCA methods. Furthermore, the linear relationship between the inventory and the characterization steps needs to be maintained. In this respect, the factors representing the environmental mechanisms and exposure routes in the classic characterization scheme may function as a paradigm for any characterization model, also in the case of impacts that are not strictly related to the emission of material substances.

As a starting point for the analysis of the remaining of this thesis, let us briefly define the main features and boundaries of the LCA framework from a computational perspective.

1.4.1
The inventory phase and its relationship to a functional unit

The life cycle of a product is classically modelled using a product system, thus a collection of unit processes or activities. Elementary flows from the ecosphere and the product flows from the technosphere (Hofstetter, 2000) are inputs and outputs of each unit process. The inventory analysis phase of LCA is concerned with the construction of such system of unit processes. All resource inputs and emissions are expressed per unit of product, thus need to be scaled, for each unit process, to the relative output that is necessary for the whole system to perform its function and achieve its goal (see ISO, 2006a; 2006b). In order to scale the output of each unit process to a common reference unit and to effectively quantify the performance of the product system under study, a functional unit needs to be selected. Every input and output to a unit process is scaled to the functional unit, allowing also for a comparison of alternatives based on a common basis. In the LCA jargon, the functional unit is not an execution-unit such as the homonymous concept defined in the field of informatics, but the representation of the function of the system under study, thus the final measure of its environmental performance and its final output to which the outputs of all unit processes contribute.

The concept of a functional unit is the fundamental nucleus of LCA and an essential component of its computational structure. It is worth here to recall the well-known matrix equation that forms the concise computational basis of LCA (Heijungs and Suh, 2002):

$$\mathbf{As} = \mathbf{f} \qquad (1)$$

hence,

$$\mathbf{s} = \mathbf{A}^{-1}\mathbf{f} \qquad (2)$$

Where $\mathbf{A}$ is the (square, non–singular) technology matrix representing the flows within the economic system ($\mathbf{A}^{-1}$ its inverse), $\mathbf{f}$ the final demand vector and $\mathbf{s}$ the scaling vector (Heijungs and Suh, 2002). The final demand vector represents the reference flow of the system, thus the amount of product that is necessary per functional unit. The scaling vector allows determining the inventory vector $\mathbf{g}$ relation to both the system of environmental flows and the economic system, and to its final demand, i.e. in the matrix notation:

$$\mathbf{g} = \mathbf{Bs} \quad (3)$$

where $\mathbf{B}$ is the intervention matrix representing the environmental interventions of all unit processes (Heijungs and Suh, 2002). The formulation, in combination with other procedural steps (e.g. cut-off, allocation; see ISO, 2006a), allows calculating the final inventory results: the emitted substances and extracted resources are aggregated over the entire product system in an inventory table. Equal interventions across a life cycle (e.g. per compartment, archetype, time, or any other specification) may be aggregated and compared, and stored before the conversion that will take place during the characterization phase of LCIA. The expressions in (2) and (3) can be combined as:

$$\mathbf{g} = \left(\mathbf{BA}^{-1}\right)\mathbf{f} \quad (4)$$

which highlights that the inventory may be solved for a variety of final demands $\mathbf{f}$ (see Heijungs and Suh, 2002).

The relationship of a product system to a functional unit and the necessity of scaling all inventory items to this common reference define one of the most stringent procedures of LCA modelling and the fundamental notion for the inclusion of any impact category into the framework. Therefore, for a matter-less stressor to be considered for impact assessment modelling, it requires that every relevant unit process can be scaled to a functional unit.

1.4.2
The characterization phase of LCA and the characterization models

Once a stressor meets the requirement needed at the inventory phase, the modeller may move on with the following phases of LCA with an eye on the practical aspects of the process of conducting an LCA study. The LCI of a product system generally represents the most challenging phase of any LCA study, since a product system is typically the combination of tens of unit processes. Once all inputs and outputs of the unit processes have been scaled to the functional unit and recorded in an inventory table, the analysis moves to the life cycle impact assessment phase (LCIA). As mentioned before, a variety of characterization models allow characterizing the inventory results. The characterization model is a function that translates the inventory results into indicator results, which reflect a certain impact category. A characterization model is usually taken from the literature, or has been selected in the LCA software as part of a comprehensive method (e.g. CML 2002, EDIP).

Back to the notation earlier introduced, the background model allows for the conversion of the $\mathbf{g}$ vector from the LCI phase into a vector of impact category indicators that are dependent on a given set of environmental interventions, as in the formulation:

$$h_i = \eta_i(\mathbf{g}) \tag{5}$$

where η_i is typically a non-linear function representing the characterization model for the impact category i , and is the indicator results, which is function of a certain inventory vector $\mathbf{g}$. Characterization factors are a first-order approximation of and are provided by the developers of the specific characterization model in the form of an ordered list of data, or a spatially-explicit map, specific to the LCI results assigned to impact categories in the classification phase (Heijungs and Suh, 2002; ISO, 2006). This is the stage at which a modeller has to investigate the way a stressor may be modelled to follow these basic assumptions.

In a compatible matrix formulation, we can write the characterization step as:

$$\mathbf{h} = \mathbf{Q}\mathbf{g} \tag{6}$$

where $\mathbf{h}$ is the impact vector, and $\mathbf{Q}$ the matrix of characterisation factors. The operational formula for characterization further stresses the link to the LCI phase and its results, converted into a common metric by the characterization step (Curran, 2012; p. 26), and the implicit link to the functional unit to which all inventory items are scaled to. The category indicator result is obtained by multiplication of the inventoried item in the LCI and the specific characterization factor, which linearly expresses the contribution of each g_j to the impact category i. The inventory data g_j is expressed in terms of e.g. mass released into the environment per functional unit (Pennington et al., 2004).

The characterization factor is the visible part of the result of a characterization model that is used by the practitioner. Every q_j is typically defined under certain conditions j. Characterization factors may be globally defined (i.e. valid for any condition of emission), or differentiated by the modeller according to local conditions (e.g. high population density), or even spatially-explicit (e.g. a 10 by 10 km cell of a raster map). The subscript j may refer to a certain substance (i.e. a quantified item in the inventory table), location of emission, location of exposure of the receptor, time of emission or exposure (e.g. day/evening/night, summer/winter), or any other further specification recorded at the inventory phase and defined for the impact category under study.

Characterization factors for an impact category i may be calculated following the classical toxics-based characterization scheme (Rosenbaum et al., 2007), defined for all effect types, compartments, and exposure routes as:

$$\mathbf{Q} = \mathbf{FF} \cdot \mathbf{XF} \cdot \mathbf{EF} \cdot \mathbf{DF} \tag{7}$$

in which:

- $\mathbf{FF}$ is the fate matrix, which links the marginal change in the background condition to the marginal increase in emission due to the functional unit;
- $\mathbf{XF}$ is the exposure matrix, which contains exposure rates and relates the amount of a certain substance or pollutant in a certain compartment to its effect on the target subjects exposed to it (e.g. by intake of a chemical substance, or by exposure to a certain non-toxic emission);
- $\mathbf{EF}$ is the effect matrix containing the effect factors, which translate the adverse effects of the exposure to a pollutant into a risk expressed in the number of cases that will be determined in an exposed population;
- $\mathbf{DF}$ is the damage matrix containing the damage factors, which discriminate in the pool of individuated cases those that will cause a disability, from those that will have lethal effects, thus determining the severity of the adverse effect of a certain case.

The characterisation factors introduced in the operational formula express the contribution of each inventory item g_j to a specific environmental concern. Thus, they represent a numerical value that relates one unit of pollutant j to an environmental indicator (e.g. eco-toxic impact). The indicator may be chosen at any stage along the impact pathway that links the vector of inventory data $\mathbf{g}$ to an area of protection. Characterization at the midpoint level allows translating the environmental relevance of the inventory data at a certain stage along the impact pathway. Characterisation at the endpoint level models the impact on a certain area of protection. The formulation in (7) represents a methodological basis and benchmark for the development of a characterization model for a matter-less stressor.

1.5
The scientific value and uncertainty of LCIA models

If a stressor is deemed to be relevant and its inclusion in the LCA framework is possible from both a computational and methodological perspective, a modeller may proceed with the development of a model adhering to the computational structure of LCA and its other specificities as defined by the ISO (2006a; 2006b) standards. Huijbregts (2013) warns, then, to evaluate the scientific value of a certain methodology before recommending it to practitioners and to promote its use once it has reached a shared consensus. To this end, a variety of statistical techniques may be used to study the structure of a characterization model and the dependence among the model inputs. Statistical techniques help to investigate the scientific validity of a model, as part of a broader analysis of the uncertainty of the results that the model calculates.

Furthermore, a thorough set of indications should be provided to the LCA practitioners to guide the use of a newly-developed methodology, especially if extra steps are needed to treat a certain stressor, compared to the classic practice of the impact categories already existing in LCA. A case study may support this process and present both the guiding principles behind the development of a characterization model and its relevance in practical applications. This process of evaluation of fit, analysis of the specialist literature, development of the theory and the factors that define a stressor, evaluation of the model structure and of dependencies among inputs, and finally the application of the models in a case study, allow for the identification of the complete process of development of a new characterization model in LCA.

1.6
Research questions: aim and scope of the thesis

In this thesis, we will consider a sub-class of matter-less stressors whose physical properties are determined by the physics of waves, and consider the case in which no mass is transported during the propagation of these waves, but only energy. The thesis deals with the process of the development of any new characterization model in LCA. While the list of potential new and underdeveloped impacts is colourful involving a number of rather different types of stressors, the thesis focuses on three matter-less stressors that have been indicated as both underdeveloped and missing from the LCA framework and from LCA studies.

The analysis in the following chapters focuses on (i) sound emissions determining noise impacts, (ii) radio-frequency electromagnetic emissions determining electromagnetic pollution and (iii) light emissions determining ecological light pollution. The three stressors share the common feature of being physically determined by the physics of waves, are often co-occurring in the urban and peri-urban environment, and are increasingly attracting the attention of health scientists and policy makers alike due to the increased amount of solid evidence that regards their impacts (see e.g. Van Kamp and Davies, 2013 and Francis and Barber, 2013, for noise impacts; Baliatsas et al. 2012 and Crumpton and Collins, 2014, for electromagnetic pollution; Kloog et al., 2009 and Gaston and Bennie, 2014, for ecological light pollution). Even though some attempts have tried to deal with sound emissions and noise impacts (see e.g. Müller-Wenk, 2004 and Althaus et al., 2009), noise impacts are still outside of case studies. Moreover, to the knowledge of the author, no methodological propositions have dealt with light emissions and non-ionizing radiation.

By centralising the aforementioned matter-less stressors in the LCA framework, this work of thesis tries to answer the following research questions:

Q1 How to make sure that the knowledge of the impacts caused by a certain stressor is sufficient for its inclusion in LCA?

Q2 How to judge on which target subjects (e.g. humans) to focus the modelling activity?

Q3 How can matter-less stressors comply with the computational structure of LCA?

Q4 How to study the model structure, the dependencies among model inputs, and the importance of the model inputs to the output of a characterization model in LCIA?

Q5 How to verify the scientific validity of a new characterization model and guide the practitioner to its use?

1.7
The outline of the thesis

The thesis is subdivided in seven methodological chapters (see Figure 1.1 below), which relate to the research questions defined that the thesis aims to answer.

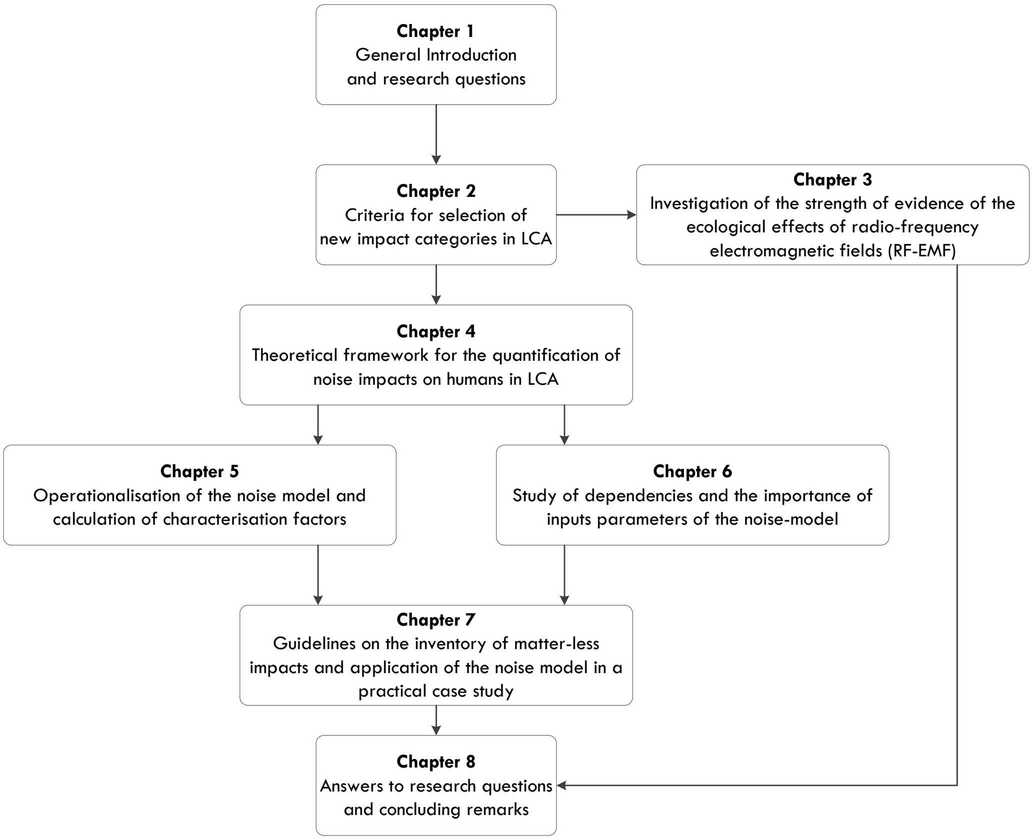

Figure 1. Outline of the thesis

The following **Chapter 2** provides guidelines for the inclusion of new impact categories in LCA and for the selection of stressors to which to give priority for improvement or original inclusion. The discussion deals both with methodological aspects of LCA, and on the strength of evidence in the specialist science field dealing with a stressor. The guidelines are tested for the cases of sound, radio-frequency electromagnetic and light emissions. Indications are given on which of these stressors should be given priority and for which a development or improvement should be started.

In **Chapter 3**, the evidence of the importance of the inclusion of radio-frequency electromagnetic emissions is further investigated from the point of view of the specialist literature dealing with this stressor. The direct experience of the review of the state of the art in the study of the impacts of radiofrequency electromagnetic fields on biodiversity is presented to demonstrate that attention needs to be paid to the evidence that is available in the specialist literature for a certain impact and to verify if a stressor is ready to be modelled in LCA. For the stressor in question, a detailed analysis of the state of the art was not yet available in the specialist literature for the case of the potential impacts on biodiversity. Therefore, an ad hoc review study involving ecologists and experts in the field was necessary to classify and evaluate the quality of the evidence.

Chapter 4 takes on the definition of a theoretical framework for the consideration of sound emissions and noise impacts in LCA. In LCA, noise impacts were indicated as relevant in a life cycle perspective since the early days of the methodological developments of the framework (Udo de Haas et al., 1992). Some methodological attempts have tried to model noise impacts, though still missing a clear relationship between sound emissions emitted by a source and a functional unit, and with a focus on traffic noise. A similar cause-effect chain as the one used for toxic emissions is applied to sound emissions and noise impacts, allowing this stressor to adhere to the computational structure of LCA. The model is defined without specifying an explicit source of sound emission, thus allowing considering any static and mobile source.

The theoretical model is further operationalized in **Chapter 5**, in which characterization factors at different level of specifications and different contexts of sound emissions are calculated for the first time in the field of LCA. The calculation of characterization factors for human noise at different levels of specification and regionalization define the first case of a complete development of a theoretical and then practical framework of analysis of sound emissions and noise impacts in LCA.

In **Chapter 6**, attention is paid to the matter of significance of LCIA models and on the use of statistical tools in the development phase of such models. The latest developments in the field of global sensitivity analysis are used to define a protocol to study the structure of any characterization models in LCA. The protocol is tested to the sound-noise model presented in the earlier chapter. The protocol and the combination of global sensitivity methods that it presents may be used to study any model used in LCA and in other contexts in the environmental sciences, in which the input-output relationship is known to the modeller.

Chapter 7 presents an LCA study, in which a variety of configurations of wind power generators are analysed to test the assumptions considered for the development of the sound-noise model, but also to give general indications on the way inventory and characterization phases should be dealt with for any other matter-less stressor. The focus of the study is on the quantification of sound emissions and the relative impacts for different configurations of wind power generators, which represent an example of new technology that are characterised by matter-less emissions during their operation.

Concluding remarks and causes for reflection close the thesis in **Chapter 8**.

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