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

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`To the generations of my ancestors`

Contents

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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):

$$\mathbf{As} = \mathbf{f} \tag{1}$$

hence,

$$\mathbf{s} = \mathbf{A}^{-1}\mathbf{f} \tag{2}$$

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:

$$\mathbf{g} = \mathbf{B}\mathbf{s} \tag{3}$$

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:

$$\mathbf{g} = \left(\mathbf{B}\mathbf{A}^{-1}\right)\mathbf{f} \tag{4}$$

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).

1

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:

$$\mathbf{h} = \mathbf{Qg} \tag{6}$$

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:

$$\mathbf{Q} = \mathbf{FF} \cdot \mathbf{XF} \cdot \mathbf{EF} \cdot \mathbf{DF} \quad (7)$$

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.

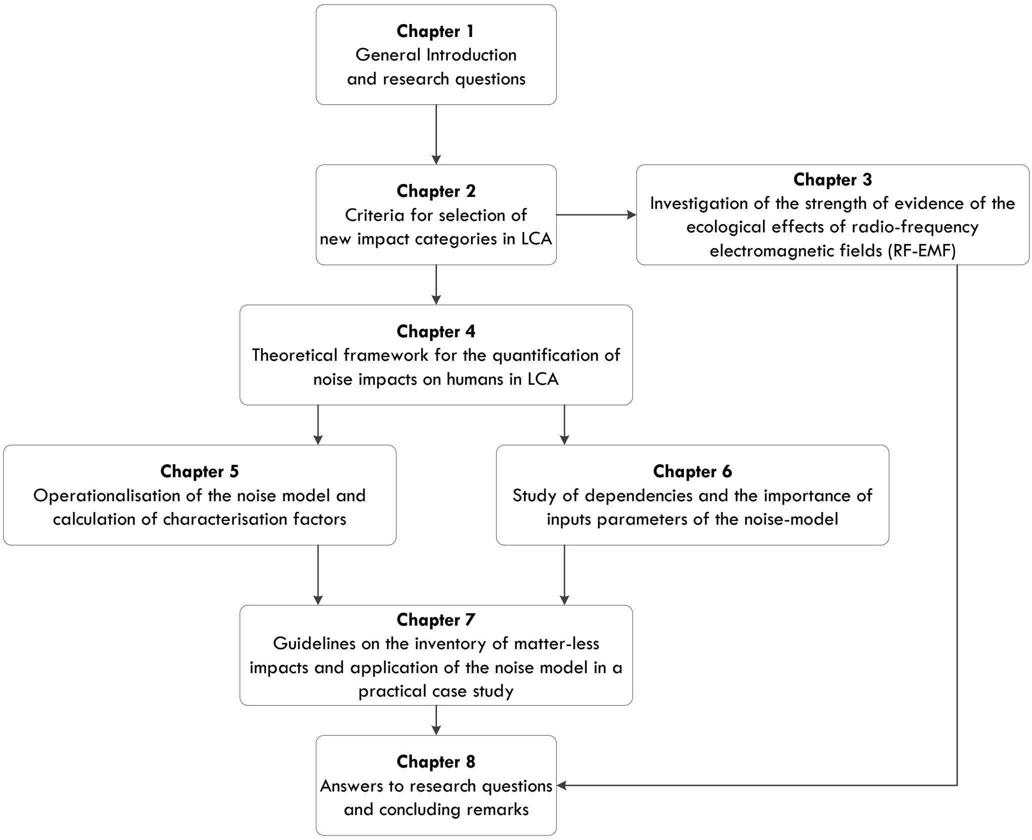

Figure 1. Outline of the thesis

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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2

A framework for deciding on the inclusion of emerging impacts in life cycle impact assessment

A framework for deciding on the inclusion of emerging impacts in life cycle impact assessment

Based on

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Abstract

As technology progresses, so does the concern about the potential health impacts on humans and biodiversity that go in hand with technological development. Emerging new impacts that are characteristic of the anthropocene require more attention in current life cycle assessment (LCA), a framework in which many relevant impact assessment models are still missing. More attention, more data and more concern require the LCA community to intervene and to start or increase the modelling efforts to accommodate new impacts in LCA. To date the process of inclusion of new impacts in LCA has not yet been formalised. To deal with this process, a framework is here proposed and tested through the analysis of three emerging impact categories, noise, ecological light pollution (ELP) and radio-frequency electromagnetic fields (RF-EMF). We show that any development must start from a careful study of the theories and investigations from other specialist fields of science than the field of LCA. The gathering of such information is fundamental to assess the maturity of the impacts, their importance and the quality of the evidence that is available. In addition, this information has to be bridged to the computational structure of LCA, to check whether the physical properties of new impacts may be adjusted to the basics of LCA. We discuss the three new potential impact categories as a paradigm for action for any new development in LCA.

Keywords

LCA; non-toxic pollutants; emerging pollutants; noise; ecological light pollution, electromagnetic fields

1 Introduction

Life cycle assessment (LCA) has developed over the last decade into a diverse and complex scientific discipline that actively involves scientists and practitioners from different fields. The development of the theory and practices of LCA has led to a fully functional methodology, which has become the reference in the sustainability assessment of products and services (ER-JRC, 2011). LCA studies are encouraged in the form of environmental policies or of recommended actions in a growing number of countries around the world (Guinée et al., 2010). A broadly agreed set of principles guides today the process of evaluating a product system throughout its entire life cycle (ISO, 2006), sustained by a constantly expanding series of publications that analyse a wide variety of methodological issues in LCA. Responding to pressures coming from its community of developers and users, the methodology has matured into a tool that answers sustainability questions at different scales, according to the problem at hand and the object of the analysis (Guinée et al., 2010).

LCA has been complemented, in a more or less harmonized manner, with capabilities that broaden its scope to quantify economic aspects (Swarr et al., 2011) and social repercussions (Dreyer et al., 2006; Klöpffer, 2012) of a product or service in a life cycle perspective. LCA, or ISO-LCA (ISO, 2006), has also been broadened through attempts to include and measure impacts for the most diverse and composite pathways. The range of impacts included in the framework has increased and includes life cycle impact assessment (LCIA) methods at a different level of development and complexity. Existing impact categories and characterization models, at both midpoint and endpoint levels, have also been expanded, as well as refined and perfected.

Over the years experts have addressed the necessity of expanding the scope of LCA, to include impacts that have not attracted the attention of model developers and to make LCA a comprehensive environmental assessment tool (Hauschild, 2002). In Bare and Gloria (2008), the complete taxonomy of impact categories that could be included in LCA is reported in a complete taxonomy. Impact categories are classified at the midpoint, endpoint and damage level. Even though the framework has been expanded, most of the impacts reported in the taxonomy are still missing in LCA.

The recent International Reference Life Cycle Data System (ILCD) effort of the European Commission (EC-JRC 2010a, 2010b, 2011; Hauschild et al., 2013) highlighted major areas of improvement for less developed impact categories, for which no specific methodology could be yet recommended, stressing that an increased perception of the risks also related to non-chemical pollutants has developed in the LCA community. Furthermore, the ILCD handbook specifies that "an open mind towards additional missing impact categories is needed" and other missing categories should be developed (EC-JRC, 2011). Impact categories that fall in the bucket labelled "missing impacts" include noise, nonionizing radiation (e.g. RF-EMF), light (e.g., from greenhouses), odour, desiccation, accidents, salination, impacts of genetically modified organisms (GMO), and erosion. Several shortcomings have limited the modelling effort for some impact categories which have been occasionally or never addressed by LCIA methods (EC-JRC, 2011). The limitations are recognized in the lack of appropriate inventory data, the lack of characterization factors, or the lack of consensus on the characterization model or principles of characterization (EC-JRC, 2011).

The authors classify these impact categories by their level of priority and amount of work needed to perform the modelling activities. The criteria by which these impact categories should be addressed are not explicitly mentioned in the handbook, nor is the scientific background that is at the basis of the impacts. Moreover, the potential lack of significant results from the investigations conducted by other scientific disciplines (e.g. epidemiology), or the lack of a precise knowledge of physical properties, cause-effect chains or dose-response relationships are also not explicitly mentioned as limiting modelling factors in this report, or in the other reference standards and publications used in the field of LCA (e.g. ISO 14044; ISO, 2006).

In this article, we propose a new framework and clear guidelines to be considered for the development of methodologies for new and emerging impact categories in the field of LCA. The newly proposed framework is tested and applied to a set of three under-developed or yet-to-be developed impact categories: noise, radio-frequency electromagnetic radiation, and ecological light pollution. All the three categories have been proposed as potential candidate for improvement or development in the LCA framework. Moreover, they share common physical properties (e.g. are non-chemical and not related to a release of matter), and are often co-occurring. We discuss the various aspects to be taken into account before and during the process of developing a characterization model for such impact categories in LCA. The importance of the study of models from the natural sciences (e.g. from the physical, ecotoxicological and epidemiological domains) is presented as part of the framework and analysed with reference to the three case studies. Significant methodological and formal aspects of LCA are presented in relationship with the proposed framework and in relationship with the three impacts used as case studies. Referring to the computational structure of LCA, indications are also given on the scientific limitations of the modelling activity, including possible issues not only at the LCIA level but also at the life cycle inventory (LCI) level.

2
The selection of a new impact category in LCIA

2.1
Mechanisms and strength of evidence

As Bryson et al. (2007) point out for a methodology to be useful to science it must provide a means of explanation and a mechanism for improving that explanation. A fundamental step of the study of any scientific development is the careful analysis of the specialist literature to identify which theories have been tested and which results have been corroborated by verifications. As much as general, this question pertains any field of science, including LCA. It is not uncommon in this field to borrow theories and models from other fields of science and to embrace them for the use in LCA. In the context of LCIA, the adoption of global warming potential (GWP) and ozone depletion potential (ODP) and the adaptation of the EUSES model for the evaluation of the impact of toxic chemicals have been in this respect trendsetting examples. However, this transition may not be always justified, or supported by evidence.

A developer should verify that the study of an impact is mature enough to be included in LCA, thus if e.g. the specialists that deal with that specific impacts have managed to define clear mechanisms. As in Popper (1963), "one can sum up all this by saying that the criterion of the scientific status of a theory is its falsifiability, or refutability, or testability". A sufficient number of critical tests, attempts of falsification and repetitions are fundamental conditions also for the inclusion of a theory and impact in LCA, especially if they have led to a standard procedure of measuring the impact. Moreover, it must be possible to establish a clear mechanistic link between the stressor and the impacts, which can be further translated into LCI results and an LCIA model respectively. The availability of sufficient information to be included in the LCI databases complements the process and ensures the future use of the methodology in practice, and also contributes to the quantification of potential sources of uncertainty. The modelling of a new impact should also avoid oversimplifying complex mechanisms in order to include them in the LCA framework.

A further analysis of the literature has to identify the extent to which an impact clearly affects a significant part of a population, videlicet human or animal. In this sense, a further distinction may be made between impacts on humans and impacts on biodiversity and ecosystems. Alternative or complementary elementary flows in LCI and pathways in LCIA may be developed for the different target systems: some impacts may be worth the development effort only for humans, or only for biodiversity. Together with the scientific validity of a theory, the magnitude of an impact reflects the urgency of the need of the modelling activity, and may determine a prioritization of a model to another at a precise point in time, as quantified e.g. for humans in terms of the amount of disability-adjusted life years (DALYs; Murray, 1994) that have been calculated for that impact in the world by a recognized agency (e.g. the World Health Organization).

Emerging issues may anticipate the need for the development of a methodology before the relative effects are quantifiable on a larger scale. Examples of such trends regard the long term issue of the by-products of nuclear energy, the consequences of the cultivation of GMO crops, or, more recently, the use of nano-technologies in multiple applications. Within the current procedures of technology assessment (Cruz-Castro and Sanz-Menéndez, 2005), the future trends of the effects of an impact should also be estimated as the result of the increase in the diffusion of a new technology. In the future, technology assessment, together with the social and ethical dimensions of a technology (Russel et al., 2010), should investigate the potential of causing new emerging impacts onto humans and biodiversity, and should also focus on the possible enlargement of the scale of impact of known impacts, as a consequence of technology penetration (Geels and Schot, 2007).

Once checks on the validity and importance have provided sufficient evidence of mechanisms, the analysis needs to identify the type of tool that is best to use to measure the impact. Therefore, before considering developing a methodology within LCA, a developer should verify whether the emission needs to be measured and whether the relative impacts are quantified within a global product system at several stages of a life cycle, or only for a local situation of exposure. Even though appealing from a research point of view, the development of a new model must answer to a real scientific and practical need for an LCIA model that will be effectively useful and preferred to other alternative tools (see Udo de Haes et al., 2004; 2006).

2.2
On the structure of LCI and LCIA: back to the basics

Once a solid body of information has been gathered from other specialist domains than LCA, the analysis must establish a clear mechanistic link between the stressor and the impacts, which can be further translated into LCI results and an LCIA model respectively. The availability of sufficient information to be included in the LCI databases complements the process and ensures the future use of the methodology in practice, and also contributes to the quantification of potential sources of uncertainty.

From a theoretical and methodological standpoint, all types of impact may be in principles included in LCA (Udo de Haes et al., 2004). The formal description of the different phases of an LCA study defined in the ISO 14040 series of standards and technical reports (ISO, 2006), together with the formalization of the computational structure of the various phases of the framework (see e.g. Wenzel et al., 1998; Heijungs and Suh, 2002), have contributed to define a baseline to which all new developments in LCA may be compared, tested, and contrasted. Therefore, it should be, at least formally, possible to include an impact in LCA in all cases in which a need is identified for the development of a new methodology to expand the scope of LCA. However, the structure of LCA is rather specific and does not always allow for an immediate adoption of models to its formal components.

Two alternative approaches have developed in the field of LCA to assess a system: the attributional and the consequential perspective. The traditional and still most commonly used attributional LCA allows analyzing the status quo of a system, as it is at a specific moment in time. The consequential LCA, on the other hand, is designed to evaluate the consequences of a decision on the system under study (Ekvall and Weidema, 2004). The two perspectives also differ in the way the inputs and outputs of the elementary flows are scaled to a functional unit. In the attributional perspective, the main material flows are described from raw material extraction to waste management using historical data. Following the consequential perspective, one should include the activities the life cycle that are affected by a change in the system, thus taking a marginal approach to account for the causal relationships and future environmental impacts that are triggered by a change in the system (e.g. a change in future demand). At the basis of both types of LCA, the relation to a functional unit sets an intrinsic limit to the type of aspects that can be meaningfully incorporated in the analysis under both perspectives. LCA has a flow character which clearly relates the material inputs and outputs of the product system (Udo de Haes et al., 2006), or elementary flows. All environmental burdens can be attributed in a consistent way to a functional unit, which allows for a comparison and a scaling of effects.

The procedure of scaling a process to a functional unit may not always be easily accommodated for all impact categories. Thus, it may be more difficult to include new impact categories in LCA if they are not based on inputs to or outputs from a product system (Udo de Haes et al., 2004). The characteristics of any new development in the impact assessment phase should hold a clear relation to a functional unit, which sets a condicio sine qua non for a category to be included in LCIA.

Typically, LCA involves the study of large product systems, with many unit processes, thus many inputs and outputs. A scaling process is needed to quantify the effective needs and flows of the system as a whole, which results in an intricate web of unit processes, many of which depend upon one another (Curran, 2012). A sufficient body of information needs to be recorded at the life cycle inventory (LCI) stage, to guarantee a full understatement of the elementary flows and their correct characterization. The temporal, spatial, physical (e.g. frequency-specific), and other context-specific elementary emission flows need to be carefully defined to take into account the complex systems of biologically-relevant processes that take place and their relevance to the specific situation of exposure of a target subject. A limit may be posed by the sheer nature of the units commonly used to measure the emissions (e.g. the use of a logarithmic unit); hence, a rigorous mathematical formulation should follow the computational and formal structure of LCI (e.g. adaptability to matrix algebra). This fundamental feature should not be overlooked or disregarded during the selection and modelling of a new impact category.

Once the inventory problem is solved, and all care has been taken to accommodate the model to the need of the LCI structure, the developer may move to the determination of a suitable impact assessment model. This model is typically providing the results which will be used for the characterization of the LCI data for a certain impact category. The characterization model is usually a simplified mathematical representation of physical, chemical and biological processes occurring along the cause-effect chain (Curran, 2012). A characterisation factor (CF; Heijungs and Suh, 2002) is provided by the impact assessment model and is usually specific to a substance (i.e. a chemical, or, per extension, any other 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 needed for the impact category under study. CFs for an impact category may be calculated following the classical toxics-based characterization scheme (Rosenbaum et al., 2007), defined for all effect types, compartments, and exposure routes. The so-called midpoint level reflects impact calculations somewhere before the end of the impact pathway, and relates the potential for each stress to cause an interim effect (e.g. acidification measured in hydrogen-ion equivalents; Curran, 2012). Midpoints are defined at the point in which a variety of substances share common mechanisms, determining a similar type of burden (Jolliet et al., 2004). At the endpoint, the point of comparison between one impact category and another is at the end of the cause-effect chain, at a stage in which no common midpoint is shared and rather areas of protection are approached (e.g. human toxicity health endpoints). When characterization is conducted at the endpoint, it may be easier for a practitioner to grasp the relationship between impacts and indicator results (e.g. loss of crop due to acid rain, instead of acidification potential).

An important simplification for the modelling process regards the assumption that the characterisation function measures a change in impact as a result of a small change in intervention determined by the product system under study, as compared to a large background of environmental interventions (Heijungs and Suh, 2002). A reference condition (e.g. a reference substance) is used to indicate that a marginal change has taken place for an impact category, as a consequence of a marginal emission e.g. of a substance x in a region y (Huijbregts et al., 2000). Therefore, the marginal changes determined by the functional unit on an additional amount of a stressor introduce very small changes on top of a possibly already perturbed background situation. Alternative approaches to the marginal one have been proposed (e.g. above-threshold in Potting et al., 1998, or a "zero-effect" or an "environmental target" in Huijbregts et al., 2011), may be evaluated case-by-case for the development of a new characterisation model. The model that best portrays the impact category under development may be the one that is recognized by the specialist literature, previously screened, as the reference for the impact under study (e.g. refers to a recognized standard).

Such assumptions need to be matched to the mechanisms that determine an impact, and to the way the fate, exposure, effect, and damage (Rosenbaum et al., 2007) for that impact may be defined. Once again also at the impact assessment level we deal with a structure that sets clear conditions on the modelling process that best accommodates the computational structure of LCA.

2.3
A stepwise approach

The considerations detailed in the previous sections may be further formalized to provide the skeleton for a stepwise checklist to be applied for any new development in LCIA. The consideration on the validity and importance of the basic theories, the relation of an impact to a product system and a set of elementary flows, the relation to a functional unit, the computational structure of the inventory and the characterization steps are all considered as sequential stages in the decision support tool shown in Figure 1. The application of the tool allows identifying which impact to prioritize when considering new developments in LCA.

Two main stages may be identified in the framework: an analysis of the specialist knowledge and an LCA compatibility test. The stages of the analysis conceptually belong respectively to the scientific domain of the classical natural sciences and to that of LCA, and are explicitly bridged by the framework. The two stages of the analysis allow respectively (i) verifying if sufficient evidence is available for a stressor and (ii) to what extent that knowledge allows to deal with the LCI and LCIA phases of LCA. The combination of these two pieces of analysis allows discerning between suitable and and non-suitable impact categories in LCA. In the first stage, the specialist literature in the field of the impact category under study is screened and analysed (step 1). The investigation of the literature focuses on the verification that sufficient evidence is available to confirm the mechanistic links between cause and effect, and that a cause-effect chain may be defined to link e.g. an emission to the impact that it has on a target subject. A thorough investigation and study of the specialist literature is advised. This process should involve the consultation of experts from the field of science by which the impact has been already investigated (e.g. ecotoxicologists, epidemiologists). The lack of agreement between relevant experts may be considered as a limiting factor for the development of a new impact. In all cases peer-reviewed publications and reports commissioned by internationally-recognised agencies should be preferred to the so-called grey literature.

In step 2, a suitable model is selected based on a standard, or on theories which have gone through sufficient rigorous validation. The model may refer to a reference standard for the propagation of an emission in a specific compartment (e.g. propagation of sound waves in air). The impact-specific physical properties (e.g. reflection, attenuation, deposition, absorption) are at this stage identified and classified. The theory should allow for the definition of a clear link between the physical properties of the impact and the effect that the impact has on the target-subject under study (e.g. by means of a dose-response relationship). The model developer may not proceed any further if clear mechanisms are not yet clearly known or supported by sufficient scientific evidence.

The importance of the impact is compared to others basing on the data provided by an international organization or by a peer-reviewed reference in the field (step 3). The importance should be used as a metric to prioritize the development of new impacts, and may be recursively re-evaluated if new evidence is available. Sufficient information should be available to deal with the collection of data and the need for the quantification of the impacts related to activities in a life cycle. The model developer should verify that there is a need to effectively quantify the impact across a life cycle, thus that LCA provides an added value compared to other environmental assessment tools.

In step 4 the information gathered is tested to verify whether a model should be developed to quantify impacts to each specific area of protection. The evidence and the theories that regard the effect of the impact on humans are gathered. Additionally, in step 4 the modeller evaluates the relationship between the impact under scrutiny and the natural environment, involving non-human life and biodiversity. The measure of biodiversity impacts also includes genetic diversity, species diversity, and ecosystem diversity (Udo de Haes et al., 2002). Finally, the modeller may evaluate if the impact is related to resources that are extracted physically for human use (i.e. abiotic resources such as fossil fuels, or biotic resources such as wood; Udo de Haes et al., 2002).

In the second stage of the process, the identified model and the body of information that has been gathered is tested for its applicability to the LCA computational structure, both at the LCI inventory phase and at the compulsory steps of LCIA (step 5, step 6). The mechanisms behind the emission and the impacts of the selected model are compared to the basic components of LCA as previously described. At first the analysis and development should deal with defining a model at the midpoint level of the impact pathway, closer to the environmental interventions. Once enough information has been gathered at the midpoint also in terms of additional uncertainty added, the model may be complemented to cover the complete impact pathway to the endpoint. The process ends with the definition of the items to be recorded in the inventory table and the identification of the best characterisation model.

The proposed checklist will be tested in the following section 3 with a selection of emerging impact categories.

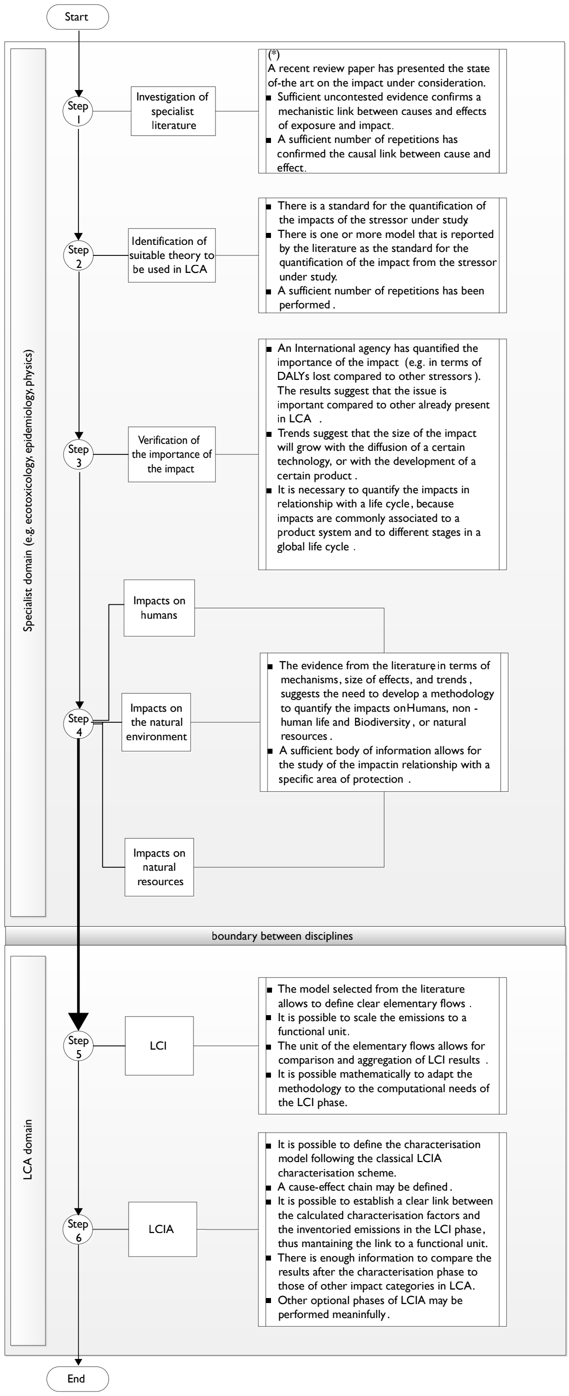

Figure 1. Decision criteria for the development of new impact categories in LCA. (*) = criteria not mutually exclusive

3
Analysis and empirical illustration with case studies. Application of the framework to new or underdeveloped impact categories

3.1
The case of the noise impact category

3.1.1 The evidence from the literature as a measure of importance and priority (Steps 1-4)

Noise relates to the exposure of a target to unwanted or disturbing sound produced by a static or mobile source. The exposure of humans to noise has been linked with sufficient scientific evidence to hearing impairment and tinnitus, hypertension, ischemic heart disease, annoyance, sleep disturbance, and decreased school performance (Passchier-Vermeer and Passchier, 2000; Fritschi et al., 2011). It has been quantified that all of these burdens contribute to the loss of at least one million healthy life years every year from traffic-related noise in the western part of Europe (Fritschi et al., 2011). Hollander et al. (1999) calculated a higher number of DALYs lost in the Netherlands from the exposure noise than from any other of the environmental factors considered (e.g. ozone air pollution, particulate air pollution). Dose-response relationships have been quantified for various levels of noise and potential effects have been demonstrated, especially with respect to annoyance and to heart conditions. The majority of the human population in the entire world is deemed to be exposed to noise levels that the WHO considers unhealthy (Stewart et al., 2012).

A considerable body of research also regards the impacts of the effect of anthropogenic noise on animals. Human activities associated with high levels of anthropogenic noise modify animal ecology of aerial, terrestrial and water organisms (Halwerk et al., 2011; Barber et al., 2010; Fewtrell et al., 2012). A work by Francis et al. (2012) has brought noise into community ecology, showing evidence that the exposure even alters fundamental ecological services such as pollination and seed dispersal, thus also having ripple effects on plant distribution and community structure (Chan and Blumstein, 2012). Anthropogenic noise is proved to alter acoustic environments determining shifts in animal communication, stress and behaviour especially in urban and road-side communities (Warren et al, 2006; Bee et al., 2007; Parris et al., 2009). Exposure to noise increases levels of stress even in the case of captive-held endangered species (Owen et al., 2004).Studies suggest that noise contributes to quality of territories and affects the behavioural ecology of territorial birds (Brumm, 2004). The exposure to noise plays a role in the shaping of the structure, diversity and density of urban bird communities, and has a direct impact on avian acoustic signals of territory defence, mate attraction and reproductive success (Slabbekoorn and Ripmeester, 2007; Halfwerk et al. 2011).

3.1.2
Relationship to LCA and the necessity to quantify impacts in relationship with a life cycle

Several phases of a life cycle may be associated with the productions of sound that can be perceived as noise. LCA often deals with product systems that involve activities that are typically sound-intensive, e.g. transportation, pile-driving, manufacturing, but it also comprehends the analysis of the use-phase of the life cycle of products when users are e.g. operating a machine determining the production of potentially harmful sounds. The appearance of noise in the LCA scientific discussion dates back to the early years of the methodology (Heijungs et al., 1992). Since then, several efforts have tried to incorporate noise in LCA, usually with a focus on transportation noise and the consequent human health effects (see e.g. Muller-Wenk, 2004; Althaus et al., 2009). A list of CFs and appropriate inventory data are not available in commonly used databases (Cucurachi and Heijungs, 2014). The ILCD handbook identified the noise impact category as one of the stressors with a high modelling priority, with a limited time effort required for its development (ILCD, 2010). The necessity of quantifying the burdens of noise on biodiversity has to date not been dealt with within the field of LCA.

3.1.2.1
The design of an appropriate functional unit (Step 5)

A logarithmic decibel (dB) scale is commonly used in the study of sound emissions and noise impacts. The dB may refer to either a sound pressure level (i.e. related to a pressure in pascal) or a sound power level (i.e. related to a power in watt; Passchier-Vermeer and Passchier, 2000). In order to consider the time a unit process is working for the functional unit, a sound power (i.e. sonic energy per time unit) in watt (i.e. J/sec) may be attributed to any source in the life cycle, by back converting the relative sound power level in dB using logarithmic algebra (Cucurachi et al., 2012; Cucurachi and Heijungs, 2014). Sound power is not location-dependent, but it belongs strictly to the sound source, therefore it perfectly suits the needs of LCI. Once the sound power is available, for each elementary flow in the life cycle it is possible to calculate the relative sound energy in joule to be inventoried in an inventory table.

3.1.2.2
LCIA model and pathway (Step 6)

A screening of the specialist literature revealed the presence of established standards for the propagation of sound through a medium (Cucurachi et al., 2012; Cucurachi and Heijungs, 2014). These include the ISO 9613-1 and ISO 9613-2 (ISO, 1992, 1996) and may be used for the evaluation of sound propagation through air. The standards allow for the quantification of the sound pressure that reaches a target at a defined distance from a source, as a function of the sound power of the source and the ambient sound power. A series of attenuation and directivity factors intervene and determine the transition from sound power to sound pressure (Cucurachi and Heijungs, 2014). The ISO standards allow for the definition of the fate factor. An effect factor, specific to the target subject under consideration, may be defined by quantifying the number of individuals living at the exposure compartment. Extra conditions are introduced to account for the species-specific perception of sound at difference frequencies and time (Passchier-Vermeer and Passchier, 2000; Fritschi et al., 2011). For the case of humans, the fate and effect factors are used to obtain characterisation factors for noise impacts on humans following the ISO 9613-1 and ISO 9613-2 and the human perception of sound in air. Characterisation factors allow at a midpoint level to calculate noise impacts from sound emitted by any source. In order to quantify a damage to the endpoint Cucurachi and Heijungs (2014) propose to move from the midpoint to the endpoint by means of a conversion factor that allows for the transition from an abstract unit of *person x pascal x second* to the DALY scale.

Specific frequency bands, sensitivity factors and penalties may be used for other targets (e.g. birds). Principles of underwater acoustics (e.g., reverberation, salinity of water) need to be considered for sound travel and attenuation in water. If the analysis needs to deal with animal targets, the conversions and calculations vary and the process requires the use of a species-sensitive biodiversity index to move to the specific area of protection.

3.2
The case of the (radio-frequency) electromagnetic pollution impact category

3.2.1
The evidence from the literature as a measure of importance and priority (Steps 1-4)

The generic term "electromagnetic radiation", as used by the ILCD report (EC-JRC, 2011), identifies a vast area of scientific knowledge which spans over several disciplines, physical properties and physical scales. The expression may as well refer to a system of natural sources of electromagnetic radiation, discharged in the earth's atmosphere by terrestrial and extra-terrestrial sources, such as thunders or the sun, to which the creatures of planet earth have always been exposed. The spectrum of electromagnetic radiation is rather complex and it extends, in fact, from extremely low frequencies with wavelengths in the range of km to gamma rays with wavelengths of the size of an atom. Radiation can be divided into non-ionizing radiation (radio waves, visible light and heat) and ionizing radiation (e.g. measured in Röntgen) that has sufficient energy to ionize an atom, breaking chemical bonds (Moller and Mousseau, 2013).

We focus in the context of this contribution on the effects of RF-EMF on humans and biodiversity, therefore on the range of the man-made electromagnetic fields of the electromagnetic spectrum many orders of magnitude above the natural background. The frequency ranges of interest are in the range of about 3 kHz to 300 GHz, with wavelengths ranging from hundreds of kilometres to about one millimetre. The main sources of RF-EMF are broadcasting transmitters (radio and television), mobile phone base stations, devices for wireless communication (e.g. cell phones, DECT phones and wireless LAN/WiFi), navigation and detection devices (e.g. radar, RFID chips, anti-theft portals), industrial machinery (e.g. plastic welding, dielectric heating, induction ovens), medical devices (e.g. MRI, hyperthermia; Baliatsas et al., 2012). All of the aforementioned sources can contribute to human exposure, with the weighted average exposure being mainly from own mobile and cordless phone use.

Apart from (local) heating of tissue, no other short term adverse health effect has been scientifically established (IARC, 2013). Some publications suggest that exposure to RF-EMF can have various biological effects from modulated RF-EMF, particularly at low-frequency modulated fields. However, to date neither plausible biological mechanisms, nor systematic or dose-dependent alterations have yet been identified. The International Committee on Non-Ionising Radiation protection (ICNIRP) published two sets of guidelines for limiting exposure for the general public and for workers (ICNIRP, 1998). These limits have been included in European Recommendation (1999/519/EC) for protection of members of the general population and in the European Directive for the protection of workers. beyond the effects of temperature elevation, it is still unclear how RF-EMF below recommended exposure limits could adversely affect the health of humans (and of other organisms, Lerchl, 2011). The recent IARC (2013) monograph on the effects of RF-EMF states that RF-EMF cannot produce physiological effects at temperature increases smaller than one degree centigrade, thus, in the range of thermal noise below measureable heating.

Sources such as mobile-phone base stations, electric power generators, transmitters, broadcast antennas, affect also other target systems (e.g., insects, birds; Baan et al., 2011). As reported by the WHO (van Deventer et al. 2011) a number of in vitro and in vivo studies of RF-EMF genotoxicity and effects on animal gene and protein expression have been carried out with mostly negative results. Cellular studies and studies on a number of animal models have found significant effects, which, however, have not been replicated or which did not provide dose-dependent responses (Feychting et al. 2005). Animal models, especially rats and mice, have been widely used to investigate potential effects of RF-EMF on humans. A review by Cucurachi et al. (2013) tried to link to ecological implications the biological evidence gathered from the review of RF-EMF animal studies, without finding significant evidence of a clear dose-response relationship for any of the analysed species group.

3.2.2
Relationship to LCA and the necessity to quantify impacts in relationship with a life cycle

Frischknecht et al. (2000) proposed a possible pathway for the inclusion of the impacts of ionizing radiation on human health in LCA, and measured the actual burden of radioactive emissions in terms of loss of life years in the population. Non-ionizing electromagnetic radiation, including RF-EMF, has to date failed to attract the attention of the LCA community. The transmission of electricity by means of power lines, or any other product group involving electricity production and use (see Huijbregts et al. 2008) are an example of a possible elementary flow of interest for LCA with respect to the impacts of RF-EMF. For higher frequencies, it would be interesting to analyse the use phase of a mobile device, base-station, or any other broadcasting device. Occupational exposures examples of interest include RF PVC welding machines, plasma etchers, and military and civil radar systems, all operating at different frequencies (IARC, 2013).

3.2.2.1
The design of an appropriate functional unit (Step 5)

The exposure to RF-EMF, as reported by the ICNIRP (2010), is usually specified in terms of physical characteristics such as modulation (continuous wave or pulsed), incident electric-field and magnetic-field strengths, incident power density (when appropriate), source frequency, type and zone of exposure (near or far field), and duration of exposure. Suitable information about these features of the exposure should be stored at the LCI phase to allow for a complete analysis of the relationship between source and target system(s).

In the context of dosimetry, the exposure of biological systems to non-ionizing radiation is estimated by means of specific absorption rate (SAR), in watt per kilogram (W/kg). A suitable conversion would have to be used to derive a convenient unit to meaningfully aggregate electromagnetic emissions over a life cycle and to connect them to a functional unit. The knowledge of the SAR allows for the quantification of the electric field strength in relationship to the density of the absorbing medium under consideration, and provides a good estimate of the temperature of the system with which it is very closely correlated. For the LCI phase, the experimental measurement or estimation of the SAR could be the relevant quantity to inventory, along with the electrical properties and wave characteristics of the source under study. The knowledge of these elements would allow to later analysing any possible mechanism of interaction independently of the source of the RF-EMF under study. A convenient definition of the elementary flow would allow for all the relevant information to be carried to next phases of the LCA. The duration of exposure as function of the time a functional unit is active in the system would provide a fundamental information to allow making a hypothesis of possible health effects.

3.2.2.2
LCIA model and pathway (Step 6)

There is no known mechanism by which RF-EMF might assert biological effects in humans or other systems, beyond the induction of local heating by RF-EMF (IARC, 2013). Moreover, as Roosli (2008) reports there is limited knowledge on how to combine high, periodic local exposure from sources close to body (e.g. mobile phone) with lower, continuous whole body exposure from environmental fields (e.g. mobile phone base station). Therefore, for the potential modelling of RF-EMF impacts a modeller could only represent at the current state of knowledge only the fate step of the complete impact pathway. The relationship between RF-EMF energy and biological systems is based on the induced electric and magnetic fields, the power deposition, energy absorption, and the distribution and penetration of the energy into biological tissues (ICNRIP, 2009). The exposure of a whole body or part of the body to a given field strength, if enough information was to be reported in the LCI, would have to be considered, and would certainly represent a complicating modelling factor. As in ICNIRP (2010), a quantitative understanding of biological responses to the exposure can be obtained if dosimetric quantities such as SAR, induced electric field, and current density, can be correlated with the observed phenomenon, thus with the relevant flow in the life cycle under study.

Computational algorithms may be used to define fate and exposure analyses and to link dosimetric values with other physical characteristics of the field (e.g. the distance from the source of emission of the RF-EMF to the target, potential dissipation of energy, and the size of the exposed population; ICNIRP, 2009). The lack of accepted mechanisms, dose-response relationships, and disability weighting scales/damage functions limits the possibility to bring the analysis further at the current state-of-the-knowledge. Therefore, the modelling of the impacts of RF-EMF cannot be tackled beyond the LCI phase and the fate step of LCIA, for both the cases of human and non-human exposure.

3.3
The case of the ecological light pollution impact category
3.3.1
The evidence from the literature as a measure of importance and priority (Steps 1-4)

ELP refers to the condition of direct glare, chronically increased illumination, and unexpected fluctuations in lighting due to a number of sources in cities, towns, industrial sites, and off-shore enlightened locations (Longcore and Rich, 2004). These may include lighted buildings, lights on vehicles, flares on offshore oil platforms, lights on undersea research vessels, highly lighted fishing and cruise fleets, and sky glow (i.e. the brightening of the sky beyond background levels due to reflected light; Longcore and Rich, 2004; Navara and Nelson, 2007). The autonomous or interactive effect of these sources may affect humans and ecosystems to varying degrees. It has been estimated that 19% of the earth surface and about two-thirds of the world population live in areas where the night sky is above the threshold set for polluted status, with 99% of European and American citizens experiencing nightly light pollution (Cinzano et al. 2001).

The chronic exposure to light at night (LAN) of shift workers has been linked to an increased incidence of breast and colorectal cancers, as a consequence of disruption of hormone production, and especially of the suppression of the antioncogenic agent melatonin and/or of disruption of clock gene function by open eye exposure to LAN (Schernhammer et al. 2003, 2004; Pauley 2004; Haim and Portnov, 2013). The link between LAN and breast cancer is now officially recognized by the WHO and the American Medical Association (Bedrosian et al., 2013). The exposure to LAN has also been linked to serious effects on mood of vulnerable individuals, directly by studies on humans or from evidence gathered from rodent studies on mice and hamsters (Bedrosian et al., 2013). Recent studies found evidence of a possible link between LAN and obesity (Fonken et al., 2010; Eckel-Mahan and Sassone-Corsi, 2013), and between LAN and diabetes (Marcheva et al., 2010).

A growing body of research regards the impacts of artificial light on biodiversity and ecosystems. The exposure to ELP may have critical effects on the natural day-night cycle of insects, amphibians, fish, birds, bats and other animals (Longcore and Rich, 2004; Rich and Loncore, 2006; Holker et al., 2010; Perkin et al., 2011; Gaston et al., 2013). Ecological impacts of ELP have been proven to determine a cascade of alteration of physiological and behavioural processes and determine a series of yet to be fully known consequences on natural ecosystem processes (Gaston et al., 2013).

3.3.2
Relationship to LCA and the necessity to quantify impacts in relationship with a life cycle

ELP is absent from LCA studies, though the quantification of its impacts may be of interest for selected life cycles. For the impacts on humans, activities involving night shifts or rotation of shifts may be considered as contributing to possible burden on human health, e.g. from the alteration of the hormone secretion system of individuals exposed to LAN. Impacts on mood alternation and sleep disturbance of individuals may also be considered for selected functional units.

A possibly wider application regards the quantification of impacts due to LAN on biodiversity (e.g. the loss of biodiversity due to exposure to LAN and sources of artificial light). The impacts of ELP (including LAN) may be considered for the LCA of streetlight technologies, lighting products, or for lights in commercial, industrial and residential premises, greenhouses, or illuminated vessels or oil platform in open sea. For the case of alternative lighting options (e.g. incandescent lamp vs. LED lamp), the potential impacts of the specific wavelength, intensity and brightness of the lighting systems may constitute an extra issue to be addressed, not yet considered in current LCA studies. Different forms of artificial lighting increased spatial, temporal and spectral distribution over the recent decades, and have, as reported by Gaston et al. (2013), unique spectral signatures all potentially influencing evolutionary and ecological processes.

3.3.2.1
The design of an appropriate functional unit (Step 5)

A sudden change in illumination over the absolute illumination levels is considered by ecologists as disruptive for human and some species (Longcore and Rich, 2004). The determination of illumination (i.e. incidence of light per unit of area) in a given place (Longcore and Rich, 2004) is one the most common measurement of ELP. Illumination is often measured in lux, an SI unit, which is the measure of the perceived power of light per unit of area, thus corresponds to 1 lumen per square meter. The emphasis of the measure is on wavelengths that the human eye is more capable to detect, thus on brightness as perceived by the human vision. In most cases, lux is the standard way used by producers of equipment, or by policy makers to communicate about light conditions.

In the case of biodiversity, supplementary biologically-relevant information is needed to fully understand the impact of ELP. As stated by Longcore and Rich (2004), the impact of the phenomenon on biodiversity is fully understood only if also further biologically-relevant information is available, such as the intensity of the light (i.e. number of photons per unit area) and its spectral content (i.e. wavelength). Therefore, the elementary flows in the LCI table would ideally include all the above information. A more suitable unit for non-human targets is the radiant flux of the emitting source, which indicates the total electromagnetic power emitted by a source. The measure (also called radiant power) corresponds to the radiant energy per unit time and its unit is the watt. Therefore, the scaling of the emission to a functional unit, basing on the time the source is active in the system would heed results to be inventoried in units of radiant energy, thus joule. The unit could be used in combination with the functional unit expressed in hours of use or lumen hours commonly considered in the existing LCA of light-emitting devices (see e.g. Tähkämö et al., 2013).

3.3.2.2
LCIA model and pathway (Step 6)

The literature on ELP is vast but lacks a synthesis within a common mechanistic framework (Gaston et al., 2013). For the case of humans, it would be challenging and uncertainty-prone to link the effects of ELP and LAN to available statistics on cancer and to a human-health factor in a suitable scale, e.g. DALY. A possible pathway is proposed by Bedrosian et al. (2013) and regards the potential influence that the exposure ELP may have on the circadian rhythm and mood of human beings, and it is based on the functioning of the human eye and its relationship to melatonin secretion.

The prediction and modelling of ELP over a location of interest may present some challenging computational and methodological issues. The ELP of a local atmosphere depends as stated by Kocifaj (2011) "on the size, shape, spatial distribution, radiative pattern and spectral characteristics of many neighbouring light source" and also from distant sources. Local atmospheric and physical conditions are also relevant influencing factors (Kyba et al., 2011). Theoretical assumptions would be necessary, since the total radiative pattern would vary from location to location.

Kocifaj (2007) proposes a scalable theoretical model of light pollution for ground sources, which takes into account the influence of local atmospherical conditions on the transmitted radiation (e.g. the impact of clouds on the light-pollution situation under study). The parametric model, tested also for planar ground-based light sources (Kocifaj, 2008), may be used in the context of LCIA to define fate and exposure factors for light pollution to be linked to the specific defined elementary flows. The model, originally not specifically developed for the ecological implications of light pollution, would have to be adapted to work with any possible LCA-relevant source of light and to further link the altered conditions of the background lightscape (as available from e.g. Cinzano et al. 2001; or Bierman, 2012) to an extra functional unit of the source of light under study. The feasibility of the approach needs to be further studied due to the necessity of dealing with highly-localised conditions of exposure.

As in the case of RF-EMF, though the relationship between the emissions of light and its propagation could be modelled, the absence of clear mechanisms would not allow to further define a complete impact pathway, thus a suitable LCIA model.

4
Discussion

For certain life cycles it is the sheer lack of a good model that determines that a flow does not have an impact in a system under study. For instance, it has been claimed that the inclusion of the impacts from noise in some LCA studies may change their final outcome (EC-JRC, 2011; Cucurachi et al., 2012), highlighting other hotspots than the ones that the latest version of the commonly used databases may yield.

In this paper, we show that an increasing awareness about potentially harmful effects of certain impacts does not necessarily lead to their immediate inclusion in LCA. The application of the proposed selection criteria needs to guide the developer in deciding which impacts at a specific moment in time are to be privileged. The methodological limitations of the framework of LCA and the physical complexity of the laws regulating the phenomena under study are key elements to analyse before engaging in any new development in LCIA.

The non-toxic impacts analysed in this contribution all share a common physical nature, which relates to energy that shows a wave-like behaviour as it travels through space or through a medium. Though holding similar features, the detailed study of each of the stressors reveals unique and rather different modelling needs, and, interestingly, a different state of knowledge that scientists have about the complex mechanisms that influence the way these emissions may potentially be harmful for living organisms. The outcome of this study (see Table 1) provides a first approximation of what to take into account when dealing with new impact categories, and in particular with noise impacts, RF-EMF impacts and impacts of ELP.

Stressor/ Impact	Mechanistic effects (Steps 1-2-3)	Impacts on humans (Step 4)	Impacts on the natural environment (Step 4)	Impact on natural resources (Step 4)	LCI (Step 5)	LCIA (Step 6)	Recommended extent of modelling effort
Sound/ Noise	Dose-response relationships have been quantified for humans and selected species	Highly relevant	Highly relevant		Sound power converted to [J] by means of time	Defined pathway for noise impacts on humans. To be developed for biodiversity. Characterisation factors for the noise impacts on humans expressed in unit of person x Pa/W	Modelling possible to midpoint for human targets. For the case of biodiversity, further studies should be conducted
RF-EMF emission/ RF-EMF pollution	No adverse health effect, beyond heating for humans. No strong evidence of a clear dose-response relationship for any of the analysed species	Contrasting evidence. Classified as carcinogenic by IARC	Potentially severe effects, but lack of repetitions		SAR [W/kg] to be converted to a suitable unit to allow for aggregation and scaling to the functional unit	Only fate factor may be modelled based on the physical properties of electromagnetic waves	Modelling not possible at the current state of knowledge for the complete impact-pathway
Light emission/ ELP	Demonstrated for humans and animals through melatonin mediation.	Evidence available in occupational contexts	High		Light power converted to J by means of time.	Only fate factor may be modelled based on the physical properties of light waves	Modelling not possible at the current state of knowledge for the complete impact-pathway

Table 1. Synthesis of the applied framework on the three matter-less stressors

A first screening of the literature in all cases presented with a clear evidence of potential harmful effects. All impacts are clearly relevant and necessitate of attention also from the point of view of the LCA community, due to their potentially severe impacts on humans and/or biodiversity. However, from a methodological point of view, the mechanisms that lead to the determination of effects are not always fully known or do not always find a consensus in the specialist scientific community of reference.

Of particular interest in this sense, are the impacts from the exposure of organisms to RF-EMF: no clear mechanisms, beyond temperature elevation, have been identified. The literature does not exclude the potentially carcinogenic effects of RF-EMF on humans, but contrasting evidence has been found (IARC, 2013). In this case, the lack of a protocol of exposure and measurement, the design of studies, the limited sample size of the studied populations and the existence of confounding variables have hampered progress to date and do not allow to define clear mechanisms. A case-by-case analysis of a certain species or family is necessary to conclude on specific mechanisms. The analysis of the specialist noise literature provides a clearer picture, with mechanisms and size of the effects defined for both humans and some species birds or sea mammals, which have interested a number of studies of high quality. Finally, the study of the ELP suggests that, for human exposure, only occupational exposure of shift workers should, at this moment in time, be taken into consideration in LCA. In the case of biodiversity, a large body of evidence provides accurate information on the way to model the exposure-response pathway, showing that artificial light has the potential to significantly disrupt ecosystems (see e.g., Hölker et al., 2010; Rodriguez et al., 2012 ; Gaston et al., 2013). Some open questions require attention, due to the lack of a common mechanistic framework and of general principles (Holker et al. 2010).

Focusing on the methodological aspects of LCA, it would be technically possible to record a sound, RF-EMF, and light emissions in an inventory table, in relation with the functional unit under study. In all cases, however, a consistent body of information would need to be registered for each elementary flow about the exact context of the emissions. This particular approach may differentiate these emissions from other flows in LCA, if we compare it to the commAson practice for toxic substances for which the specification of the emission compartment may deal with limited extra information (e.g., high or low population; Frischknecht et al., 2005).Until the moment that a vast amount of information would be stored in the commonly used LCA databases about possible inventory flows, LCA practitioners would have to deal with such challenging tasks. This approach may be feasible for local studies, dealing with just a few elementary flows, but may prove challenging when the system under study is more complex, as is typically the case of most

LCA studies. More, and more detailed information would be needed for thousands of basic processes and flows. This consideration has to be taken into account also in view of the current tendency of highly-regional and highly-spatial explicit characterization factors. While giving the possibility of portraying any possible context of emission, and exposure, these developments may yet clash with the reality of a limited visibility of flows and processes for a life cycle that spans over a global system. The solution of the LCI problem is key to the effective use of an impact assessment model. The possibility of calculating CF by considering average conditions representative of regions of the world, or of the entire globe, may contribute to control these limitations. The recent work by de Baan et al. (2013) provides an interesting application of the average approach for the case of the impacts of land use. The determination of archetypes of typical contexts of emission, though increasing uncertainty, will certainly help the users towards this goal.

At the LCIA phase, the good knowledge available of the physics of waves for all of the three impact categories considered allows to model the path between the emission compartment and the exposure compartment. This also includes the modelling of the possible attenuations and local conditions (e.g., temperature, humidity; see Cucurachi and Heijungs, 2014 for the case of sound emissions). We saw in section 3 that the knowledge of the mechanisms that relate the fate and exposure factors to a possible effect factor and, eventually, damage factor (Curran, 2012) are not always clear. An issue at this stage may determine a lack of significance of the model, thus suggest that it should not be taken into consideration given the knowledge that it is available at the current state. This will hamper the effective use also of a methodology otherwise rigorously developed. Developments in the understatement of the mechanisms of exposure-effect-damage will be necessary for a suitable model development. For the development of an impact assessment model, it is also necessary to have sufficient information on the background exposure levels, i.e. spatially and temporally, before any functional unit involving the emissions under consideration is considered. In the examples considered, while such information is available for the case of noise in the form of noise maps and for ELP in the form of light pollution maps, only recently it is available in the context of RF-EMF at the sole demographical level for Europe (Gajšek et al., 2013).

Based on such findings, in both the cases of RF-EMF and ELP we provide evidence that the LCI phase could be modelled, and the knowledge of the physics of waves would allow representing the physical propagation of waves, their attenuation and relationship to a functional unit. The LCIA modelling would, however, stop at the fate phase since no clear mechanisms are available to explain the specific impacts of each stressor on any target.

For the case of noise, on the other hand, it is possible to define for human targets the complete impact pathway to the midpoint level of LCIA modelling.

In the case of the impacts on biodiversity, the current metrics used in LCA do not seem to provide a sufficient accurate measure to be matched to those mechanisms that are known. A paradigm-shift towards a species-by-species approach would be needed to consider only those impacts that are clearly known and proven, therefore bringing LCA to a rather different approach than the potential risk of global loss of biodiversity that is currently preached for in the community. The use of biodiversity indicators (e.g., mean species abundance of original species as in Alkemade et al., 2009) calculated for a specific biome (de Baan et al., 2012), has to be complemented with the specialist knowledge of the mechanisms existing at a specific species level. The effectiveness and the feasibility of such an approach need to be further studied, due to the considerable amount of data to be gathered, analysed, and processed.

5
Conclusions

The proposed framework allows to judge to which impacts to give priority in LCA. The analysis of the three unusual impacts taken into consideration provided sufficient information to evaluate the possibility to include them in LCA, given their importance in a number of relevant life cycles. The necessary modelling effort differs across the three categories, as does the knowledge of the seriousness of the effects and the clarity of the underlying mechanisms. This clearly puts a priority for research towards impact categories with compatible characteristics. Other tools rather than LCA need to be used until then, and possibly preferred, if a highly specific local study has to be conducted.

We showed that the inclusion of such categories may not be constrained neither by the complex physical principles that are at the basis of the relative sciences, nor by the specificity of the structure of LCA. The overview of some basic elements of the computational structure of LCA, has defined some criteria for the development of new impact assessment models. For the emergent impacts here presented, it seems sensible to say that we are not incurring in what Udo de Haes (2006) has called the 'Cinderella-effect', thus we are not physically squeezing the physics of waves to the needs of LCA, or vice versa. Though some attention is still required at the LCI phase due to the type of information that needs to be gathered and stored, we can conclude that there are reasonable and scientific solutions to define elementary flows. What requires more attention is the knowledge that we have at this moment in time of the mechanisms that determine an effect, which are fundamental to define a characterization model. This clearly puts a priority for research towards noise impacts and ecological-light impacts, rather than on RF-EMF impacts. Other tools rather than LCA, need to be used until then and possibly preferred if a highly specific local study has to be conducted.

The expansion of LCA to include complex impacts, such as the ones dealt with in this paper, may determine a barrier to practitioners lacking a specialized knowledge of the literature and mechanisms that determined the modelling of the impact assessment models. A detailed knowledge of a characterization model will be increasingly required if LCA expands and deepens its focus by incorporating newly available scientific evidence. This work may be considered an integral part of the development and improvement of the LCA framework.

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3

A review of the ecological effects of radio-frequency electromagnetic fields (RF-EMF)

A review of the ecological effects of radio-frequency electromagnetic fields (RF-EMF)

Based on:
S. Cucurachi , W.L.M. Tamis , M.G. Vijver, W.J.G.M. Peijnenburg, J.F.B. Bolte, G.R. de Snoo. 2013. *Environment International,* 51, 116-140.

Abstract

Objective*: This article presents a systematic review of published scientific studies on the potential ecological effects of radiofrequency electromagnetic fields (RF-EMF) in the range of 10 MHz to 3.6 GHz (from amplitude modulation, AM, to lower band microwave, MW, EMF).*

Methods*: Publications in English were searched in ISI Web of Knowledge and Scholar Google with no restriction on publication date. Five species groups were identified: birds, insects, other vertebrates, other organisms, and plants. Not only clear ecological articles, such as field studies, were taken into consideration, but also biological articles on laboratory studies investigating the effects of RF-EMF with biological endpoints such as fertility, reproduction, behaviour and development, which have a clear ecological significance, were also included.*

Results: *Information was collected from 113 studies from original peer-reviewed publications or from relevant existing reviews. A limited amount of ecological field studies was identified. The majority of the studies were conducted in a laboratory setting on birds (embryos or eggs), small rodents and plants. In 65% of the studies, ecological effects of RF-EMF (50% of the animal studies and about 75% of the plant studies) were found both at high as well as at low dosages. No clear dose–effect relationship could be discerned. Studies finding an effect applied higher durations of exposure and focused more on the GSM frequency ranges.*

Conclusions: *In about two third of the reviewed studies ecological effects of RF-EMF was reported at high as well as at low dosages. The very low dosages are compatible with real field situations, and could be found under environmental conditions. However, a lack of standardisation and a limited number of observations limit the possibility of generalising results from an organism to an ecosystem level. We propose in future studies to conduct more repetitions of observations and explicitly use the available standards for reporting RF-EMF relevant physical parameters in both laboratory and field studies.*

Keywords
Radiofrequencies, EMF, biodiversity, electromagnetic field exposure, ecological effect, mobile telecommunication**

Abbreviations.* ***ELF-EMF *= extremely low field electromagnetic field;* ***CW*** *= continuous wave;* ***MW*** *= microwave;* ***PW*** *= pulsed wave ;* ***GSM*** *= global system for mobile communications;* ***UHF*** *= ultra-high frequency;* ***VHF*** *= very-high frequency;* ***DECT*** *= digital enhanced cordless telecommunications;* ***UWB*** *= ultra wide band; AM = amplitude modulation;* ***FM*** *= frequency modulation;* ***GTEM*** *= gigahertz transverse electromagnetic cell;* ***UMTS*** *= universal mobile telecommunications system;* ***CDMA*** *= code division multiple access;* ***TDMA*** *= time division multiple access;* ***WCDMA*** *= wideband code division multiple access;* ***Wi-Fi*** *= Wireless Fidelity;* ***WLAN*** *= wireless local area network;* ***WiMAX*** *= worldwide interoperability for microwave access.*

1
Introduction
1.1
Scope

Anthropocene is a term which has been proposed for the current epoch, due to the global environmental effects of increased human population, the economic and industrial development and to the deep overall domination and contamination of the human over the environment (Crutzen and Stoermer 2000; Zalasiewicz et al. 2010). Amongst the many changes, a radical modification has taken place also in the exposure of beings to man-made electromagnetic fields. A continuous, chronic, exposure to a wide range of modulated radiofrequency electromagnetic fields (RF-EMF) burdens all species and groups across the globe.

In terms of mechanisms, the WHO confirms that to date the accepted health effects ascribable to RF-EMF are caused by temperature elevation (van Deventer et al. 2011). Though, several studies have identified possible effects of RF-EMF on organisms, no alternative effect mechanisms have been confirmed to date. Most of the literature has focused on human and occupational health, largely based on animal model studies under laboratory conditions and test subjects exposed to lower frequencies of the spectrum (i.e. extremely low field, ELF -EMF). From the available studies, it became clear that, especially under higher dosages, effects of RF-EMF may be observed. As a response, occupational and human health threshold values and guidelines, proposed by international organisations (ICNIRP 2010), have been increasingly incorporated into national regulations of states (EU 2011). However, results are still not conclusive and there is still some uncertainty about the low dosages and non-thermal effects applied in some studies which did find an effect, and the overall quality of the setup of research in the field. The ever increasing use of RF-EMF in the cellular phone ranges (e.g. GSM, UMTS) and the newer forms of wireless communication (e.g. WiFi, WLAN, WiMAX), which are rarely present in the available studies, require new investigations which will look at possible short and long-term effects.

Over time several monographs and reviews have been compiled as to the biological effects of RF-EMF on humans, and on animals (see among others: Michaelson and Dodge 1971; NCRP 1986; Bryan and Gildersleeve 1987Adair 1990; Verschaeve and Maes 1998; Juutilainen 2005; Balmori 2009; Pourlis 2009; ICNIRP 2010). While of great relevance for the understanding of the phenomenon, these studies lack in the consideration of potential effects which may directly affect other organisms or ecosystems, because of the very limited attention which is usually received by the adverse ecological effects of RF-EMF.

1.2
Problem definition

Limited research and reviews have focused on investigating the possible ecological effects of RF-EMF. It can be argued that many human-related biological studies using animal models (e.g. rats, rabbits, etc.) may provide also relevant information about potential ecological effects. Many ecological endpoints (e.g. fertility, reproduction, growth) studied at the level of the individual animal, are also crucial from an ecological point of view. Ecology is, one of the sub-disciplines of biology, which studies all living organisms (including human beings), at all organisational levels (i.e. from the smallest molecular system to the largest ecosystem levels). Ecology is the scientific study of the distribution and abundance of organisms and the interactions that determine distribution and abundance (Begon et al. 2005). Those interactions refer to the abiotic and the biotic environment. By definition ecology focuses on the higher organisational levels of populations, communities and ecosystems. Despite the lack of information of the ecological effects of RF-EMF, following this definition, it is then plausible to link biological studies with ecological endpoints at the individual animal level to ecological interpretations at a higher organisation level.

This field of research is of crucial importance for the understanding of mechanisms of interaction between complex ecosystems and the environment. Animal studies have still been identified as a major research agenda point by the WHO (Van Deventer et al. 2011). The WHO stated that high priority in the field should be given to research on the effects of RF-EMF on development and behaviour, on aging and reproduction of animal subjects. The result of these studies might be ecologically interpreted, because they include ecologically relevant endpoints.

As far as strictly ecological research has been conducted, it was mostly presented in the form of non-peer-reviewed grey literature. A review of Balmori (2009) is the only oriented at the effects of RF-EMF on wildlife. However, the contribution by Balmori (2009) has some methodological issues. The criteria for the screening of the literature or the rationale for the inclusion or exclusion of relevant articles have, in fact, not been presented. The review is also missing a detailed analysis of the selected papers (e.g. of the duration of exposure, of the physical parameters, etc.) and it includes only studies finding a significant effect of RF-EMF.

1.3
Research focus

Evidence suggests that there is a large lacuna in research regarding the ecological effects of RF-EMF. The aim of this contribution is to conduct a scientifically sound review of potential ecological effects of RF-EMF. Using the definition and guidelines provided in the clinical sector by Higgins and Green (2006), a systematic review on potential ecological effects of RF-EMF was performed.

The study focuses on the range from 10 MHz to 3.6 GHz (i.e. from AM to the lower band MW EMF), using a transparent, comprehensive and objective substantive review approach and analysis of the available scientific literature on the ecological effects of RF-EMF. The literature search was based on a clear and objective research strategy (see section 2) performed using two databases: ISI Web of Knowledge and Google Scholar. The experimental, physical and biological parameters, which were provided by the selected papers were classified and analysed to look for trends and possible links between dosages and effects.

Papers evaluating ecological endpoints as part of biological investigations were selected with a focus on higher organisational biological levels: ecosystem, community, and species. As much as possible also biological studies, present in biological reviews or in relevant papers, if relevant from an ecological point of view, were included in this review and analysed.

A complete review of the biological literature was beyond the scope of this paper. However, laboratory studies on animals and plants that investigated biological endpoints can still provide information relevant for the ecological level.

First in Section 2 the methods are described, in Section 3 the general results are presented, and in Section 4 the specific results are given for each of the analysed groups (i.e. birds, insects, other vertebrates, other organisms, and plants). The final sections (Section 5 and Section 6) provide a synthesis, with possible links between dose-response relationship, the setup and dosage of the studies, together with general conclusions and recommendations.

2
Review method
2.1
Criteria of literature search

The literature research was conducted, in the second half of 2011, using ISI Web of Knowledge and Google Scholar databases. Publications on ecological effects of RF-EMF on all relevant endpoints on non-human organisms and parts of organisms (e.g. tissues, cells) were taken in consideration. Additional scientific articles published after December 2011were added upon indication and suggestion of experts.

In order to maintain a high scientific standard for this review paper, only publications which were peer reviewed were considered. As criterion for peer review, the presence of the publication in the ISI Web of Knowledge was used. As for papers present only on Google Scholar an expert selection was made based on the ecological relevance and quality of the studies. The criteria used were based on quality criteria defined by relevant methodological reviews (Repacholi and Cardis 1997; Stam 2010). Repacholi and Cardis (1997) suggest that reviews should take into consideration only literature published in scientific peer-reviewed journals to guarantee a selection of articles free from methodological deficiencies and with rigorous analysis and conclusions. They also suggest care when dealing with peer-reviewed reports not published in scientific journals as well as conference abstracts, which are usually not peer-reviewed. In this review, only peer-reviewed papers have been selected. In a limited number of cases peer revision could not be guaranteed: the case of a study conducted by Harst et al. (2006) on honey bee (Apis mellifera), in which no sufficient information could be found on the review procedure of the relative journal, and the studies by Van Ummersen (1961; 1963), Carpenter et al. (1960), and Clarke (1978) which were reported by the (peer-reviewed) review by Bryan and Gildersleeve (1988).

The literature search was limited to the range of frequencies from 10 MHz to 3.6 GHz. Papers on the biological and ecological effects of ELF- EMF in the range of 1 Hz – 100 KHz (e.g. power line fields) were not considered. Date of publication was not used as a restriction and all publications falling within the above selection criteria were analysed, including those which did not find significant effects.

The keywords used in the literature research process are reported in the appendix to this review. Two main categories were defined: RF-EMF specific keywords (e.g. GSM, DECT, 1800 MHz) and ecological keywords (e.g. growth, population, eco*).

2.2
Description of the literature search

Main search strategy:

A step-wise search strategy was conducted to find the most relevant articles in the RF-EMF range selected.

As a first step, the literature research was conducted, following the criteria previously described, on the ISI Web of Knowledge website, which provided 451,031 hits. Since this number of articles was too large to handle, a selection process was started. The collection was further refined by selecting only articles, reviews and proceeding papers as document types (440,528 hits). Then, specific categories were selected: applied physics, cell biology, plant sciences, environmental sciences, biophysics, zoology, ecology, biology, microbiology. The number of hits was so reduced to 98,620.

In order to reduce the number of hits, all the results clearly outside the RF-EMF field of research, or beyond the scope of this review, were excluded. This process reduced the number of hits further to 90,408 hits. A further screening was conducted selecting keywords from the RF-EMF specific and from the ecological defined groups, using one or two of RF-EMF keywords singularly or in combination with a single keyword from the ecological group. The obtained results ranged from 10 hits to 600. Titles were then screened one by one to select papers that could be of interest.

An analogous pattern of searches was performed on Google Scholar and only articles that had not yet been found on ISI Web of Knowledge were added. The number of hits for the initial combination of keywords was 3,600,000, and then reduced with an analogous procedure as described in ISI, but with a more attentive look at the content and the source of the selected papers.

After this first step of the searching process, 709 presumably relevant articles were identified. A one-by-one screening of titles and abstract was performed to investigate which papers would meet the defined criteria (e.g. frequency range, biodiversity exposure to RF-EMF). This second screening led to a new selection of 307 papers.

A closer analysis of the content of these 307 selected papers revealed that most of them regarded highly specific and technical strictly biological studies (e.g. rat tissues, cell-line studies, neuronal studies, calcium signalling, etc.), which were difficult to link directly to ecological effects, and, therefore, discarded. The final selection was reduced to 55 clearly relevant papers.

Related-references search

As a second step, it was decided to proceed by using a selected number of the 57 available articles to create a search based on "related references" to the ones used by their authors. The first articles used were those that clearly met the scope of the review in terms of focus and content: e.g. Balmori (2005), Panagopoulos et al. (2010)

and five others. The screening of a total of 4,000 hits provided 32 additional relevant hits.

Also a selection of the relevant references was conducted from the four relevant reviews (Bryan and Gildersleeve 1987; Verschaeve and Maes 1998; Juutilainen 2005; Pourlis 2009) and this resulted in 15 additional articles.

Regular updates were conducted until October 2012 to include also the most recently published relevant literature. After a careful analysis of all gathered information a total of 113 articles was selected and described in detail in the following sections. The total number of experiments carried out in these articles was 152.

3
General overview of results

The biggest share of the articles (c. 90 %) involves laboratory studies with biological endpoints with a clear ecological relevance. The remaining part regarded ecological field studies (Table 1).

Most of the laboratory studies included had growth, development, behaviour and reproduction/fertility as biological endpoints. The endpoints analysed in field studies were behaviour, shift in populations and fertility. In circa 65% of the studies a statistical significant effect of RF-EMF on ecological relevant endpoints has been found (Table 1). There were no clear differences in percentage effects between articles included in reviews or not included in reviews. Development seemed to be less significantly affected in percentage than growth and fertility.

Table 1. General overview of effects and no-effects studies across articles types, endpoints and species groups.

General findings of articles	
	Count
Included in review (including 80 articles, 4 reviews and 18 articles from these reviews)	113
Finding an effect	74
Not finding an effect	39
Laboratory studies	106
Field studies	8
Endpoints investigated	152

Subdivision of articles among species		
	Effect	No effect
Birds	18	8
Insects (including bees, fruit-flies and ants)	15	2
Other vertebrates (mostly animal models)	25	25
Other organisms (nematodes, bacteria, etc.)	4	0
Plants	12	4

End points studied in screened articles		
	Effect	No effect
Birds	**20**	**18**
Growth	3	4
Development	4	3
Fertility/reproduction	4	8
Behaviour/stress	3	0
Mutation	4	0
Mortality	0	1
Population decline	2	2
Insects	**22**	**3**
Growth	-	-
Development	4	0
Fertility/reproduction	9	1
Behaviour/stress	6	1
Mutation	-	-
Mortality	0	1
Population decline	1	0
Other vertebrates	35	27
Growth	4	1
Development	9	5
Fertility/reproduction	7	11
Behaviour/stress	13	7
Mutation	1	1
Mortality	1	2
Population decline	-	-
Other organisms	4	0
Growth	2	0
Development	-	-
Fertility/reproduction	-	-
Behaviour/stress	2	0
Mutation	-	-

Mortality	-	-
Population decline	-	-
Plants	**22**	**2**
Growth	12	0
Development	3	0
Fertility/reproduction	1	0
Behaviour/stress	3	1
Mutation	3	1
Mortality	-	-
Population decline	-	-

The most represented groups include vertebrates, other than birds (i.e. predominantly rats, mice, rabbits), then birds and plants. Articles which found significant effects of RF-EMF were found more frequently in the case of birds, insects (i.e. mostly honey bees and fruit flies) and plants. The group of other vertebrates (Table 1) was equally distributed among significant and non-significant effects. Effects were significant in all the articles on other organisms.

The type of endpoints studied differed across groups. Fertility was the mostly analysed endpoint for the birds. Growth was affected in all the experiments conducted on plants and other organisms, while it was affected In 25% of the studies on other vertebrates and ca. 40% on the birds. The effects of RF-EMF on behaviour were found in thirteen of the twenty of the studies on other vertebrates and in 85% ca. of the studies on insects.

4
Ecological effects of RF-EMF
4.1
Birds

Birds have been widely used to analyse the environmental significance of exposure to nonionizing radiation. The ability of birds to detect magnetic stimuli has been documented by several studies (see Keeton 1971; Wiltschko and Wiltschko 1996; Thalau et al. 2005; Wiltschko et al. 2011). A total of 26 articles was selected from the screened literature with 38 relevant endpoints. With the exception of five field studies, all studies were conducted in a laboratory setting.

Of the 26 studies, 70% have been significantly related to the effect of RF-EMF (Table 1). In most cases the effects studied were growth and fertility and were conducted, until the early nineties, under a continuous microwave system of exposure (i.e. 2450 MHz). The physical parameters usually reported regarded the measured level of power flux density and specific absorption rate (SAR). These parameters were either measured using probes or specific detectors or were based on the information of the manufacturers of the exposure devices.

Chicken (Gallus domesticus) and Japanese quail (Coturnix coturnix subsp. japonica) represented the most studied experimental system in laboratory studies on birds. Approximately 60% of the laboratory studies considered a system at the embryo or egg stages of development.

4.1.1
Laboratory studies

3

Embryo and egg

In the eighties and early nineties researchers focused on the effects of MW EMF. There was a high level of interest especially in the ranges that would be relevant, at that time, for the possible implementation of new source of renewable power based on the collection of solar energy in space by means of solar power satellites (SPS add to abbreviation list) and its transmission to earth via MW EMF (Glaser 1968; Wasserman et al. 1984). The three more recent studies (Table 2) investigated the typical cellular phones range of frequencies.

All the measured physical parameters varied greatly across studies. The estimated SARs ranged between 0.001W/kg and 140 W/kg (Kleinhaus et al. 1995; Van Ummersen 1961), while the duration of the exposure was as little as 9 seconds (McRee and Hamrick 1977) with peak values of 45 days (Grigoryev 2003). The variation which was found for the power density ranged from 4.4 x 10^{-6} mW/cm^2 as in Reijt et al (2007) to the 400 mW/cm^2 measured in Van Ummersen (1961).

The endpoints included growth, hatchability, development based on evidence of abnormal weight of hatchlings, incidences of abnormalities and mortality. Nine of the 15 experiments showed significant differences between RF-EMF and controlled/sham-exposed eggs.

It is a common opinion among experts (Baranski and Czerski 1976; Bryan and Gildersleeve 1987) that the results obtained in most of the studies until the 1980s (i.e. until Inouye et al. 1982 in this selection) relate to increases in the temperature of the egg due to the consequences of hyperthermia a few degrees above normal incubation temperature. An abnormal increase in temperature gradient of 3.5 degrees Celsius had been already observed in the early study by Van Ummersen (1961, 1963), reported in the review conducted by Bryan and Gildersleeve (1987). In a later study, Byman et al. (1985) found no effect on the growth and normal development of born chicks of birds nesting in proximity to antennas. Temperature rise was controlled and the measured power density was 25 mW/cm^2. Analogous results were obtained by Gildersleeve et al. (1987) who kept the internal temperature of irradiated and sham-exposed eggs to a mean of 37.5 degrees Celsius without detecting any deficiency in the reproductive performance of males and females allowed to hatch.

Among the three more recent studies, Bastide et al. (2001) and Grigoriev (2003) found a significant increase in mortality due to RF-EMF on chicken (Gallus gallus subsp. domesticus) embryos exposed to RF-EMF emitted by a GSM device during the duration of the incubation period.

Also Batellier et al. (2008) studied the effect of exposure to GSM and UMTS frequencies on chicken eggs over the entire period of incubation. Four replicates with a total 240 eggs each were used in the experiment to assess mortality rates. Results showed an increased mortality of 42.2% for embryos under a regime of controlled temperature, humidity and external EMF. However, it was not possible to establish a proportional relationship between the intensity of the electric field and embryo mortality.

Juvenile and adult

Five studies focused on the impact of RF-EMF at a later phase of development of chickens: four studies on juvenile and only one on adult subjects (Table 2). The endpoints studied were growth, fertility, rate of egg production, hatchability and mortality.

The only study which found a significant difference between exposed and control/sham groups is the study by Giarola and Krueger (1974) on juvenile chickens. The authors examined exposure to very-high frequency (VHF) and ultra- high frequency (UHF), together with investigation of MW EMF. Exposure determined reduced growth of chicks and consumption. In a follow-up study Krueger et al. (1975), did not find effects either on fertility or hatchability with a continuous exposure period of 12 weeks at a power density (calculated) of 1 mW/cm^2. Experts from the U.S. department of energy (NASA 1978) attributed the difference in results to the cage used in the first study which may have determined a higher dose of energy absorbed by the target subjects.

4.1.2
Field studies

There were five field studies on the impact of RF-EMF exposure at various frequencies and physical conditions on populations of birds living in areas in the vicinity of cellular phone masts or base-stations. Anomalies and deviations from normality in the behaviour of exposed subjects and in the level of productivity were found in all these studies.

The values of power density provided by studies ranged from 4.4 x 10^{-6} mW/cm^2 in the study on sparrows by Everaert and Bauwens (2007) to the highest measured value of 155 mW/cm^2 in Wasserman et al. (1984). In this last case, exposure caused a steady temperature raise which determined a continuous gaping for the total duration of exposure of the exposed population of sparrows (Zonotrichia albicollis) and juncos (Junco hyemalis). Values for the SARs were provided only by the study of Wasserman et al. (1984) and ranged from 0.85 to 0.92 W/kg. The endpoints studied were density, reproduction, behaviour and community composition. In all the studies and experiments conducted, effects of the RF-EMF were found from a variation of 10% to a maximum of 70% compared to control.

Balmori (2005) monitored the variation of a population of white storks (Ciconia ciconia) in the vicinity of a GSM base station.(I.e. 900-1800 MHz with 217 Hz modulation) in search of possible effects from the exposure. Total productivity within 200 m was on average 46% less than that found at a distance greater than 300 m from the emitting station. An analogous significant difference was found in the breeding success: in 40% more of the cases no new-born chicks were found in the nest.

In another study, Reijt et al. (2007) studied the influence of long term exposure to RF-EMF from radar (200-1300 MHz) on a population of Great tits (Parus major) and Blue tits (Cyanistes caeruleus) living around a military radar station. Possible other sources of co-variance (e.g. from human interactions with the location of birds, other pollutants, etc.) were not considered in the study. Unlike in the case of Balmori (2005), the exposure seemed not to have affected the number of nesting tits, but the distribution of the different species. The authors state that the results contradict with the study of Balmori (2005), probably because of the exposure of targets to radar MW (i.e. 1200-3000 MHz), instead of mobile phone exposure (i.e. 900-1800 MHz with 217 Hz modulation).

Additionally, Reijt et al. (2007) found that exposed nests were occupied, compared to control, by the less dominant species of tits (Blue tit), which would suggest that birds can perceive high frequency RF-EMF as a stressful factor and, thus, would try to avoid nesting in those areas. An average of 50% of the great tits moved from a more exposed section of the study area to a less exposed one: in the interaction with the great tit, the blue tit is usually less dominant according to behavioural studies by Tanner (1966) and Tanner and

Romero-Sierra (1974). Therefore, the Great tit would move to areas where the power density is lower, and therefore the Blue tit would have to nest elsewhere.

Figure 1 presents a plot of the effect with the relative measured power density, from studies with a significant effect (see Table 2 for details on the studies). It is not possible to define a clear dose-effect relationship, but also at low values of power density strong effects of RF-EMF are found.

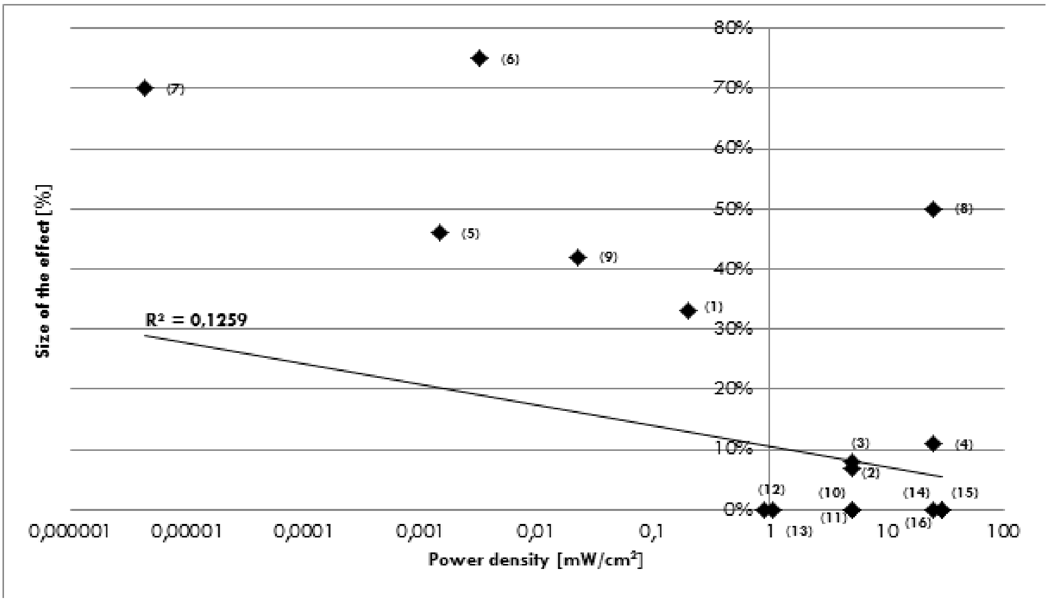

Figure 1. Size of the ecological effects of RF-EMF on birds related to the power density of exposure. Articles reported in graph: (1) - Hills et al. (1974); (2) - Inouye et al. (1982); (3) - McRee et al. (1975); (4) - Wasserman et al. (1984); (5) - Balmori (2005); (6) - Balmori and Hallberg (2007); (7) - Everaert and Bauwens (2007); (8) – Reijt et al. (2007); (9) - Batellier et al. (2008); (11) – McRee et al. (1975); (12) - Krueger et al. (1975); (13) - Davidson et al. (1976); (14) - McRee and Hamrick (1977); (15) - Byman et al. (1985); (16) - Gildersleeve et al. (1987). See Table 2 for a complete description of studies. Data is reported for studies from which information could be extracted. The equation of the regression line is y = -0,0078x + 0,2908.

Summary

Most studies on birds were laboratory investigations. The target subjects were in the majority of laboratory studies chicken and Japanese quail. Older laboratory studies exposed targets to high level of MW EMF which probably determined an uncontrolled raise in temperature which affected the exposed systems. Amongst the more recent laboratory studies, evidence of an effect of RF-EMF on mortality and development of embryos was in all cases found at both high and low dosages. In all the five field studies found a significant effect of RF-EMF on breeding density, reproduction or species composition. Field observations give a closer representation of real-life exposure, thus RF-EMF, especially in the 900 MHz GSM band could be a certain factor influencing the ecology of birds.

Table 2. Summary of articles reporting ecological effects of RF-EMF on birds.

Reference	Country	Species	Scientific name	Life stage [a]	Type of study [b]	Number of subjects [c]	Duration of exposure	Frequency [MHz]	Wave / Modulation [d]	Power Density [mW/cm^2] [e]	SAR [W/kg] [f]	Effect [g]	Effect size [h]
Carpenter et al. (1960)	USA	Chicken	*Gallus gallus subsp. domesticus*	Emb	Lab	n/a [i]	1-15 mins	2450	MW CW	200 280 400	70 98 140	Teratogenic effects on the embryo idem idem	+
Van Ummersen (1961, 1963)	USA	Chicken	as above	Emb	Lab	n/a	1-15 mins	2450	MW CW	200 280 400	70 98 140	Inhibition of growth idem idem	+
Hills et al. (1974)	Canada	Chicken	as above	Emb	Lab	n/a	20-300 sec; first 2 days of incubation	2450	MW CW	0.2 246 1020	n/a	Reduced chicken hatchability	+ (33%)
Giarola and Krueger (1974)	USA	Chicken	as above	Juv	Lab	n/a	28 days idem	880 260	UHF CW VHF CW	0.5 0.5	n/a n/a	Reduced growth rate Reduced growth rate	+ +
Hamrick and McRee (1975)	USA	Japanese quail	*Coturnix coturnix subsp. Japonica*	Emb	Lab	n/a	24 hrs	2450	MW CW	30	14	Reduced hatchability, altered/ organ development	-
McRee et al. (1975)	USA	Japanese quail	as above	Emb	Lab	57 (4)	4 hrs for first 5 days of incubation	2450	MW CW	30	14	Altered development	-

Krueger et al. (1975)	USA	Chicken	as above	Ad	Lab	5 (5)	12 weeks	260	VHF	0-1	n/a	Unaltered fertility, reproduction and hatchability	-
							idem	915	UHF	1.25	n/a	Unaltered fertility, reproduction and hatchability	-
							idem	2450	MW CW	1	n/a	Unaltered fertility, reproduction and hatchability	-
Davidson et al. (1976)	Canada	Chicken	as above	Juv	Lab	n/a	4.5-6 sec	2450	MW	1.043	n/a	Unaffected egg production	-
											n/a	Unaltered growth, reproduction, mortality	-
McRee and Hamrick (1977)	USA	Japanese quail	as above	Emb	Lab	n/a	First 12 days of incubation	2450	MW CW	5	4.03	Unaltered development	-
Clarke (1978)	USA	Chicken	as above	Emb	Lab	n/a	34th-60th hr of incubation	2450	MW PW (mod. 60 Hz and 12 Hz)	100	n/a	Behavioural changes in hierarchy positioning as adults	+
Fisher et al. (1979)	Canada	Chicken	as above	Emb	Lab	n/a	4-5 days	2450	MW CW	3.5	n/a	Early embryonic development	+
Cabe and McRee (1980)	USA	Japanese quail	as above	Emb	Lab	n/a	First 12 days of incubation	2450	MW CW	5	4.03	Altered response to behavioural tests as adults	+

Inouye et al. (1982)	USA	Japanese quail	*as above*	Emb	Lab	n/a	First 12 days of incubation	2450	MW	5	4.03	Develop-mental retardation of Embryos. No diffe-rences after week 8	+ (7%)
McRee et al. (1983)	USA	Japanese quail	as above	Emb	Lab	270 (120)	First 12 days of incubation	2450	MW CW	5	4.03	Reduction in reproductive capacity	+ (8%)
Wasserman et al. (1984)	USA	Sparrow; junco	Zonotrichia albicollis; Junco hyemalis	Var	Field	12 flocks (2 flocks)	20 mins; 200 mins	2450	MW	25	0.85-0.92	Variation in level of aggression of birds after exposure	+ (11%)
Byman et al. (1985)	USA	Japanese quail	as above	Egg	Lab	30 (90)	60 mins du-ring 17 days incubation	2450	MW CW	20-50	0.5	Unaltered growth or abnormal development	--
Gildersleeve et al. (1987)	USA	Japanese quail	as above	Emb	Lab	468 (468)	12 days during incubation	2450	MW CW	5	4.03	Unaltered fertility, reproduc-tion and hatchability	-
Kleinhaus et al. (1995)	Israel	Migratory birds	n/a	n/a	Sim	n/a	n/a	4-26	Broadcast station	n/a	0.001-0.004	Unaltered development and populati-on levels	
Bastide et al.(2001)	France	Chicken	as above	Emb	Lab	300 (300)	Incubation period	900	GSM	n/a	n/a	Increased mortality. Inhibition of normal development	+ (53%)
Grigoriev (2003)	Russia	Chicken	as above	Emb	Lab	n/a	21 days	900	GSM	n/a	n/a	Increased mortality	+

Balmori (2005)	Spain	White stork	Ciconia ciconia	Pop	Field	60 nests	2 months	900-1800	GSM base station	0.001477 (mean within 200 m); 7.45093 x 10^{-5} (mean farther than 300 m)	n/a	Severe decline in productivity	+ (46%)
Balmori and Hallberg (2007)	Spain	Sparrow	Passer domesticus	Var	Field	40 visits (1200 datapoints)	3 years and 8 months	1MHz-3000	GSM to MW	0.00325 (max); 4.24403 x 10^{-5} (mean)	n/a	Decline in bird population and dose-effect relationship found between electric field strength and population decline at specific locations	+ (75%)
Everaert and Bauwens (2007)	Belgium	Sparrow	as above	Var	Field	150 locations	4 months during the breeding period	925-960	GSM base station	4.34589 x 10^{-6}	n/a	Significant relationship between number of house sparrows and levels of power density	+ (70%)
							idem	1805-1880	GSM base station	9.07759 x 10^{-6}	n/a	Idem	
Reijt et al. (2007)	Poland	Great tit; Blue tit	Parus major; Cyanistes caeruleus	Ad	Field	72 (42)	45 days	1200-3000	Radar	20-50	n/a	Unaltered fertility and growth.	-

Batellier et al. (2008)	France	Chicken	*as above*	Egg	Lab	240 (240)	Incubation period	900	GSM	0.00306-0.04197	n/a	Possible shift in species distribution Reduced hatchability. Increased Embryo mortality	+ (50%) + (42%)

[a] Life stage refers to the age of the tested subject at the moment of the experiment. **Emb** = embryo, **Ad** = adult, **Egg**= egg

[b] Studies divided in laboratory and field studies. **Lab** = laboratory study, **Field** = field study.

[c] Number of subjects involved in the experiment or field study where reported in the study. In brackets information about number of control subjects.

[d] Wave/Modulation indicates the type of RF-EMF applied/measured in the study. **CW** = continuous wave, **MW** = microwave, **PW** = pulsed wave **GSM** = Global System for Mobile Communications, **UHF** = Ultra-High Frequency, **VHF** = Very high frequency.

[e] Values of power density are reported as provided by authors or recalculated by conversion of electric field values (PD=EF2/3770) and expressed in mW/cm^2.

[f] Values of SAR are reported as provided by authors and expressed in W/kg.

[g] Biological or ecologically relevant endpoints studied.

[h] Size of the effect where significant. It indicates the ration between maximum effect and percentual difference compared to control. A sign + indicates a significant effect, a – sign indicates that no significant effect was found.

[i] n/a indicates that data was not provided by authors.

4.2
Insects

Insects are a useful target system for the investigation of RF-EMF because of the limited size, the short life cycle and the possibility of easily detecting developmental defects (Schwartz 1985). It has been demonstrated that insects can sense magnetic fields as a means for navigation and orientation (Kirschvink et al. 2001; Abraçado et al. 2005; Liedvogel and Mouritsen 2010; Wajnberg et al. 2010; Winklhofer 2010). Magneto-reception has been associated with the use of ferromagnetic iron oxide particles embedded in tissue or through pairs of molecules with unpaired electrons (known as radical pairs) that are associated with a light sensitive photoreceptor (Ritz 2000; Knight 2009; Vácha et al. 2009). The exposure to RF-EMF might disrupt this magneto-reception mechanism, which could in turn affect the survival of insects. The most commonly studied species are the honey bee (Apis mellifera) and the fruit fly (Drosophila melanogaster).

3

4.2.1
Honey bees (*Apis mellifera*)

Over the past few years, a phenomenon known as Colony Collapse Disorder (CCD) has increased the attention of experts on the survival of colonies of honey bees (Schacker 2008; Balmori 2009). The reduction in population of bees worldwide could have serious ecological, economic and, thus, political implications given their role as pollinators. It has been estimated that 15% of wild plant species in Europe (Kwak et al. 1998) and 35% of the global crops produced (Klein et al. 2007) are visited by honey bees. Bees are interesting for this reason from an economic perspective: their economic role has been estimated to be around 153 billion euros in the year 2005 (Gallai et al. 2009). RF-EMF has been classified as one of the possible causes of honey bee colonies collapse (Ratnieks and Carreck 2010). Even though the interest of media and the public in the effects of exposure of honey bees to mobile communication RF-EMF has drastically increased, there does not seem to be a thorough body of research into their effects in the scientific literature. As a result, the screening conducted in this contribution identified only eight studies which matched the defined criteria (Table 3), for a total of 12 experiments. Six of the studies focused on the frequency ranges specific to mobile communication and in all cases found a significant relationship between the exposure to the field and the effects studied. Only two of the studies found were not produced in the last decade (Westerdahl and Gary 1981a, b). These studies were the only ones which did not find any significant effect on flight, orientation of behaviour of bees exposed to CW microwaves (i.e. 2450 MHz) at power densities from 3 to 50 mW/cm^2.

Among the studies that did find an effect, Sharma and Kumar (2010), Kumar et al. (2011)

and Sahib (2011) found a critical reduction of all studied parameters of the exposed colonies of bees as a response to RF-EMF. In all cases, an acute decrease in the breeding performance or even a collapse of the entire colony resulted as a consequence of exposure to RF-EMF. However, the studies provide limited statistical information on the scale of the effect found and did not take into account other confounding parameters (e.g. the placement of the emitting device inside the hive).

The work by Harst et al. (2006) and Kimmel et al. (2007) from a German research group seems to support the previously described findings, but do not provide any statistical measure of the effects found and did not report any system of control or sham-exposure.

Clearer conclusions can be drawn from the study by Favre (2011), which seems to be the most complete and qualitatively interesting contribution. Using sound-analysis techniques, the author investigated the changes that were triggered in the behaviour of a population of honey bees of the carnica group (Apis mellifera subsp. carnica). The sounds produced by the bees from five healthy and unexposed hives were used as a negative control and compared with recordings made when the same hives were exposed to a mobile phone handset in a calling position. Another inactive mobile phone was placed, at an earlier stage, to investigate the possible disturbing influence of the sheer presence of the tool in the hives. The analysis of the recorded sounds revealed that the bees produced sounds at higher frequency and amplitude after about 25 to 40 minutes after the communication had started and became quiet when the handset was switched off.

No particular difference in behaviour and sounds was found for exposure to the inactive handsets. The analysis of the sound data revealed that the bees were, in fact, producing the so-called "worker piping", which usually serves as a signal for swarm exodus as a response to danger or stress, thus RF-EMF directly affected the community of bees under exposure.

4.2.2
Fruit flies (*Drosophila melanogaster)*

The screening of the literature identified five studies on the fruit fly (*Drosophila melanogaster*) for a total of nine experiments (see Table 3). All the available studies found a significant effect. The RF-EMF applied focused on the GSM 900 MHz and GSM 1800 MHz (named also DCS –Digital Cellular System) systems.

RF-EMF power density was measured in the range of 0.0002 to 0.0407 mW/cm^2, several order of magnitudes lower than those measured in the previously analysed laboratory studies on birds and bees. All the values can be considered typical for digital mobile telephony handsets and in most cases fall within the current exposure criteria (ICNIRP 1998). Unlike the previous cases, in most studies it was possible to collect information about the magnetic flux density, which ranged from to the time-averaged 0.003 μT of Panagopoulos et al. (2004) measured for a DCS frequency to 0.09 μT in the study by Panagopoulos et al. (2010). SAR levels were, when provided, obtained by elaboration of data provided by the manufacturer (i.e. for the human head) of the system used for exposure and not directly measured.

The ecologically relevant endpoints analysed in the studies were growth and reproduction. All of the analysed studies found a significant effect compared to the control. With the exception of a study by Weisbrot et al. (2003), all studies were conducted by a research group from the University of Athens, Greece. In the study of Weisbrot et al. (2003) the irradiation determined a beneficial effect on the reproductive success of the exposed system. The number of off-springs even increased of up to 50% compared to control. All the other studies found a significant depression of growth and reproduction as a response to exposure. Several studies performed by Panagopoulos and co-authors (see Table 4) found a maximum decrease in the endpoints of at least 40% compared to control. Exposure duration lasted for six minutes per day or increased over time up to a maximum of twenty-one minutes over a period of six or five days. The reproduction of experiments performed at several distances from the emitting system (i.e. a telephone device) suggested in all cases a quasi-linear decrease at increasing durations of exposure (Panagopoulos and Margaritis 2010) and increase in proximity to the source of the emission (Panagopoulos et al. 2010). In this last study a window-effect was found at distances of 20-30 cm from the device, which resulted in the highest decrease of the measured values.

4.2.3
Effect on other insects

The remaining studies in this section focus on the Tobacco Hornworm (*Manduca sexta*), on the American cockroach (Periplaneta americana) and on a species of ant (*Myrmica sabuleti;* Table 3).

The study by Schwartz et al. (1985) analysed differences in development, reproduction and mortality in Tobacco Hornworms exposed during their larval stage to PW RF-EMF at a frequency of 2695 MHz and a power density of 4 MW/cm^2. All the measured parameters were affected and effect size was as high as 50% lower compared to control.

The studies on the American cockroach (Vácha et al. 2009) and the ant (Cammaerts et al. 2012) focused on the effects of RF-EMF on the magneto-reception of the insects. In the study by Vácha et al. (2009), it was found that, during and after the rotation of the natural geomagnetic field, the insects turned around, as a response of the detection of the field. However, their ability to detect the geomagnetic field was disrupted after exposure to a field at 1.2 MHz with a magnetic flux density between 12 and 18 nT.

Cammaerts et al. (2012) investigated the impact of RF-EMF on the acquisition and loss of olfactory and visual cues of six experimental colonies of the ant Myrmica sabuleti. The exposure to a GSM- generated signal determined a loss in the acquired association between food and a visual cue (40% worse than control), a decreased retention of acquired knowledge, and a total loss of visual memory.

The representation of the size of the effect compared to the power density (Figure 2) shows that significant effects are found at both at high and low dosages, revealing no clear dose-response relationship. In one of the analysed studies, no effects were found at high levels of power density.

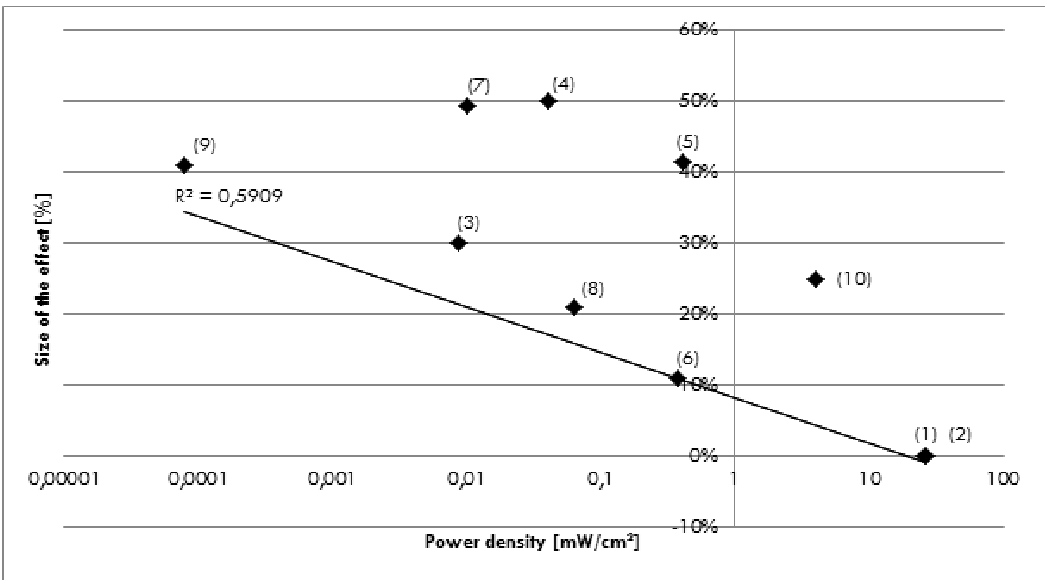

Figure 2. Size of the effects of RF-EMF on insects compared to the power density of exposure. Articles reported in graph: (1) - Westerdahl and Gary (1981a); (2) Westerdahl and Gary (1981b); (3) - Sharma and Kumar (2010); (4) - Panagoupolos et al. (2004); (5) - Panagoupoulos et al. (2007); (6) - Panagoupoulos et al. 2010; (7) - Panagoupoulos and Margaritis 2010; (8) – Panagoupoulos (2012); (9) - Schwatz et al. (1985); (10) - Cammaerts et al. (2012). (See Table 3 for a complete description of studies.

Summary

A limited set of articles regards the possible impact of RF-EMF on honey bees is available in literature. Most of the analysed studies found an effect on the target colonies. The most affected endpoints seemed to be behaviour and orientation of exposed bees, which lead to disruptive consequences in the colonies. The majority of the studies did not provide statistical analysis and did not use clear control measures to analyse results. One exception is the study conducted by Favre (2011), in which the behaviour of the bees seems to be comparable to that experienced by colonies exposed to extreme danger and stress.

The studies analysing the effects of RF-EMF on fruit flies found in all cases a significant effect. One study results show an increased reproductive success after exposure. The remaining studies, which were conducted by the same research institute in Greece, found in all cases a significant depression of growth and reproduction at both 900 and 1800 MHz. Two studies on the American cockroach and a species of ant analysed the effects of exposure to RF-EMF on the magneto-reception and orientation of the insects. The behaviour of target systems was disrupted by the exposure to RF-EMF.

Table 3. Summary of articles on ecological effects of RF-EMF on insects.

Reference	Country	Life stage [a]	Type of study [b]	Number of subjects (or distances if specified) [c]	Duration	Frequency [MHz]	Wave/ Modulation [d]	Power Density [mW/ cm^2] [e]	SAR [W/kg] [f]	Effect [g]	Effect size [h]
Honeybee (Apis mellifera)											
Westerdahl and Gary (1981a)	USA	Adult foragers	Lab	50(50) bees	30 mins for 10 days	2450	MW CW	3-50	0.075-1.25	No impact of radiation on flight, orientation and homing abilities at any power density	-
Westerdahl and Gary (1981b)	USA	Adult	Lab	50(50) bees	30 mins for 10 days	2450	MW CW	3-50	0.075-1.25	No differences in longe-vity between exposed and sham exposed at any power density	-
Harst et al. (2006)	Germany	Various	Field	25 bees selected from 4 colonies	n/a [i]	1900	DECT base station (mod. 100 Hz)	n/a	n/a	Reduced weight of bees. Colony collapse and abnormalities in behaviour	+ (21%)
Kimmel et. al. (2007)	Germany	Various	Field	5 at full exposure, 3 at 50% exposure(8)	4 days, 2 months, 45 mins per day	1800	DECT (mod. 100Hz)	n/a	n/a	Change foraging flight	+ (14%)
Sharma and Kumar (2010)	India	Various	Field	2(2) colonies	Continuous for 15 min. 2 x day , 2 x week, from Feb. to Apr. (11-15 hrs)	900	GSM	0.0086	n/a	Decline in colony strength and in the egg laying rate. Decline in the number of returning bees and total number of foragers. Decline in the storing ability of honey	+ (62%) (22%) (16%)

Favre (2011)	Switzerland	Various	Field	5 hives	12 experiments of 40 mins	900	GSM	n/a	0.271-0.98	Effect on behaviour: worker piping signal was observed 25 to 40 minutes after the onset of the mobile phone	+
Kumar et al. (2011)	India	Adult worker	Field	10(20) bees	40 mins	900	GSM	n/a	n/a	Decreased lipid level in the organism of exposed bees.	+
Sahib (2011)	India	Various	Field	3(3) colonies	10 days, 10 mins per day	900	GSM	n/a	n/a	Decreased returning ability bees in exposed hives; reduced strength; reduced egg laying rate of queen	+ (58%)
Fruit fly (Drosophila melanogaster)											
Weisbrot et al. 2003	USA	n/a	Lab	n/a	2 times for 60 mins with an interval of 4 hrs, for 10 days	1900	GSM PW	n/a	1.4 (human head)	Irradiation increased the number of off-springs, enhancing reproductive success	+ (36% mean; 50% max)
Panagoupolos et al. (2004)	Greece	n/a	Lab	n/a	6 mins/day for 5 days	900	GSM device (in talk mode)	0.041	n/ a	Decreased reproductive capacity	+ (50%)
Panagoupoulos et al. 2007	Greece	n/a	Lab	2 distances (1 control)	6 mins/day for 6 days	900	GSM PW phone antenna	0.407 (± 0.061)	n/a	Decrease of reproductive capacity, seemingly dependent on field intensity more than on frequency	+ (41.4% mean; 55.2% max)
						1800	DCS PW phone antenna	0.283 (± 0.043)	n/a	Idem	
Panagoupoulos et al. 2010	Greece	n/a	Lab	12 distances (1 control)	6 mins/day for 6 days	900	GSM CW phone antenna	0.378 (± 0.059; max value at 0 cm from antenna)	0.89	Reproductive capacity decreased at all distances studied at increasing pwoximity to the antenna. A window effect was revealed at distances of 20-30 cm.	+ (11% mean; 40.6% max)

								0.0004 (± 0.0001; min value at 100 cm from antenna)	Idem	Idem	Idem
						1800	DCS CW phone antenna	0.252 (± 0.05; max value at 0 cm from antenna)	Idem	Idem	Idem
								0.0002 (± 0.0001; min value at 100 cm from antenna)	Idem	Idem	
Panagoupoulos and Margaritis 2010	Greece	n/a	Lab	n/a	1-21 mins for 5 days	900	GSM PW phone antenna	0.01 (time averaged; ± 0.002 at a distance of 30 cm)	0.795	Almost linear decrease in reproductive capacity at increasing durations of exposure.	+ (49.3% mean; 67.4% max)
					1-21 mins for 5 days	1800	DCS PW phone antenna	0.011 (time averaged; ± 0.003 at a distance of 30 cm)	0.795	Idem	Idem
Panagoupoulos 2012	Greece	n/a	Lab	n/a	6 mins for 5 times	900	GSM CW phone antenna	0.063	0.795	Decreased ovarian size after two exposures.	+ (21% mean; 29.5% max)

Other insects: Tobacco Hornworm (Manduca sexta), American cockroach (Periplaneta americana), ant (Myrmica sabuleti)												
Schwatz et al. (1985)	Canada	Adults exposed at larval stage	Lab	n/a	From larva to pre-pupal stage	2695 (500 pulse per second)	Anechoic chamber, horn antenna PW	4	23	Decreased food consumption and larval body weight after 20 days. Deformed adults. Higher mortality. Lower number of laid eggs.	+ (50%) (2%) (20%) (23%)
Vácha et al. (2009)	Czech Republic	n/a	Lab	11(11 non exposed)	3 hrs	1.2-7	RF generator	n/a	n/a	Rise in the locomotor activity and disruptive effect at 1.2 MHz.	+ (14%)
Cammaerts et al. (2012)	France	Various life stages	Lab	6 large naive colonies	Three exposure periods: 4.5 days; 6 days; 1.5 days	900	GSM from vector signal generator	7.95 x 10-5	n/a	Diminished acquired association between food and a olfactory and visual cues.	+ (40%) (42.5%)

[a] Life stage refers to the age of the tested subject at the moment of the performance of the experiment. [b] Studies divided in laboratory and field studies. **Lab** = laboratory study, **Field** = field study. [c] Number of subjects involved in the experiment or field study where reported in the study. In brackets information about number of control subjects. Further specifications of type of subjects involved in the studies are reported if provided by authors. In the case of studies regarding the fruit fly the distances applied are reported. [d] Wave/Modulation indicates the type of RF-EMF applied/measured in the study. **CW** = continuous wave, **MW** = microwave, **GSM** = Global System for Mobile Communications, **DECT** = Digital Enhanced Cordless Telecommunications. [e] Values of power density are reported as provided by authors or recalculated by conversion of electric field values (PD=EF2/3770) and expressed in mW/cm^2. [f] Values of SAR are reported as provided by authors and expressed in W/kg. [g] Biological or ecologically relevant endpoints studied. [h] Size of the effect where significant. It indicates the ration between maximum effect and percentual difference compared to control. A sign + indicates a significant effect, a - sign indicates that no significant effect was found. [i] n/a indicates that data was not provided by authors.

4.3
Other vertebrates

The impossibility of conducting laboratory experiments into the effects of RF-EMF on humans steadily increased the number of scientific studies on laboratory vertebrate models. As suggested by the WHO (2006), studies conducted on immature animals can, for instance, provide a useful indicator of possible cognitive and behavioural effects on children. The vast majority of studies focused on the analysis of intracellular pathways, for instance through changes in calcium permeability across membranes (e.g. Maskey et al. 2010); or on gene expression, namely on the neurons of rats exposed to RF-EMF (e.g. Salford et al. 2003; Zhao et al. 2007); or on possible chromosomal damage in mice cells (e.g. Nikolova et al. 2005).

A total of 50 scientific articles were selected for a total of 62 relevant ecological experiments (Table 4). The endpoints analysed which were of interest were fertility, growth, behaviour and mortality (Table 1).

With the exception of one study on bats (*Pipistrellus pipistrellus; Pipistrellus pygmaeus; Myotis daubentonii; Myotis nattereri*) breeding nearby a wind turbine and one study on the tadpoles of frogs (*Rana temporaria*), all studies were conducted in a laboratory setting. The animal systems under investigation were rats commonly used in laboratory studies (Wistar albino rat; Sprague Dawley rat), mice (*Balb/c; Balb/c/f*), rabbits (*White New Zealand Rabbit*), rhesus monkeys (*Macaca mulatta*). Of the total of 50 articles, 50% of the studies were conducted on rats. A total of 27 experiments (43%) showed no significant results of an impact of RF-EMF under the physical and experimental settings used. The power density ranged from 0.6 x 10-6 to 20 mW/cm^2, which was the maximum value measured for MW CW exposures (Table 4). The SARs values measured ranged from 0.00194 to 44 W/kg, with a peak value measured at 2450 MHz for MW PW exposure. In the studies in which higher level of exposure to RF-EMF were applied and temperature was not controlled, results may be related to an increase in body temperature as a consequence of exposure.

A large share of the studies on vertebrate animal models focused on changes in behaviour as a result of exposure. This choice may be related to investigating of possible influences of RF-EMF on the behaviour and cognitive performance of humans, who use mobile phone devices in close proximity to their heads. Some commonalities between human and rat response to noxious substances have been explored by other fields of science (Hammond et al. 2004). Lai et al. (1994) suggested that rats suffer from a deficit in spatial working memory function when exposed to RF-EMF (50% decreased performance compared to control). The repetition of the experiment with similar conditions of exposure by Cassel et al. (2004), Cobb et al. (2004), and Cosquer et al. (2005) found no effects on learning abilities of rats in the performance of spatial tasks and no evidence of altered brain development.

Another example in this direction is the work of Daniels et al. (2009), who investigated the effect of RF-EMF in the mobile phone range on the behaviour of the rat with controversial results. Spatial memory was tested using the Morris water maze test (Morris 1981), and mood disturbances and anxiety-like behaviour were tested in an open field test, for twelve radiated and twelve control subjects. Results showed no significant differences between groups in the Morris test, suggesting no significant difference in the behaviour of exposed and control rats. However, male rats performed significantly worse (60%) in the open field test.

The articles by Lee et al. (2009; 2012), Imai et al. (2011) are the only studies focusing on the impact of the frequencies network standards found in 3G mobile communication (Smith and Collins 2000), working with protocols like wideband code division multiple access (W-CDMA) or CDMA. All experiments, on mice and rats, did not have any observable adverse effect on development, reproduction or mutation of tested subjects. No effects on the development of rats were also observed by the study of Poullettier de Gannes et al. (2012), where Wireless Fidelity (Wi-Fi) signal at 2450 MHz was applied on rats, and by the study of Jiang et al. (2012), where mice were exposed to a wireless transmitter at 900 MHz. These studies represent the first attempt to investigate the effects of wireless communication on health.

The field experiment of Balmori (2010) on the behaviour and growth of the tadpoles of frogs (Rana temporaria) placed 140 m from a field station provides evidence of the effect of RF-EMF. The exposed group showed low coordination of movements, an asynchronous growth and a high mortality (90%). The control group was exposed to the same environmental conditions, but placed inside a Faraday cage. As a result, the coordination of movements was normal, the development was synchronous, and the mortality rate was 4.2%. The research goal of the field study by Nicholls and Racey (2009) was to test whether PW RF-EMF emitted by a radar could be used as a method of preventing bats from death caused by collisions with wind turbines. The authors analysed 20 foraging sites. The exposure of bats to a pulsed wave radar system determined a significant reduction in foraging activity of bats.

The plotting of the size of the effect with the relative measured power density (where the value was provided by authors) of positive studies does not show any detectable trend (see Figure 2). No clear pattern is visible from the analysis of the data and effects were found both at high and low levels of power density.

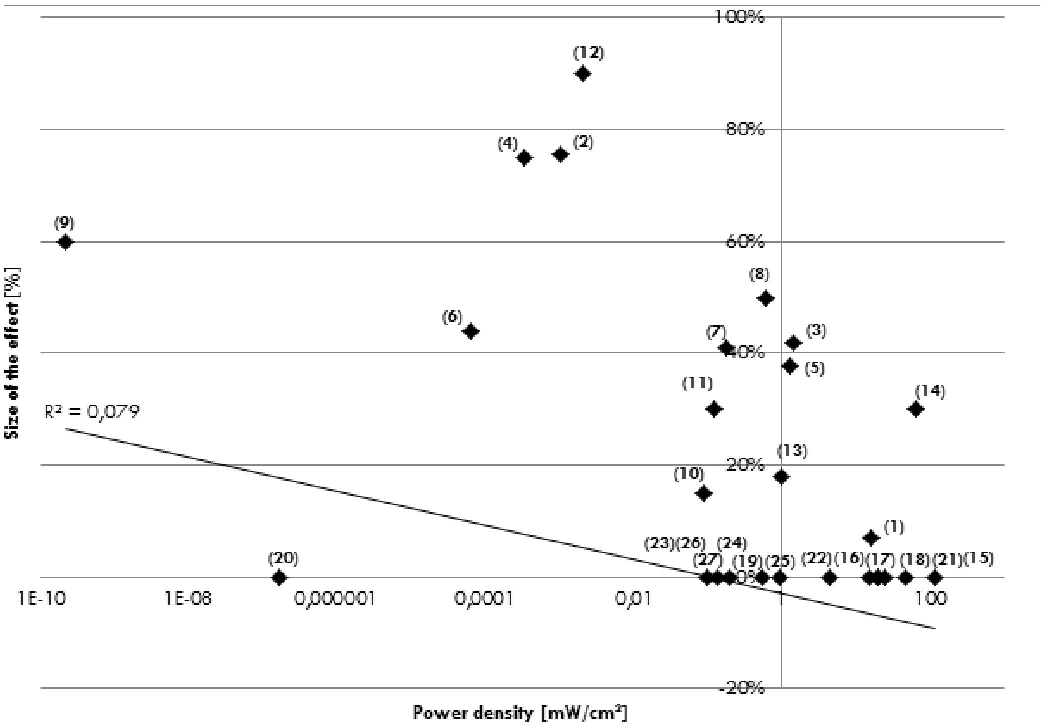

Figure 2. Size of the effects of RF-EMF compared to the power density of exposed vertebrate animal models. Articles reported in graph: (1) - Berman et al. (1992); (2) - Magras and Xenos (1997); (3) - Khillare and Behari (1998); (4) - Nittby et al. (2008); (5) - Mathur (2008); (6) - Salama et al, (2010a); (7) - Kesari et al. (2011); (8) – Lai et al. (1994); (9) – Daniels et al. (2009); (10) – Nicholls and Racey (2009); (11) – Fragopoulou et al. (2010); (12) – Balmori (2010); (13) – Hao et al. (2012); (14) – Yang et al. (2012); (15) – Jian et al. (2012); –(16) - Chernovetz et al. (1975); (17) - Jensh et al. (1982); (18) - Lary et al. (1983); (19) - D'Andrea et al. (1989); (20) - Sherry et al. (1995); (21) - Klug et al. (1997); (22) - Jensh (1997); (23) - Bornhausen and Scheingraber (2000); (24) - Dasdag et al. (2007); (25) - Lee et al. (2009); (26) - Sommer et al. (2009); (27) - Sienkiewicz et al. (2000). See Table 4 for a complete description of studies

Summary

Rats and rabbits exposed to RF-EMF in a laboratory setting represented the most studied animal model. Changes in behaviour as a result of exposure were analysed in most studies and presented contradictory results. As for the other endpoints, significant effects were found under various conditions of exposure and under different laboratory setups. A field study showed a significant effect of exposure on the growth and mortality rates of tadpoles of frogs under field conditions. In another RF-EMF reduced the foraging activity of bats.

Table 4. Summary of articles on ecological effects of RF-EMF on other vertebrates (than birds).

Reference	Country	Species (Scientific name)	Life stage [a]	Number of subjects [b]	Duration of exposure	Frequency [MHz]	Wave/ Modulation [c]	Power Density [mW/ cm2] [d]	SAR [W/kg] [e]	Effect [f]	Effect size [g]
Chernovetz et al. (1975)	USA	Rat (Rattus norvegicus)	n/a [h]	n/a	11-14 days, 10 mins	2450	MW CW	20	38	No effect on deve-lopment	-
Berman et al. (1978)	USA	Mouse (Mus musculus)	Emb	n/a	1-17 days, 100 mins/day	2450	MW CW	3.4-28	2-22	Reduced foetal weight and hampered development	+
Berman et al. (1980)	USA	Rat (as above)	n/a	n/a	80 hrs, 4 weeks	2450	MW CW	n/a	5.6	Transient reduction in fertility	-
Jensh et al. (1982)	USA	Rat (as above)	Ad	12 (59; 4)	6 hrs/day (preg-nancy period)	2450	MW CW	20	5.2 3.6	No changes in development idem	-
Kowalczuk et al. (1983)	Great Britain	Mouse (as above)	Ad	50 (50)	30 mins	2450	MW PW	n/a	44	Significant effect on reproduction: decre-ased sperm count, increased abnormal sperm	+ (35%) (330%)
Lary et al. (1983)	USA	Rat (as above)	Ad	n/a	6-11 days, 24 hrs/day	100	FM	25	0.4	Unaltered develop-ment	-
Nawrot et al . (1985)	USA	Rat (as above)	Emb	n/a	6-15 days, 8 hrs/day	2450	MW CW	30	40	Altered development	+
Lebovitz and Johnson (1987a)	USA	Rat (as above)	n/a	n/a	6 hrs/day, 9 days	1300	PW (600 Hz pulse)	n/a	7.7	No effect on reproduction/fertility: sperm production, sperm morphology	-

Lebovitz and Johnson (1987b)	USA	Rat (as above)	n/a	n/a	8 hrs	1300	CW	n/a	9	No effect on reproduction/fertility: testicular function	-
D'Andrea et al. (1989)	USA	Rhesus monkey (Macaca mulatta)	Juv	5 (same test group, sham-exposed)	1 session of 60 mins per day per 1 week	1300	MW PW	0.92 mean (peak of 0.1318)	0.09 mean in the head (15 peak in the head)	No change in behaviour as compared to sham-exposed sessions	-
Berman et al. (1992)	USA	Rat (as above)	Juv/Ad	119 (0; 129)	22 hrs/day, 18 days (from 1st through 19th day of gestation)	970	n/a	n/a	0.07	Unaltered development	-
									2.4 4.8	Unaltered development Foetal development alterations	- + (7%)
Lai et al. (1994)	USA	Rat (as above)	Juv	n/a	n/a	2450	PW	n/a	0.6	Decreased performance in behavioural tasks in T-maze. Deficit in memory function	+ (50%)
Sherry et al (1995)	USA	Rhesus monkey (as above)	Ad	6 (no control or sham-exposed group)	2 mins (7200 pulses)	100-1500	MW UWB	1.65782 x 107	0.5 (whole body average)	Unaltered behavioural test performance	-
Klug et al. (1997)	Germany	Mouse (as above)	Emb	53 (65)	36 hrs	150	AM	0.95491-95.4907	n/a	Unaltered growth	-
									0.2	idem	
									1	idem	
									5	idem	
						900	GSM	1.33714	0.2	idem	
									1	idem	
									5	idem	

Jensh (1997)	USA	Rat (as above)	Juv/Ad	n/a	6 hrs/day, 5 days 6 hrs/day, 5 days	915 2450	GSM CW MW CW	10 20	n/a n/a	Unaltered growth idem	-
Magras and Xenos (1997)	Greece	Mouse (as above)	Juv	36	5 pregnancies	88.5-950	FM; UHF TV; GSM	1.053 $\times 10^{-3}$ 168×10^{-6}	1.936×10^{-3} idem	Progressive decrease in the number of new-borns per dam leading to irreversible infertility Improved prenatal development parameters idem	+ (76%) + (27%)
Khillare and Behari (1998)	India	Rat (as above)	Ad	18 (18)	2 hrs/day, 35 days	200	AM (mod. 16Hz)	1.47	1.65-2	Decreased fertility observed in exposed tests. Unaltered development	+ (42%) -
Bornhausen and Scheingraber (2000)	Germany	Rat (as above)	Ad	12(12)	20 days (pregnancy period)	900	GSM (mod. 217 Hz)	0.1	0.75	Unaltered growth	-
Sienkiewicz et al. (2000)	UK/USA	Mouse (as above)	Ad	n/a	45 mins 10 days	900	PW (mod. 217Hz)	0.54	0.05	Unaltered learning in the performance of tasks	-
Yamaguchi et al. (2003)	Japan	Rat (as above)	Ad	168	1 hr/day for 4 days; 45 min daily for 4 days; 1 hr/day for 5 days and 2 days of rest for 4 weeks	1439	PW TDMA	n/a	1.7	Unaltered learning abilities in the performance of tasks	-
Cassell et al. (2004)	France	Rat (as above)	Ad	n/a	45 mins	2450	PW	n/a	0.6	Unaltered learning in the performance of tasks	-

Cobb et al. (2004)	USA	Rat (as above)	n/a	n/a	45 mins, 10 days	2450	MW PW	n/a	0.6	Unaltered brain development and performance of spatial tasks	-
Cosquer et al. (2005)	France	Rat (as above)	Juv	48	45 mins	2450	PW	n/a	0.6	Unaltered performance in spatial tasks	-
Dasdag et al. (2007)	Turkey	Rat (as above)	Ad	14 (10 control; 7 sham-exposed)	2 hrs/day, 7 days/week, 10 months	900	PW	0.02384-0.17561	0.07-0.57	Unaltered fertility	-
Kumlin et al. (2007)	Finland	Rat (as above)	Juv	18(6)	2 hrs/day, 5 days/week, 5 weeks	900	PW	n/a	0.3 (mean value)	Improvement in learning abilities of rats	+ (20%)
Ribeiro et al. (2007)	Brasil	Rat (as above)	Juv	16 (8)	1 hr/day, 11 days	1850	PW	1.4	n/a	Unaltered fertility	-
Yan et al. (2007)	USA	Rat (as above)	Ad	16	2 times/day for 3-hrs periods for 18 weeks	1900	CDMA	n/a	1.8	Higher incidence of sperm cell death	+ (37%)
Mathur (2008)	India	Rat (as above)	Juv	n/a	2 hrs/day, 45 days	73.5	AM (mod. 16Hz)	1.33	0.4	Abnormal behavioural response to noxious stimuli	+ (38%)
Nittby et al. (2008)	Sweden	Rat (as above)	Ad	28 (16; 8 sham-exposed)	2 hrs/week, 55 weeks	900	Lower power level GSM	3.3×10^{-4}	0.62×10^{-3}	Behavioural abnormalities: altered performance of rats during episodic-like memory test	+ (75%)
								n/a	0.37×10^{-3}	idem	
							GSM	33×10^{-4}	62×10^{-3}	idem	

									37×10^{-3}	idem	
Daniels et al. (2009)	South Africa	Rat (as above)	Juv	12 (12)	3 hrs/day, 12 days (2 days after birth)	840	RF signal generator	2.1247×10^{-10} (d=0.93 m)	n/a	Decreased behaviour. Decreased locomotive activity. Unaltered performance of memory tasks	+ (60%) -
Gathiram et al. (2009)	South Africa	Rat (as above)	Ad	32 (32)	8 hrs/day, 10 days	100 - 3000	Unique field system	n/a	n/a	Unaltered fertility of exposed male and female individuals	-
Lee et al. (2009)	Korea	Mouse (as above)	Ad	17 (14)	90 mins/day (15 mins break) 17 days (gestation period)	848.5	CDMA	1.4174-8.2501	0.69-4.04	Unaltered development	-
								n/a	2 (Power= 30W)	Unaltered development	-
				20 (20)	90 mins/day (15 mins break) 17 days (gestation period)	1950	WCDMA	1.0923-7.0043	1.11-7.13		
Mailankot et al. (2009)	India	Rat (as above)	Juv	n/a	1 hr/day, 28 days	900-1800	GSM	n/a	n/a	Detrimental effects on fertility	+ (53%)
Nicholls and Racey (2009)	UK	Bat (Pipistrellus Pipistrellus)	n/a	n/a	20 hrs (bat activity); 16 hrs (insect count); 3 fields	n/a	PW radar	3.8101×10^{-3}-1.7275×10^{1} (peak values at distance of 10-30 m)	n/a	Reduced foraging and activity of bats	+ (16% in bat counts; 13% bat passes)

										No effect on the abundance of insects	-
Sommer et al. (2009)	Germany	Mouse (as above)	Multi-gen.	128 male 256 female,3 generations	570 days (chronic exposure), 30 mins/day break	2000	UMTS	0.135	0.08-0.144	Unaltered fertility and development	-
								0.68 2.2	0.4-0.72 1.3-2.34	idem idem	
Fragopoulou et al. (2010)	Greece	Mouse (as above)	Juv	12 (12)	4 days, 2 hrs/day	900	GSM	0.05-0.2	0.41-0.98	Deficits in consolidation and/or retrieval of learned spatial information	+ (30%)
Balmori (2010)	Spain	Frog (Rana temporaria)	Juv	70 (70)	2 months from egg phase until prior to metamorphosis	648-2155	Cell-phone base station	8.5942 x 10-4- 3.2493 x 10^{-3}	n/a	Increased mortality rate. Asynchronous growth of exposed subject; disrupted behaviour	+ (90%)
Salama et al. (2010a)	Japan	Rabbit (Oryctolagus cuniculus)	Ad	8 (8; 8 sham-exposed)	8 hrs/day, 12 weeks	800	PW	6.2910 x 10-5- 2.2616 x 10^{-3}(mean value over time at minimum to maximum distance from the phone)	0.43 (whole body)	Significant decrease in sperm concentration at week 8. Decrease in motile sperm population at week 10. Overall effect on testicular function and reproduction ability	+ (62%) (25%)

Salama et al. (2010b)	Japan	Rabbit (as above)	Ad	8 (8; 8 sham-exposed)	8 hrs/day, 12 weeks	800	PW	6.2910 x 10^{-5}- 2.2616 x 10^{-3} (mean value over time at minimum to maximum distance from the phone)	0.43 (whole body)	Detrimental effects on sexual behaviour: increased number of mounts, increased number of mounts without ejaculation	+
Imai et al. (2011)	Japan	Rat (as above)	Juv	24 (24;24)	5 hrs/day, 7 days/week, 5 weeks	1950	WCDMA CW	n/a	0.4	No effects on reproduction and development	-
Kesari et al. (2011)	India	Rat (as above)	Juv	6 (6 sham-exposed)	2 hrs/day, 35 days	900	n/a	9.2558 x 10^{-2} (peak value at 20 m); 8.2819 x 10^{-2} (peak value at 30 m)	0.9 (Power= 2mW)	Potential significant effect on reproduction (fertilizing potential of spermatozoa)	+ (41%)
Sarookhani et al. (2011)	Iran	Rabbit (as above)	n/a	18	2 hrs/day, 2 weeks	950	GSM	n/a	n/a	Decreased reproductive capacity	+ (90%)
Aldad et al. (2012)	USA	Mouse (as above)	Ad	39 pregnant (42 sham-exposed)	0 to 24 hrs/ day from day 1 to day 17 of gestation	800 1900	GSM	n/a	1.6	Behavioural and neurophysiological alterations	+ (7%)
Bouji et al. (2012)	France	Rat (as above)	Middle-aged	9 (9 sham-exposed)	15 mins	900	GSM PW	n/a	6	Altered behaviour and increased stress	+ (47%)
Hao et al. (2012)	China	Rat (as above)	n/a	16 (16)	2 times/day for 3 hrs/day, for 5 days/week, for 10 weeks	916	Mobile phone antenna	1	n/a	Altered learning. Altered memory. Adaptation to field after long term exposure	+ (18%) (18%)
Jiang et al. (2012)	China	Mouse (as above)	n/a	5 (5; 5 exposed to gamma radiation; 5 exposed to	4 hrs/day for 1 to 14 days	900	Wireless transmitter	120	0.548	No effect on mutation	-

				combined RF and gamma radiation)							
Lee et al. (2012)	Korea	Rat (as above)	n/a	5 (5; 5 exposed to gamma radiation; 5 exposed to combined RF and gamma radiation)	45 mins/day, 5 days/week, 12 weeks	848.5	CDMA	n/a	2 (4 combined with CDMA)	No effect on reproduction	-
				idem	idem	1950	WCDMA	idem	2 (4 combined with CDMA)	idem	-
Ozlem Nisbet et al. (2012)	Turkey	Rat (as above)	Juv	11 (11;11)	2 hrs/day for 90 days	900	GSM	n/a	0.003	Increased testosterone level and sperm motility. Altered morphology	+ (15%) (3%)
				idem	idem	1800	GSM	idem	5.3×10^{-5}	idem	+ (14%) (2%)
Poullettier de Gannes et al. (2012)	France	Rat (as above)	Various	20 (20;20)	2 hrs/day, 6 days/week, 18 days	2450	W-LAN Wi-Fi	n/a	0.08	No abnormalities in reproduction and development	-
Yang et al. (2012)	China	Rat (as above)	Ad	12 (12 sham-exposed)	20 mins	2450	MW PW	65	6	Stress response elicited in rat hippocampus	+ (30%)

[a] Life stage refers to the age of the tested subject at the moment of the performance of the experiment.

[b] Number of subjects involved in the experiment or field study where reported in the study. In brackets information about number of control subjects. Further specifications of type of subjects involved in the studies are reported if provided by authors.

[c] Wave/Modulation indicates the type of RF-EMF applied/measured in the study. **CW** = continuous wave, **MW** = microwave, **GSM** = Global System for Mobile Communications, **DECT** = Digital Enhanced Cordless Telecommunications, **PW** = pulsed wave, **UWB** = ultra wide band, **AM** = amplitude modulation, **FM**

= frequency modulation; **UMTS** = Universal Mobile Telecommunications System; **CDMA** = Code division multiple access; **TDMA** = time division multiple access; **WCDMA** = Wideband Code Division Multiple Access.

[d] Values of power density are reported as provided by authors or recalculated by conversion of electric field values (PD=EF2/3770) and expressed in mW/cm^2.

[e] Values of SAR are reported as provided by authors and expressed in W/kg.

f Biological or ecologically relevant endpoints studied.

[g] Size of the effect where significant. It indicates the ration between maximum effect and percentual difference compared to control. A sign + indicates a significant effect, a - sign indicates that no significant effect was found. h n/a indicates that data was not provided by authors.

4.4
Other organisms

This section includes studies on the effect of RF-EMF on the bacterium (Escherichia coli), the nematode (*Caenorhabditis elegans*), and the land snail (*Helix pomatia*), which constitute the species not yet included in the previous sections.

The screening of the literature identified four studies for a total of eight experiments (Table 5). In all cases effects were significant. The RF-EMF applied were mainly the GSM 900 MHz and GSM 1800 MHz (DCS –Digital Cellular System) systems, with the exception of the study of Grospietsch et al.(1995) and de Pomerai et al. (2002), which studied respectively a pulsed wave modulated frequency at 150 MHz and a microwave continuous wave frequency at 1000 MHz (Table 5).

3

RF-EMF power density was measured in the range of 0.0005 to 0.679 mW/cm^2. All the values can be considered typical for digital mobile telephony handsets and in most cases fall within the current exposure criteria (ICNIRP 1998).

The ecologically relevant endpoints analysed in the studies were growth, reproduction and stress. All of the analysed studies found a significant effect compared to the control. The exposure of the bacteria E. coli and the nematode C. elegans suggests that RF-EMF tend to enhance growth of the organisms. The study on the land snail (Nittby et al. 2012) found a beneficial non-thermal analgesic effect on a group of 29 land snails placed on a hot plate. The response time to heat of GSM-exposed snails was 20% higher than that of the control. The study by Daniells et al. (1998), which exposed a transgenic nematode (C. elegans PC72) to RF-EMF at a frequency of 750 MHz, found a significant drastic effect on the stress levels (i.e. 150% higher than control) of the exposed target system.

Summary

Studies on the effects of RF-EMF on the bacterium (*Escherichia coli*), the nematode (*Caenorhabditis elegans*) and the land snail (*Helix pomatia*) reported in all cases a significant effect on behaviour and growth of target subjects and under all laboratory setups applied. The study on the E. coli and C. elegans beneficially affected growth. The exposure of the land snail to RF-EMF retarded the response to heat determining a beneficial analgesic effect.

Table 5. Summary of articles on ecological effects of RF-EMF on the bacterium Escherichia coli, the nematode Caenorhabditis elegans, the land snail Helix pomatia.

Reference	Country	Species	Scientific name	Duration of exposure	Frequency [MHz]	Wave / Modulation [a]	Power Density [mW/cm²] [b]	Magnetic flux density [µT] [c]	SAR [W/kg] [d]	Effect [e]	Effect size [f]
Grospietsch et al. (1995)	Germany	Bacterium	Escherichia coli	6 hrs	150	PW (mod. 72 Hz)	6.7905	5.4	n/a [g]	Enhanced growth at higher field frequencies, identical at various modulation frequencies	+
				idem	150	PW (mod. 217 Hz)	6.7905	5.4	n/a		
					150	PW (mod. 1100 Hz)	6.7905	5.4	n/a		
					150	CW	6.7905	5.4	n/a		
Daniells et al. (1998)	UK	Nematode	Caenorhabditis elegans strain PC72	2-16 hrs continuous	750 300	MW TEM cell	n/a	n/a	n/a	Stress reporter gene induction after 2 and 16 hours of exposure	+ (150%)
de Pomerai et al. (2002)	UK	Nematode	Caenorhabditis elegans	20 hrs	1000	MW CW	5.37×10^{-5}	n/a	0.001	Enhanced growth as a consequence of exposure	+ (9.8% mean; 11.2% max)
Nittby et al. (2012)	Sweden	Landa snail	Helix pomatia		1900	GSM modulated signal	0.068	n/a	0.048	Beneficial induced analgesia	+ (20%)

[a] Wave/Modulation indicates the type of RF-EMF applied/measured in the study. Modulation value reported if provided by authors. **CW** = continuous wave, **MW** = microwave, **GSM** = Global System for Mobile Communications, **PW** = pulsed wave, **DCS** = digital cellular system. [b] Values of power density are reported as provided by authors or recalculated by conversion of electric field values (PD=EF2/3770) and expressed in mW/cm². [c] Values of magnetic flux density if provided by authors. d Values of SAR are reported as provided by authors and expressed in W/kg. [e] Biological or ecologically relevant endpoints studied. [f] Size of the effect where significant. It indicates the ration between maximum effect and percentual difference compared to control. A sign + indicates a significant effect, a - sign indicates that no significant effect was found. [g] n/a indicates that data was not provided by authors.

4.5
Plants and yeasts

The influence of the earth's natural magnetic field or that of superimposed artificial magnetic fields on plants has been known for many years. Static magnetic fields, in fact, have been proven to have a beneficial impact on the stimulation of growth and germination of plants (Savostin 1930; Pittman 1965; Dulbinskaya 1973), or inhibitive impact depending on the species and their physiological state (Krizaj and Valencic 1989; Ruzic et al. 1998). According to Soltani et al. (2006), until now no proper physiological explanation has been provided for the described effects, though the biological effects of weak static MF do not only depend on the physical conditions of the exposure (e.g. power density, frequency), but also on the environmental conditions in place.

The analysed literature considered that plants are continuously exposed to RF-EMF as they cannot avoid them, by moving away from the source of emission. As in the case of the studies explored in earlier sections, little is known about a possible mechanism explaining how exposure to RF-EMF may cause biological/ecological effects, and therefore most of the investigations were aimed at the possible mechanisms underlying the effects in plants.

In total, 16 studies and 29 experiments were selected based on the ecological relevance of the endpoints studied (Table 6). Ten experiments investigated the impact of RF-EMF on the inhibition of the regular growth of plants. Four experiments directly investigated the stress levels of plants exposed to RF-EMF as a variation in specific test methods. The remaining studies focused on abnormalities as a consequence of the exposure, and on the effect on the photosynthesis.

The frequency investigated ranged from as low as 10 MHz from an AM CW system (Haider et al. 1994) to 2450 MHz MW CW EMF (Schmutz et al. 1996). Power density ranged from 0.015 mW/cm^2 to 50 mW/cm^2, therefore lower than the values measured in the previous section on the fruitfly (*D. melanogaster,* in section 4.4) and in line with the applications measured for birds and bees (section 4.1 and section 4.2). When measured and provided, SAR values were in the range of 0.0-4.7 W/kg (see Table 6).

The experiment by Schmutz et al. (1996) investigated the effects of a long term exposure to 900 MHz MW on the spruce and the beech (*Picea abies; Fagus silvatica*). At a measured power density of 10 mW/cm^2, growth parameters and photosynthetic activities of the systems were not affected. No evidence was found on the mutation and the stress levels of yeast (*Saccharomyces cerevisiae*) in the laboratory experiment by Gos et al. (2000) and on mutation in the study by Chen et al. (2012). No information was provided on the levels of power density.

Among the studies with a significant effect on plants, three were published in 1996 by a Latvian group of researchers (Balodis et al. 1996; Magone 1996; Selga and Selga 1996). The researchers focused on the area of Skundra, Latvia, where a radio location station had been operating for 20 years. The three studies provide a unique experience of a complete set of experiments and field studies conducted around a radio station in the short as well as in the long term. The area of study also allowed for the investigation of RF-EMF effects at different distances from the station. The effects of other environmental and anthropogenic factors (e.g. pollution levels, population density, etc.) were also evaluated without revealing any significant effect on the parameters studied. As a result, the non-thermal RF-EMF under investigation indicated that the effects of short term exposure (i.e. up to five days) are dependent on the stage of growth of Great duckweed (Spirodela polyrhiza; Magone 1996) at the time of exposure. The vegetative growth of young plants decreased as a consequence of exposure, while it even accelerated in the case of older plants. The exposed population of adult plants was on average growing 150% more than the control unexposed samples. In the other two studies the pine tree (Pinus sylvestris) was under investigation. The effects of RF-EMF emitted by the radio station were analysed using retrospective tree ring data in Balodis et a (1996): a significant negative correlation between the measured electric field at specific sample locations and the mean relative 4additional annual increment of pines has been identified. Selga and Selga (1996) found significant cytological and ultra-structural changes in exposed pine needles and cones.

Duckweed (*Lemna minor*) was used as a model plant for the monitoring of effects on growth and other physiological responses also in two studies by Tkalec et al. (2005; 2007), which confirmed that under most of the investigated conditions of field frequencies, modulation, and exposure time growth was significantly reduced (i.e. 29% on average less) compared to control.

A connection between exposure and very rapid molecular stress responses was made in the studies performed by Roux et al. (2006; 2008) focusing on the molecular responses of tomato plants (*Lycopersicon esculentum Mill* VFN8). The study was based on the use of several stress related transcripts (e.g. energy charge, protease inhibitor). Great differences were found in the exposed population compared to the control (up to 300%). The data supports the evidence that plants respond to exposure as they would respond to any other injurious treatment. Even though the RF-EMF used was non-thermal and the total power used was low, results, as the authors commented, are strikingly similar to those found when plants are wounded, cut or burned.

Plotting of the size of the effect and the power density measured in studies (i.e. where provided) did not show any identifiable trend (see Figure 4): effects were found at high and low dosages and the size of effects varied greatly across studies.

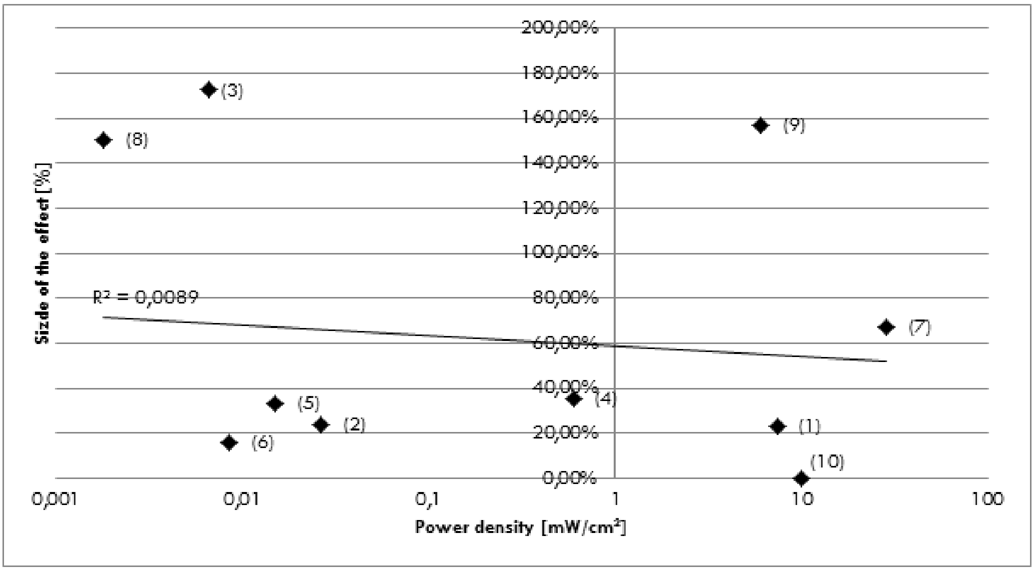

Figure 4. Size of the effects of RF-EMF compared to the power density of exposed plants. Articles reported in graph: (1) - Tkalec et al. (2005); (2) – Tkalec et al. (2007); (3) - Roux et al. (2008); (4) - Ursache et al. (2009); (5) -Jinapang et al. (2010); (6) - Sharma et al. (2009); (7) - Urech et al. (1996); (8) – Magone (1996); (9) - Haider et al. (1994); (10) - Schmutz et al. (1996). See Table 6 for a complete description of studies

Summary

Significant effects of RF-EMF were found mostly on the inhibition of the growth of exposed plants. Oxidative stress (e.g. for tomato plants or duckweed) and continuous abiotic stress have been presented in some studies as possible determinants of the mechanism. Of interest is the case of studies performed for an extensive period of time in an area in Latvia around a radar station and involving both field and laboratory investigations. These studies showed possible effects of RF-EMF on the radial growth of pine trees (*Pinus sylvestris*), and on the growth of duckweed (*Lemna minor*) or great duckweed (*Spirodela polyrhiza*).

Table 6. Summary of articles on the ecological effects of RF-EMF on plants.

Reference	Country	Species	Scientific name	Life stage [a]	Type of study [b]	Number of subjects [c]	Duration of exposure	Frequency [MHz]	Wave / Modulation [d]	Power Density [mW/cm²] [e]	SAR [W/kg] [f]	Effect [g]	Effect size [h]
Haider et al. (1994)	Austria	Spiderwort	Tradescantia	Plant cuttings with young flower buds	Field	n/a j	30 hrs	10-21	AM CW	0.43	n/a	Clastogenic effect at all distances and electric field levels	+ (157% mean)
								14		1.3	n/a	idem	
								10		0.43	n/a	idem	
								14		2.15	n/a	idem	
								18-21		0.0003 (200 m from broadcasting area)	n/a		
								18-21		1.1207 (mesh cage at 10 m from the slewable curtain antenna)	n/a		
Balodis et al. (1996)	Latvia	Pine	Pinus sylvestris	50-90 yrs old	Field	20 trees per plot, 8 plots	21 years	154-162	Radio transmitter with horizontal polarization	n/a	n/a	Diminished radial growth near source	+
Magone (1996)	Latvia	Great duckweed	Spirodela polyrhiza Schleiden	Plants of different age	Lab	10-30 plants, 5 flasks	5 days	156-162	PW	0.0018 (max value)	n/a	Accelerated reproduction rate. Developmental abnormalities compared (after 30 to 80 days).	+ (150% mean) (58%)

Schmutz et al. (1996)	Switzer-land	Spruce; beech	Picea abies () Karst.; Fagus silvatica	Seedling	Field	135 (3 replicates)	3 yrs, 7months	900	MW	10(600W of power); 30;1;3;0.1;0.3	n/a	Unaltered growth and photosynthe-tic activity. Decreased calcium and sulphur in beech leaves at increasing po-wer densities	-
Selga and Selga (1996)	Latvia	Pine	Pinus sylvestris	Needles and cones	Lab	n/a	n/a	154-162	Radio transmit-ter (*horizontal polarization)	4.2440 x 10^{-7}-16.578	n/a	Cytological and ultra-structural changes	+
Urech et al. (1996)	Switzer-land	Lichens	Parmelia tiliacea Hypogymnia physodes	n/a	Lab	n/a	24 hrs/day, up to 800 days	2450	MW CW	0.2-50	0.9 (mean wet)	Reduced growth rate at 50 mW/cm^2 (thermal effect). No alterations at 5 mW/cm^2 or below. No alterations at 9.5 MHz	+ (67%) -
								2450	MW CW	50	0.9 (mean wet)	-	
								9.5	Short-wave broadcast transmitter	14.65	0.0004 (mean wet)	-	
Gos et al. (2000)	Switzer-land	Yeast	Saccharo-myces cerevisiae	Cell	Lab	4 (strains)	1 hr	900	GSM PW	n/a	0.13	No effect on mutation or stress	-
							36 hr				1.3		

3

Tkalec et al. (2005)	Croatia	Duckweed	Lemna Minor	Cultures of young and old leaves	Lab	n/a	2-14 hrs	400	CW; GTEM cell	0.0265 (for 14hrs); 0.14 (2 hrs and 4 hrs); 0.446 (2 hrs); 40.345 (2 hrs)	n/a	Reduced growth	+ (15% mean after 8 days)
								400	AM CW	0.140	n/a	Reduced growth	(14% mean after 8 days)
								900	CW; GTEM cell	0.0265(for 14hrs); 0.1403(2 hrs and 4 hrs); 0.4459 (2 hrs); 40.3448 (2 hrs	n/a	Reduced growth	(37% mean after 8 days)
								900	AM CW	0.140	n/a	Reduced growth	(29% mean after 8 days)
								1900	CW; GTEM cell	0.0265	n/a	Decrease in growth	(22% mean after 8 days)
Roux et al. (2006)	France	Tomato	Lycopersicon esculentum VFN8.	3 weeks old	Lab	n/a	10 mins	900	GSM	0.0066	n/a	Evidence of stress-related responses	+ (173% mean)
Tkalec et al. (2007)	Croatia	Duckweed	Lemna Minor	Cultures	Lab	10-12	2 hrs	400-900	GTEM cell	0.0265	n/a	Depending on the field frequencies applied and on strength modulation and exposure time, induced oxida-tive stress	+ (25% mean)

										1.403	n/a	idem	
										0.4459	n/a	idem	
										3.8196	n/a	idem	
							2-4 hrs			1.403	n/a	idem	
Roux et al. (2008)	France	Tomato	Lycopersicon esculentum VFN8	Cell cultures	Lab	58 plants, 4 replicates	10 mins	900	CW	0.0066	n/a	Strong correlation between stress-related parameters and exposure	+ (6% mean treated; % mean shielded)
Sharma et al. (2009)	India	Mung bean	Vigna Radiata	Seedling	Lab	50 (50)	0.5 hr; 1 hr; 2hrs; 4 hrs	900	GSM CW	0.00855	n/a	Inhibition of germination. Inhibition of root growth as a consequence of oxidative stress	+ (16% mean)
Ursache et al. (2009)	Romania	Maize	Zea mays	Seedling	Lab	25, 5 replicates	1 hr; 2 hrs; 4 hrs; 12 hrs	418	CW;TEM cell	0.6	n/a	Increased photosynthesis efficiency.	+ (60% higher chlorophyll content; 35% higher carotene content)
Jinapang et al. (2010)	Thailand/ USA	Mung bean; water convolvuluses	Vigna Radiata ; Ipomea aquatica	Seedling	Lab	240 (15) , 3 replicates	1 hr; 2hrs; 4 hrs	425	CW;TEM cell	0.015 (power 10W)	n/a	Improved growth. Optimum respectively at: 100 mW for 1 hr and 1 mW of power for 2 hrs	+ (33% mean mung bean; 28% mean water convolvuluses)

3

Vrhovac et al. (2010)	Croatia	Yeast	Saccharo-myces cerevisiae	Strains (FF18733, FF1481, D7)	Lab	3	15-60 mins	905	MW PW; GTEM cell	n/a	0.12	Affected growth of three strains of Saccharomyces cerevisiae, due to DNA damage	+ (34% mean)
Chen et al. (2012)	China	Yeast	as above	Cells	Lab		5 mins with system on, 10 mins with system off for 6 hrs	1800	GSM PW	n/a	4.7	Altered gene-expression	+

[a] Life stage refers to the age of the tested subject at the moment of the performance of the experiment.

[b] Studies divided in laboratory and field studies. **Lab** = laboratory study, **Field** = field study.

[c] Number of subjects involved in the experiment or field study where reported in the study. In brackets information about number of control subjects. Further specifications of type of subjects involved in the studies are reported if provided by authors. [d] Wave/Modulation indicates the type of RF-EMF applied/measured in the study. **CW** = continuous wave, MW = microwave, **GSM** = Global System for Mobile Communications, **PW** = pulsed wave, **UWB** = ultra wide band, **AM** = amplitude modulation, **FM** = frequency modulation, **GTEM** = gigahertz transverse electromagnetic cell.

[e] Values of power density are reported as provided by authors or recalculated by conversion of electric field values (PD=EF2/3770) and expressed in mW/cm2.

[f] Values of SAR are reported as provided by authors and expressed in W/kg.

[g] Biological or ecologically relevant endpoints studied.

[h] Size of the effect where significant. It indicates the ration between maximum effect and percentual difference compared to control. A sign + indicates a significant effect, a - sign indicates that no significant effect was found. j n/a indicates that data was not provided by authors.

5
Synthesis
5.1
General
The reviewed literature focused on birds, insects, plants and other vertebrates studied as model species. Other important ecological groups such as e.g. bumble bees, were underrepresented. Field studies were limited and mostly focused on the analysis of the response of birds and honey bees to RF-EMF. Irrespective of the studied group, development and reproduction were the most studied ecological endpoints.

3

The number of studies finding effects was highest for plants (90%) and insects (90%), lower for birds (70%), other vertebrates (56%) and other organisms (50%). In all the available field studies significant effects of RF-EMF were found. In laboratory experiments, birds and vertebrate animal subjects were in most cases tested at higher frequencies than smaller organisms (e.g. fruit flies) and plants. Older experiments on birds were often carried out at relatively high frequency MW (i.e. 2450 MHz and higher) and dosages (power density greater than 100 mW/cm^2), which possibly determined a thermal increase of body temperature. In later experiments temperature was kept under control.

The quality of the reported RF-EMF characteristics was heterogeneous. Some studies only provided the frequencies of the RF-EMF emitting device and one dosage parameter (e.g. power density in mW/cm^2). A limited number of studies supplied the full list of physical parameters needed for an adequate description of the exposure (e.g. modulation, spatial connotation of field, polarization, field pattern, modulation, measuring techniques). The reporting of the measured or extrapolated power density values and relative electric field values were discordant and no precise information was given on measurement or calculation procedures. Also relevant biological parameters were often neglected or not described (i.e. size, tissue dielectric properties, size, geometry, relation to polarization; see Michaelson 1991).

The overall quality of the studies varied across and within groups. In the case of the studies regarding bees (with the exception of the study of Favre, 2011) a limited definition of the characterisation parameters of the exposure, and a low number of control/sham measurements limits the possibility of generalising results and for possible ecological effects.

5.2
Dose-effect relationships

The studies that did find an effect did not always refer to the existence of a dose-effect relationship. Two studies from a Greek research group (Panagopoulos and Margaritis 2010; Panagopoulos et al. 2010) described a non-linear window-effect of RF-EMF at a specific distance from the emitting source. Despite a high number of studies finding a significant effect, there was no clear relationship between applied dosage and size of effect, at the level of ecological groups. However, the analysis was hampered by the use of different and scarcely comparable physical parameters to characterize dosage and the use of different ways of shielding control groups (e.g. not always a Faraday cage was used). Experimental groups were not always shielded from extraneous sources of RF-EMF and other types of RF-EMF not expressly taken into consideration.

One important conclusion is that even at low dosages, high effect percentages were described in the range of between 10 and 90%. There seem to be no specific physical parameters and experimental conditions that seem to determine an effect. In the field experiment the proximity to the emitting device (i.e. usually a base station) contributes to increase the size of the effect.

5.3
From biological to ecological mechanisms and effects

In studies involving RF-EMF exposure temperature increase is often the only recognised and recognisable agent causing an effect. WHO (2010) considers temperature as the only clear mechanism active, especially in the studies exposing subjects to higher dosages. Most studies only report an effect of RF-EMF, without paying any attention to possible explanations. Stress is often mentioned as a possible influential element. Studies which use a sham-exposed group investigating also the possible influence of the sheer presence of the emitting device in the test area tend to exclude stress as the sole triggering factor for the effect, suggesting that the effect should be ascribed totally to the physical composition of the EMF and to the exposure conditions.

In the case of plants, an used theory is that the effects of RF-EMF- could be described and explained, also at non-thermal exposure dosages, as an ordinary stress factor, like drought or heat. The size of effects mentioned in studies with effects is relatively large in comparison with the control situations, and therefore it may be tentatively concluded from these studies that RF-EMF might have a significant ecological effect.

5.4
Differences between effect and no-effect studies: a possible bias?

The differences in articles between effect and no-effect RF-EMF studies were compared regarding the country of the origin, the exposure duration, the applied RF-EMF frequencies, and the impact factor of the journal of publication (see Table 7).

Table 7. Analysis of differences in articles between RF-EMF effect and no-effect studies.

Parameter	Effect	No effect
Country (number)†		
USA	18	17
India	8	3
Greece	8	2
France	5	8
Croatia, China, Germany, Latvia, Spain, UK	3	
Canada, Japan, Switzerland	2	
Others	10	12
Exposure duration [mins]††		
Mean	146960,5	63241,26
Median	1800	1800
Mode	30	300
Standard Deviation	836108,1	232212,2
Sample Variance	6,99E+11	5,39E+10
Minimum	5	0,0875
Maximum	7257600	1238400
Based on number of articles	79	39
Frequency ranges [MHz](number)‡		
0-30	3	2
31-200	7	2
201-900	38	9
901-1200	7	1
1201-1800	4	5
1801-2000	3	4
>2000	19	16
Journal Impact Factor ♠		
Mean	2,079973	2,449725
Median	2,291	2,371
Mode	0,73	2,291
Standard Deviation	1,094949	0,897919
Sample Variance	1,198914	0,806259
Minimum	0,13	0,246
Maximum	4,411	4,411
Based on number of articles	73	40

3

[a] Country: location of the university where main author or research group are based. Data tested by Fisher Exact Test (p-value = 0.1595). [b] Exposure duration [mins]: duration of exposure of target subject in minutes as reported by author. Data tested by Kruskal-Wallis (p-value = 0.9514). [c] Frequency ranges [MHz]: type of RF-EMF frequency ranges applied in studies. Data tested by Fisher Exact Test (p-value = 0.03531). [d] Journal Impact Factor: impact factor of journal of publication, if available, of RF-EMF study as reported by Journal of Citation Reports on the Web (JRC WEB). Data tested by Kruskal-Wallis (p-value = 0.3233)

The comparison of the countries of origin of the main authors and research groups showed in both groups a clear prevalence of studies coming from the USA (Table 7). Among the studies that did find a significant effect the most represented countries were India, Greece, France, Croatia, Germany, and Latvia (see Table 7). A lower variation in countries was found in the case of no-effect studies.

The analysis of the duration of the exposure showed that exposure was on average twice as high in the case of positive studies than in studies with no significant effects. Minimum and maximum values were also higher in the first case (see Table 7).

The distribution of studies according to the RF-EMF frequencies applied confirmed a clear prevalence of the range between GSM and MW lower band in the case of studies finding an effect. Most of the studies which did not find an effect applied RF-EMF frequencies higher than 2000 MHz (see Table 7). The analysis of the impact factors (JRC WEB 2012) of the journals where the selected articles were published showed on average a higher score for studies not finding an effect (see Table 7).

In conclusion, possible ecological effects of RF-EMF seem to be found more at higher duration in the GSM bands and in the MW frequency bands (> 2000 MHz).

5.5
Minimum requirements for studies ecological effects RF-EMF

In Michaelson (1991) and Beers (1999) attention is paid to the experimental set up of RF-EMF experiments, and to the criteria to conduct biological (therefore, also ecological) RF-EMF field and laboratory studies. The criteria are in line with the propositions of WHO (van Deventer et al. 2011) and their proposed research agenda. None of the studies analysed in this review reported the use of these standard procedures of exposure and analysis.

According to Michaelson (1991) and Beers (1999), experimental conditions should be meticulously defined, selecting the most appropriate animal species to investigate the effect of RF-EMF: intrinsic physical and physiological dissimilarities between species could be confounding elements. The experiments/studies should include a total precise duration of exposure, the length of periods of exposure, intervals (if any) between exposures and heating amplitude. Relatively to the SAR levels, the experts warn that they are often predicted using models which fail to characterise specific features of the species exposed (bone, tissue, energy deposition, etc.). All the factors that can influence biological responses at the same SAR level (e.g. sex, age, number of subjects, etc.) need to be reported.

As for the setup of laboratory experiments, standard laboratory stressors should be avoided or at least accounted for (e.g. using sham-exposure). The effects of other intervening factors (e.g. temperature, noise, chemicals) should be considered (or avoided).

Relative to the characteristics of the RF-EMF, some effects might be related to (or influenced by) the local geomagnetic field and, oddly enough, by the variation occurring in RF-EMF because of lunar phases (Beers 1999). Other factors that affect the absorption of the RF-EMF (e.g. frequency, polarisation, modulation, field pattern) have to be considered and reported, together with other possible confounding elements (e.g. RF-EMF alien to the experiment/study under investigation).

In the number of studies analysed in this review, it appears that too little attention is paid to these important recommendations. The majority of the reviewed research has been done using small rodents. Scaling of results to other species is needed to further investigate and extend results to the ecosystem level. Some exposure setups are capable of reflecting or focusing the EMF, inducing the SAR levels to increase more than experimenters may have realised, which may lead to erroneous conclusions. There is a clear need for proper dosimetry in experimental procedures with a detailed description of the methods. A special point of attention is the control: not only a control situation, but also a sham situation should be included. This procedure might introduce some extra difficulties in field situations but might still be possible (e.g. by experimentally shutting down the communication stations for a period of maintenance).

There is a great need for more ecological experiment/studies on the effects of RF-EMF, taking into account the reported guidelines. From this ecological review it became, in fact, clear that the way in which RF-EMF were applied and measured was very heterogeneous, limiting the possible comparison of the effects found.

6
Conclusions and recommendations

The screening of literature in the field ranges that were analysed provided a limited number of strictly ecological studies. The distinction between biological studies and ecological studies as intended in this review has been detailed in section 1 of this contribution. Only endpoints that may provide an ecologically relevant picture were selected, in order to quantify significant biological effects, which may provide valuable hints on the ecological implications of results. The effects of RF-EMF on different biological groups were investigated. With reference to the groups under investigations in the selected studies (i.e. birds, honeybees, mammals, plants, Drosophila and others) there is ecologically relevant evidence that the RF-EMF caused an effect in about 50% of the animal studies and about 90% of the plant studies. No studies, in fact, were found on the impact of RF-EMF at the ecosystem level. The sole study by Reijt et al. (2007) investigated the alteration in the interaction among two species of Tits. Only eight studies were conducted in the field.

Nevertheless, an ecological interpretation of the biological studies under review was necessary. The information and results on effects gathered in laboratory studies may need to be cautiously handled due to the sheer nature of the laboratory solutions adopted. The conditions applied in the laboratory studies, in fact, do not always reflect real conditions of exposure, and at times it is important to carefully evaluate the plausibility that biological systems exposed to RF-EMF could likely translate into ecologically relevant effects.

As suggested by the expert panel to the European Commission SCENIHR (2009) and Foster and Repacholi (2004), while it seems appropriate to perform experimental studies using pure experimental RF fields, it may be necessary to emulate the complex modulation patterns and intensity variations typical to real RF-EMF exposure. Few of the studies found were performed in the field and engaged in real exposure conditions and only few laboratory studies dealt with real-exposure modulation.

The ICNIRP guidelines (1998; 2010) provide limiting values as basic restrictions and reference levels for the exposure of humans to RF-EMF. These guidelines have been adopted by most European countries which have imposed limits (EU Commission Implementation Reports 2008). To our knowledge, there are currently no guidelines for the exposure of biodiversity to RF-EMF. The available data has so far been inadequate to judge whether the ICNIRP guidelines and other environmental standards should be the same or significantly different from those appropriate to protect human health (EU 2011).

However, if we consider that the guidelines might protect biodiversity (i.e. with the consideration of differences in size and exposure conditions), in some studies analysed we encountered applications of dosages hardly experienced by animals and plants in case of real outdoor conditions. As a general trend, no clear relationship was determined between maximum effects found in different studies and the dosage of the RF-EMF applied. Also at very low dosages significant ecologically relevant effects were found. These values are compatible with real field situations, and could be found under environmental conditions. From the limited number of field studies decreasing effects could be determined at increasing distances from the emitting source, but residual relevant effects were still detected as far as 300 metres away and with an average measured electric field of 0.53 V/m, thus 7,45x10-5 mW/cm^2 (ICNIRIP limit for general human population 0,0004 V/m).

As ICNIRP suggests (2010), when reference levels are exceeded restrictions values are not necessarily exceeded. Further investigations, need to be undertaken. For instance, localized fields in excess of the reference levels can be emitted by certain devices (i.e. wireless or remotely-controlled devices) but there might be a weak coupling of the field with the body of the exposed target subject (e.g. due to the size of the exposed subject). Therefore, while it is not possible to rule out the adverse ecological relevance of effects, ICNIRP (2010) and WHO (2010) suggest to extrapolating only cautious indications on the global impact of RF-EMF on ecosystems.

Considering the relevant remark of Beers (1999) “a long list of reports of positive results yielded by inadequate experiments may appear impressive in a review and yet mean little”. No clear relationships, in fact, could be found between dosage and effects because of a wide variety of exposure strengths, durations, conditions, frequencies, time between exposures, assessment methods, measurement systems, replications efforts, and adequate dosimetry. In the older laboratory studies the interpretation of results needs to be filtered by the consideration of a lack of control of temperature. In the other studies the balance of experimental evidence points towards a non-thermal effect of RF-EMF exposure. In field studies additional confusion might be caused by the simultaneous exposure to multiple field strengths and frequencies and other environmental confounding variables. A similar conclusion can be drawn for those laboratory studies that did not adequately control the exposure to other sources of electromagnetic fields, in which also the influence of other variables on the result was usually not handled in the design or in the analysis.

The plotting of the size of the ecologically relevant effects in relationship to the dose conditions applied did not seem to define a trend. Thus, the result of the graphical meta-analysis leads to no definitive conclusions about whether the effects are real, not real, or can be found only under certain conditions. The study of the differences between significant and non-significant studies presented in section 5 revealed differences in the duration of the exposure of the target subjects, in the selection of the frequency band of exposure and in the impact score of the journals where articles were published.

Potential further sources of bias should be further examined using tools such as *funnel or forest plots* (Egger et al. 1997; Peters et al. 2006, 2008). These might reveal asymmetries due to: location biases (e.g. language bias, citation bias, multiple publication bias), heterogeneity (e.g. intensity of intervention, differences in odds ratios), data irregularities (e.g. poor or inadequate analysis), poor choice of effect measure, and chance.

At the current state of our knowledge, it is possible to conclude that there is an urgent need for repetitions of experiments and field studies by other research groups and under other (standard) situations and setup in order to confirm the presence/absence of effects. We, once again, refer to the ICNIRP statement of 2010, suggesting that results can only be accepted 'for health risk assessment if a complete description of the experimental technique and dosimetry are provided, all data are fully analysed and completely objective, results show a high level of statistical significance, are quantifiable and susceptible to independent confirmation, and the same effects can be reproduced by independent laboratories (Repacholi and Cardis 1997). If the significant conclusions found by studies are confirmed, they will be important for a mechanistic understanding of the interaction of RF fields with ecosystems.

In the synthesis the requirements to conduct an adequate study of the (ecological) effects of RF-EMF have been described in detail. Advances in dosimetric investigations in terms of precision and resolution were appreciable in some of the more recent studies, while standards seemed to be totally neglected in others. The application of the suggested best practise would allow to handle the information on the reported effect or absence of effect with greater precision.

Our review highlights that there is a clear need for the study of the effects of RF-EMF on more species and organisms and, by means of field studies, on populations and interactions between species. Studies at the ecosystem level should start from the consideration of micro-ecosystems and micro-cosmos, which would allow for laboratory results to be more informative and ecologically-relevant, also at a policy level.

The number of experiments assessing new technologies is limited: only 5 matched the ecological criteria set in this review. Experiments evaluating the impact of newer wireless technologies (e.g. WiMAX, WLAN, WiFi), together with studies analysing new generations of mobile phone technologies (e.g. 3G, 4G) would shade some light on the impact of these technologies for ecosystems. To our knowledge solely the study on mice by Lee et al. (2009) investigated the possible impacts of these technologies. In order to minimize the uncertainties as efficiently as possible a number of situations with limited number of studies should be investigated: the long-term monitoring of selected species and/or ecosystems, field studies under a controlled system of exposure, laboratory studies following given recommendations, and studies on important ecological groups, other than those here analysed, would be a solid base on which to focus future studies.

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Appendix

Keywords for literature screening.

Main search strategy

RF-EMF OR SAR OR electromagnetic OR "power density" OR "internal electric field" OR "current density" OR non-ionising OR non-ionizing OR RF OR "electric field" OR "magnetic field" OR Wi-Max OR WiMax OR W-LAN OR WiFi OR Wi-Fi OR modulation OR DCS OR GSM OR FM OR UMTS OR AM OR television OR TV or FM or AM or radio OR transmitter OR broadcast OR antenna OR aerial OR "base station" OR phone OR wireless OR DECT OR TETRA OR radar OR phone mast

AND

reproduction OR fecundity OR mortality OR behaviour OR behavior OR activity OR density OR growth OR navigation OR orientation OR eco* OR malformation OR insect OR honey bee OR bee OR bat OR fruitfly OR mammal OR plant OR fauna OR biodiversity OR community OR population OR wildlife OR animal OR organism OR tree OR plant OR fish OR invertebrates OR fauna OR flora OR fungi OR birds OR vegetation

4

Towards a general framework for including noise impacts in LCA

Towards a general framework for including noise impacts in LCA

Based on:
Cucurachi, S., Heijungs, R., Ohlau, K. 2012. *The International Journal of Life Cycle Assessment,* 17(4), 471-487.

Abstract

Purpose: *Several damages have been associated with the exposure of human beings to noise. These include auditory effects, i.e. hearing impairment, but also non-auditory physiological ones, such as hypertension and ischemic heart disease, or psychological ones, such as annoyance, depression, sleep disturbance, limited performance of cognitive tasks or inadequate cognitive development. Noise can also interfere with intended activities, both in day time and night time. ISO 14'040 indicated the necessity of introducing, together with other less developed impact categories, also noise in a complete LCA study, possibly changing the results of many LCA studies already available. The attempts available in the literature focused on the integration of transportation noise in LCA. Although being considered the most frequent source of intrusive impact, transportation noise is not the only type of noise that can have a malign impact on public health. Several other sources of noise, such as industrial or occupational, need to be taken into account to have a complete consideration of noise into LCA. Major life cycle inventories (LCI) typically do not contain data on noise emissions yet and characterization factors are not yet clearly defined. The aim of the present paper is to briefly review what is already available in the field and propose a new framework for the consideration of the human health impacts of any type of noise that could be of interest in the LCA practice, providing indications for the introduction of noise in LCI and analysing what data is already available and, in the form of a research agenda, what other resources would be needed to reach a complete coverage of the problem.*

Main features: *The literature production related to the impacts of noise on human health has been analysed, with considerations of impacts caused by transportation noise, as well as occupational and industrial noise. The analysis of the specialist medical literature allowed for a better understanding of how to deal with the epidemiological findings from an LCA perspective and identify areas still missing dose-response relations. A short review of the state-of-science in the field of noise and LCA is presented with an expansion to other contributions in the field subsequent to the comprehensive work by Althaus et al. (2009a; 2009b). Focusing on the analogy between toxicological analysis of pollutants and noise impact evaluation, an alternative approach is suggested, which is oriented to the consideration of any type of noise in LCA, and not solely of transportation noise. A multi-step framework is presented as a method for the inclusion of noise impacts on human health in LCA.*

Results and discussion: *A theoretical structural framework for the inclusion of noise impacts in LCA is provided as a basis for future modelling expansions in the field. Rather than evaluating traffic/transportation noise, the method focuses on the consideration of the noise level and its impact on human health, regardless of the source producing the noise in an analogous manner as considered in the fields of toxicology and common noise evaluation practices combined. The resulting framework will constitute the basis for the development of a more detailed mathematical model for the inclusion of noise in LCA. The* *toxicological background and the experience of the analysis of the release of chemicals in LCA seem to provide sufficient ground for the inclusion of noise in LCA: taken into account the physical differences and the uniqueness of noise as an impact, the procedure applied to the release of chemicals during a product life cycle is key for a valuable inclusion of noise in the LCA logic.*

Conclusions: *It is fundamental for the development of the research in the field of LCA and noise to consider any type of noise. Further studies are needed to contribute to the inclusion of noise sources and noise impacts in LCA. In this paper, a structure is proposed that will be expanded and adapted in the future and which forms the basic framework for the successive modelling phase.*

Keywords
Noise impact assessment - LCA - Human health – Generic noise sources

1 Introduction

Within life cycle impact assessment (LCIA), the study of noise impacts is an underdeveloped field (ILCD 2010). The sheer nature of sound and noise has limited the possibility of developing a methodology usable for the evaluation of impacts determined by any source of noise and in principle expandable to the analysis of impacts on other species than humans. The dearth of data in other fields than transportation noise stimulated the focus of researchers on this only field. Ad hoc methodologies developed solutions that are scarcely linked to the LCA practice commonly adopted for other pollutants and, in general, for impact assessment and which are based on the consideration of a specific traffic situation rather than on the evaluation of the noise emissions which are explicitly linked to activities in the life cycle of a specific functional unit. Fundamental concepts in LCA, such as system boundaries and functional unit, seem to fall into the background of the analysis. The proposed models lack the required flexibility to expand them from impacts on humans to other target subjects.

The intent of this paper is to propose a new framework for the evaluation of noise impacts (section 3), after briefly reviewing the literature in the field of LCA and noise and having assessed what the impacts of noise from an epidemiological perspective (section 2) are. While section 2 is based on existing reviewed knowledge, section 3 aims at assembling and expanding it to a new framework which may help towards the modelling and operalisation of noise impacts assessment for human health and possibly to the health of other species.

Basing on the approach taken in human and environmental risk assessment and the approaches commonly adopted in LCIA for other impact categories, the framework goes beyond the only consideration of transportation and road noise and aims at developing a comprehensive cause-effect chain methodology usable for the evaluation of any source of noise. Even though transportation noise can, in fact, represent a main source of noise impact in the life cycle of some products, in some others, e.g. construction works, it can represent a minor source of impact. The proposed framework will be the skeleton for the future modelling activity which will be presented, together with the necessary developments in the field, in the research agenda section of this paper (section 4).

2
Fundamentals of sound and noise
2.1
Generation of a sound wave

If an object is moved at one place in a medium, e.g. air, there is an appreciable disturbance which travels through the medium, which we can refer to as vibration or sound. In the case of air as medium, a sudden movement of the object compresses the air causing a change of pressure which pushes on additional air, which in turn is compressed leading to extra pressure and to the propagation of the generated (sound) wave. To obtain a sound wave it is necessary that molecules moving from a region with higher density and higher pressure move, transmitting momentum to the ones at lower density and pressure in the adjacent region (see, for example, Feynman 1970 for a complete description). Audition is not static: something in the world has to happen to produce a sound, meaning that a sound source has to be involved in a physical action for the production of what is defined as a sound event or multiple types of sound events (Niessen 2010). The recognition of a sound event by human listeners (auditory event) determines their cognitive representation of it (auditory episode) and therefore their reaction to it; when intolerable, unwanted, annoying or completely disruptive of the daily sonic experience of individuals, a sound becomes noise.

2.2
Sound, noise and noise impacts

Since ancient times sleep disturbance and annoyance were already considered main issues for the life of citizens (Ouis 2001). Chariots in ancient Rome, for instance, were banned from night circulation, since their wheels clattered on paving stones (Goines and Hagler 2007). Growing attention of research on noise impacts has emerged in the last century as a consequence of ever increasing levels of intensity of unwanted noise: in 1994 almost 170 million Europeans were found to be living in zones that did not provide acoustic comfort to residents (Miedema 2007), requiring a close evaluation of the increasing magnitude of the presence and role of noise among ambient stressors.

In the 1960s, noise had already been identified as a health stressor and most of its public health impacts had been recognised (Ward and Fricke 1969). They were later reviewed scientifically and confirmed in the 1970s to provide policy makers with recommendations (Health Council of the Netherlands 1971; US EPA 1974). Evidence has since then been found to corroborate the existence of a causal relationship between noise and specific effects on human beings, but also with respect to other forms of living creatures, affecting their ability to communicate when noise masks their communication sounds, e.g. birds or marine species, or also directly threatening their survival and reproduction (Brumm 2004; Slabbekoorn et al. 2010).

The definition of noise as unpleasant, unwanted sound makes the evaluation of its perception quite subjective and less prone to a scientific and robust modelling of its health burdens, indicating the need to employ more than physical measures for operational purposes (Shepherd 1974). Personal traits influence the reaction of people to noise as well as what is commonly defined as their subjective sensitivity to noise or attitude to noise in general (Stansfeld 1992). A complete and literature-summarizing definition of noise sensitivity is found in Job (1999): "Noise sensitivity refers to the internal states (be they physiological, psychological [including attitudinal], or related to life style or activities conducted) of any individual which increase their degree of reactivity to noise in general". It is then clearly indispensable to evaluate the subjective component of noise when evaluating its impacts on human health: some individuals can express more annoyance than their neighbours to a particular level of noise (Griffiths and Langdon 1968; Bregman and Pearson 1972; Stansfeld 1992), some others high in trait anger might show stronger emotional reactions when disturbed by noise (Miedema 2007). Moreover, the concept of soundmarks, i.e. sounds to which a certain community associate a specific feeling of recognition (Adams et al. 2006), and keynote sounds (Schafer 1994), i.e. sounds heard by a particular society frequently enough to constitute the background against which any other sound is perceived, contributes to making the local situation where a sound event takes place fundamental to understand the relative impact of noise.

Scientific evidence confirms that it is clear that noise pollution is widespread and imposes long term consequences on health (Ising and Kruppa 2004; Babisch 2006). Following, in fact, the WHO (1947, 1994) definition of health as "a state of complete physical, mental and social wellbeing and not merely the absence of disease and infirmity" it is clearly understandable that noise impacts human health in manifold ways, which can be more easily detectable and linkable to the source as in the case of hearing loss but less evidently in causing other more subtle health effects. Moreover, it appears from the application of the available computational assessment models to case studies that not only is noise more directly perceived as disturbing by humans in comparison to chemical emissions or resource uses, but it objectively represents, for some processes in a life cycle, the most relevant of the health burdens. Considering, for instance, the overall health impacts of transportation within a life cycle it is possible to conclude that the impact from noise-related health burdens, evaluated using common metrics (see section 2.5), are of the same order of magnitude or higher than those that are attributable to other emissions (Doka, 2003; Muller-Wenk, 2004). It has to be noted that the assumption of linearity and the implication of averaging conditions could, however, have lead to an overestimation bias and a misdjudgement of the overal health impacts due to noise (Franco et al.. 2010)

2.3
Noise exposure and non-physiological effects on humans

Disturbance of activities, sleep, communication, and cognitive and emotional response usually lead to what is generally referred to as annoyance. Miedema (2007) defines this as a primary influence of noise and, as reported by Job (1999), it may include other more specific effects such as "apathy, frustration, depression, anger, exhaustion, agitation, withdrawal, and helplessness". Annoyance is certainly the most well documented response to noise, seen as an avoidable source of harm.

Several effects on the sleeping activity have been associated with nocturnal noise. Physiological reactions lead to primary sleep disturbances, distressing the normal functioning of individuals during daytime and potentially disrupting personal circadian rhythm with consequential effects on health and well-being (Pirrera et al. 2010). A clear relationship has been found between transportation noise and altered aspects of the sleeping process and the quality of it, in terms, among others, of increased body motility (Williams et al. 1964), sleep stages redistribution (Pirrera et al. 2010) and self-reported sleep disturbance (Miedema 2007).

In the context of verbal interactions of people, exceeding levels of noise cause frustration of communications, implying the necessity of raising the voice of the speaker to allow conversations and free speech, altering the social capabilities of individuals and leading to problems such as uncertainty, fatigue, lack of self-confidence, misunderstandings and stress reactions. Significant is the impact on vulnerable groups, "such as children, the elderly, and those not familiar with the spoken language" (Goines and Hagler 2007).

Prolonged exposure to noise sources negatively affects processes which require attention and concentration. Experiments demonstrated a direct altering of memory and comprehension functions of individuals exposed to noise, especially sensitive subjects such as children (Clark and Stansfeld 2007), with the manifestation of semantic errors, text comprehension errors, errors in the strategy selection for carrying out tasks, or reduction in connections between long-term memory and working memory (Hamilton et al. 1997; Enmarker 2004).

2.4 Noise exposure and physiological response of humans

The direct exposure to continuous and loud sources of noise, especially if prolonged, and the synergic combination of the stressors previously described can lead to predictable physiological responses.

The direct exposure to noise leads to hearing impairment, caused by a mechanical damage to the ear or in some cases by the interference of noise with the basic functions of the auditory cells (Chen and Fechter 1999). Hearing loss is dependent on a number of variables, such as type, duration, intensity, and frequency of the noise (Rao and Fechter 2000); but to be considered are also other factors such as periods between noise exposures (Henselman et al. 1994), and of course the previously mentioned noise sensitivity and individual variability. Hearing impairment can be associated with abnormal loudness perception, distortion, and temporary or prolonged tinnitus (Berglund and Lindvall 1995; Axelsson and Prasher 2000).

The exposure to noise levels at or above 85 dB (e.g. the noise of a heavy truck traffic on a busy road) for a 8-hour-time-weighted average working day over a lifetime is associated to a hearing impairment at 4000 Hz of about 5-10 dB for most workers (Lusk et al. 1995). It is generally considered that a hearing impairment that exceeds 30dB, averaged over 2000 and 4000 Hz at both ears, can constitute a social handicap (Passchier-Vermeer and Passchier 2000). Noise-induced hearing loss is the most common occupational disease (NIOSH 1996). Interesting is the example of construction workers, who usually do not only operate in a single working setting but move around job sites, being exposed not only to the noise coming from tools or equipment of their own, but also to the noise of those owned by the surrounding workers (Lusk et al., 1998).

The so-called leisure noise (usually exceeding 120 dB) has been closely studied epidemiologically and can be a cause of hearing impairment (Davis et al. 1998; Axelsson and Prasher 1999), with young adults being the category of people mostly exposed, in environments such as clubs or discotheques. WHO (1995) recommends a maximum of 4 hrs of exposure, for a maximum of 4 times/year, to unprotected leisure noise levels exceeding 100 dB. 140 dB is identified as the threshold for pain; even the shortest exposure at levels greater than 165 dB can cause immediate acute cochlear damage (Berglund and Lindvall 1995). Effects of somatic nature include stress-related cardiovascular disorders. It is important to underline how studies on this type of effects are complicated, because of the different sensibility, susceptibility and genetic predisposition of individuals to the impairment, and because of the difficulty in evaluating precisely past noise exposure of the subjects under study (Passchier-Vermeer and Passchier 2000). The most complete studies available in the literature are generally focused on the exposure to traffic noise and aircraft noise with a dearth of data in the other fields of noise exposure, apart from limited studies in the field of occupational noise (Rai et al. 1981; Fogari et al. 2001).

In-bedroom and laboratory studies (Hofman et al. 1995) found that sound peaks due to transportation noise caused an increase in heart rates as a direct response to the stimulus in individuals living along highways with high traffic density. Sleep disturbance has been directly associated with collateral cardiovascular effects, including increased blood pressure, increased pulse amplitude, vasoconstriction, cardiac arrhythmias (Verrier et al. 1996), as well as increased use of sleep medication and cardiovascular medication (Franssen et al. 2004).

Babisch et al. (2005) and Babisch (2006, 2008) found evidence to support the hypothesis that chronic exposure to traffic noise increases the risk of myocardial infarction especially in male individuals with predisposition to high systolic and diastolic pressure in the range between 45 and 55 years of age, as confirmed by de Kluizenaar et al. (2007), but also in young adults aged 18–32 years (Chang et al. 2009). Less such evidence of association was found by Babisch and van Kamp (2009) in the case of aircraft noise. However, a Swedish study confirmed that hypertension was higher among people exposed to time-weighted energy-averaged aircraft noise levels of at least 55 dB(A) or maximum levels above 72 dB(A) around the Arlanda airport, in Stockholm (Stansfeld and Matheson 2003).

Exposure to noise also activates the sympathetic and endocrine systems, intervening with the excretion of hormones. Increased levels of catecholamine were found in people exposed to road traffic noise as a response to stress levels (Babisch et al. 2001), but also in workers of a textile factory in Vietnam (Sudo et al. 1996). Irregular excretion of corticosteroids, adrenalin and nor-adrenalin (Slob et al. 1973) was found in laboratory tests on men as well as upon laboratory animals.

In the context of this article we are interested in analysing those effects that have been confirmed to have an impact on human health and which can be possibly modelled for their analysis in LCA and specifically in the life cycle impact assessment (LCIA) phase.

2.5
Sound and noise metrics and rating indices

The physical quantity which is of interest for the quantification of noise is sound pressure, defined as the incremental pressure due to the passage of the sound wave in the air, oscillating above and below ambient pressure (Ouis 2001). Sound pressure level (Lp) is defined as:

$$Lp = 10\log\left(\frac{P^2}{P_{ref}^2}\right) = 20\log\left(\frac{P}{P_{ref}}\right) \tag{1}$$

where p is the sound pressure in Pa. The logarithmic unit is used to account for the large scale of the human sound pressure sensitivity and P_{ref}, which is equal to $2*10^{-5}$ Pa, usually considered as the the lowest sound pressure detectable by the human ear (Lp = 0dB). In other media (e.g. underwater) a different reference might be used. The sound pressure level is a dimensionless quantity (the logarithm of the ratio of two pressures), but the unit-like indication dB (decibel) is added to indicate the logarithmic scale. The multiplication by 10 is related to the choice for decibel instead of bel and it is then multiplied by a factor 2 following common properties of the logarithm function.

In subsequent elaborations, Lp has been refined to take into account the time-dependent character of noise, with differences of impact on human health and of response to noise identifiable with nocturnal and diurnal noise, and also to take into account the duration of the noise itself.

So-called A-weighting mode, expressed in dB(A), is the type of scale introduced to account for the subjective nature of noise exposure, which represents sound pressure levels at different frequencies comparable to that of the human hearing organ and its lower sensitivity to high and low frequencies (Passchier-Vermeer and Passchier 2000). Together with the A-weighting mode a scale of octave bands frequencies or one-third octave-band frequencies is commonly selected, taking into account a specific range of frequencies, with a lower cut-off frequency and an upper cut-off frequency selected according to the specific objective of the measurement (e.g. target subject).

The Equivalent Continuous Sound Pressure Level (Leq) measures the A-weighted sound pressure level over a specified time of measurement T, which can be taken as 1, 8 (i.e., working day), 12, or 24hrs:

$$Leq = 20\log\left\{\left[\left(\frac{1}{T}\right)\int_0^T P_A(t)dt\right] / P_{ref}\right\} \tag{2}$$

4

where $P_A(t)$ represents the instantaneous A-weighted sound pressure in Pascal and T is a specified time interval. Penalties are introduced by other measures to account for exposures happening at specific times of a day. This is the case of Ldn, which represents the day-night level and accounts for an increased penalty of 10 dB(A) between 11PM-7AM. Similarly, Lden, the day-evening-night level, uses an analogous construction but sound levels during the evening, between 7PM-11PM, are increased by 5 dB(A), and those between 11PM-7AM are increased by 10 dB(A).

For single noise events the preferred measure is the sound exposure level (SEL), which is the equivalent sound level during an event (e.g. the overflight of a plane) normalised to a period of 1 second (Passchier-Vermeer and Passchier 2000). In general, as established with the Directive on Assessment and Control of Environmental noise EC-2002/49 (EC 2002), Lden proved to be a good indicator for long term effects and especially annoyance.

The study of noise levels, exposure and human health led to the definition of synthesis curves that quantify the exposure-response relationship of subjects exposed to variable levels of noise. Relations for which sufficient quantitative data are available typically regard transportation noise. Miedema and Vos (1998) integrated the results from 55 different datasets on noise and established summarizing functions to quantify the relationship between annoyance and the incidence of noise, developing a measure of the percentage of highly annoyed people (%HA) as a function of the Lden level. Criticism has been in the past raised (Probst, 2006) over the use of the %HA as a measure of the effect of noise on humans with the consideration that the metric provides a weak weighting of noise levels and does not reflect the perception of the local communities over the noise level experienced. However a position paper of the European Commission (EC 2002) and a guide on good practices on noise exposure and effects by the European Environment Agency (2010) included the %HA as a suitable measure but considered also a larger number of endopoints with a dose-effect relationship. Noise-induced behavioural awakenings, chronic increase of motility, self-reported sleep disturbance, learning and memory difficulties and increased risk of hypertension were found to have sufficient evidence of dose-effect relations or of a threshold value.

Monetised estimates of health damages, also referred to as external costs or externalities (Navrud 2002; ExternE 1995), are commonly used to associate an economic value to the impact of a xenobiotic substance or a pollutant (e.g. noise) onto human health and quantify a loss in life quality in monetary units. Cost-benefit analysis represents a form of evaluation in which the health and non-health aspects of the exposure to a pollutant are evaluated in monetary terms. The procedure allows for an easier inclusion of non-health aspects for the evaluation of criteria such as well-being, personal life satisfaction, and productivity (de Hollander 2004). These analyses include the willingness to pay (WTP) of households for a reduction of the noise level in a specific area, measured in euro per dB per household per year, and the willingness to accept (WTA), related to the acceptance level of individuals of the risk to which they are exposed, with the focus often oriented to evaluate productivity loss and health care use as a consequence of health impairment or non-health burdens (Krupnick and Portney 1991; de Hollander et al. 1999).

Health adjusted years (HALYs) are generally the human health metrics used to transform any type of morbidity, including health issues from noise exposure, into an equivalent number of life years lost (Hofstetter and Hammitt 2002). To the macro-category of HALYs belong quality adjusted life years (QALYs) and disability adjusted life years (DALYs). QALYs measure the actual health quality integrated over time, which usually requires variations and adjustments for the time preference of individuals or societes (Hofstetter and Hammitt 2002; see Pliskin et al. 1980 for a theoretical basis of the measure). DALYs refer to the loss in health that an individual would be exposed to in the case of a morbidity compared to a hypothetical profile of perfect health which would have died at a standard expected age; they are the sum of years of life lost (YOLL) and the number of years lived with a disability (YLD).

Both cost-based and health-adjusted life years find methodological objections (Diener et al. 1998) in the literature, which usually include the consideration of the limited reliability of questionnaire-based surveys and the consideration of health as an economic good (de Hollander and Melse 2004), as well as the substantial uncertainty related to the measures even though found to be less than one order of magnitude (Burmaster and Anderson 1994). Equity principles and morale often come into the argument of one choice to be made over the other or to exclude both of them on the basis of various reasons. For the context of this article a detailed exemplification of the pros and cons of the methodologies described is not considered beneficial towards the improvement of the state-of-science in the field of LCA and noise, since both measures provide a useful framework for the explicit evaluation and comparison of health impairments associated with environmental exposures (de Hollander and Melse 2004).

3 Sound and noise in LCA

3.1 The current situation

Compliance to the ISO standards is often seen as a fundamental measure of quality for LCA studies. ISO 14'040 (2006) and ISO 14'044 (2006), together with the setting of the standards for LCA, specified the feature and the phases of the analysis, including the description of the life cycle inventory (LCI) and of the life cycle impact assessment (LCIA) phases.The addition of the effects on human health due to exposure to noise, also according to the ISO standard requirements, should – whenever possible – be assessed in the LCIA phase and data regarding noise included in LCI. Nevertheless, in the words of Franco et al. (2010) "several methodological shortcomings still hinder the inclusion of transport noise as an established impact category within life cycle assessment" and "earlier attempts […] yielded valuable results […], but these were of limited use in the context of everyday LCA practice". This remark highlights two main aspects of how research in the field of noise and LCA has progressed.

The investigation of possible ways of incorporating the evaluation of noise into LCA has considered primarily and almost exclusively "transport noise" (or traffic noise as it is often referred to) losing the focal point that noise effects in LCA need to relate to the functional unit,which is the transport and not the traffic situation (Althaus et al. 2009a). The two terms, "traffic" and "transport", seem to overlap in the literature, while a distinction should be made to stick to the process causing the noise and not to the situation in which the event takes place. It is necessary to evaluate for each specific life cycle under investigation what sources of noise is preponderant and develop a method that could be applicable to any noise situation relevant to the LCA practice.

The second element emerging from the words of Franco et al. (2010) is the limited use in the everyday LCA practice of the results so far available in the field, still not allowing for a revision of already available LCA analyses. Characterization factors of the impact category noise are still not included in the main LCIA systems and few studies have developed models and software of limited use in common practice and that do not yet provide application to upscaled and larger systems at a European and World level (LC-IMPACT, 2010), nor do LCI databases which do not include data on noise. Back in 1993, Fava et al. already concluded that "a few processes – blasting minerals, for example – require attention, and certain products – for example, gasoline-powered lawn mowers, leaf blowers, edging tools [...] should be included in an LCA if feasible".

Althaus et al. (2009a) reviewed the methodology and state-of-science for the integration of traffic noise in LCA. Strengths and weaknesses of 66 LCA case studies were studied and combined with data regarding the study of LCA and traffic noise to define a set of requirements, thus a "profile for noise inclusion methods for LCA" (see p.564, Althaus et al. 2009b). Even though the profile was seemingly not directly referring to a specific type of noise, but generally to "noise inclusion", the list is specific to the traffic/transportation noise inclusion in LCA. Five different methodologies were analysed in detail to check for their coherence with the explained requirements, covering the whole spectrum of methods available in the field of study of traffic noise and LCA: CML guide for LCA (Guinée et al. 2001); Ecobilan method (Lafleche and Sacchetto 1997); Danish LCA guide method (Nielsen and Laursen 2005); Swiss EPA method (Muller-Wenk 2002, 2004); Swiss FEDRO method (Doka 2003). Among these methods, only the CML guide for LCA seems to focus on the consideration of the physical nature of sound/noise, and on the construction of an indicator that could be used for any stationary source of noise. Althaus et al. (2009b) also propose a framework, which is consistent with the requirement profile individuated and based on the Swiss EPA method. The method is adequate for the consideration of "generic and specific road transport" and, following Muller-Wenk's method (2004), focuses on the consideration of additional noise emissions due to additional vehicles, based on the official Swiss emission model SonRoad (Heutschi 2004b). The proposal allows for a specific consideration of various vehicles, contexts and traffic situations in terms of space, time, speed and volume, but it does not take into account noise from mixed transportation (Lam et al. 2009). Percentage of highly annoyed individuals (%HA or frequently disturbed or instantaneously disturbed) and DALYs are the measures commonly used in the methods for the evaluation of impacts on human health at various levels of noise.

On the same lines moved Franco et al. (2010), who expanded on the work of Muller-Wenk by incorporating state-of-the-art noise emission models of the series of "improved methods for the assessment of the generic impact of noise in the environment" (IMAGINE 2005, 2007a, 2007b).

In the above mentioned methodologies, background is dealt with (or not as in Guinée et al., 1992 and Doka, 2003) in various manners and commonly the background situation defines a baseline condition and starting point from which developing the calculations.The Danish LCA guide method (Nielsen and Laursen 2005) explicitely considers the impact of noise on humans as a function of the part of the noise exceeding the background noise level (Althaus et al., 2009). Muller-Wenk (2002, 2004) evaluates the background noise situation through the use of data calculated by available computer models using pre-existent traffic intensities and ground properties at specific locations. Franco et al (2010) take background noise into account and incorporate it in their developed methodology by comparing the impacts of various specific traffic scenarios with or without (i.e. with the sole consideration of the background noise level) the consideration of a specific traffic flow. Lafleche and Sacchetto (1997) consider calculated or measured noise levels along roads as their starting point for the calculation of the area affected by a noise level above a defined threshold (Althaus et al,, 2009a).

On the impact side, the impact of noise on human health is quantified in terms of the number of annoyed people, using solely annoyance as a comprehensive indicator of impact and Lden as a descriptor of noise levels.

The methods presented in the review by Althaus et al. (2009a) and the work by Franco et al. (2010) represent the full spectrum of methods currently available in the field of LCA and noise.

One approach needs to be highlighted. Meijer et al. (2006) describe how the LCA of dwellings could incorporate health effects of traffic, not as part of the life cycle of these dwellings (so not relating to the transport for the materials of the house), but for other life cycles, which just happen to have impacts for the residents of these dwellings.

3.2
Requirements for the assessment of noise in LCA

Ensuring the wide applicability of a noise evaluation model in LCA (Althaus 2009b) means that we should allow for the consideration of any type of noise which is proved to cause harm to human health. We can translate this into the following fundamental requirements:

1. Consideration of generic and specific sources of noise in LCA

2. Separate treatment of different routes of noise emission within a LCA analysis

3. Accounting for noise emissions from activities in different geographic contexts and evaluation of differences in noise-treatment policies

4. Accounting for different temporal and spatial contexts of noise emission and impact on human health

5. Accounting for all the activities in the life cycle which can be associated with a noise emission, with particular attention to cases of noise levels above a given threshold

6. Extendibility to other target organisms

The first requirement ensures the accuracy of data included in LCA studies, with the focus placed on considering any source of noise. Separate treatment of emission routes ensures that all the possible routes of noise emission, deriving from the transportation of a product from A to B or from the laying of the groundwork of a building, are considered in a complete LCA. Different noise levels from activities have also to be considered among the characteristics and configuration of the context where the emission takes place. Spatial differentiation is fundamental in the context of noise in order to have a clear view of the measures in place at different locations (e.g. noise barriers) to protect citizens from being exposed to a source of noise and to account for the vicinity of the listener to the source when a noise event takes place. The temporal importance of the evaluation of noise levels has already been stressed in the previous sections, given the increased level in annoyance and stress levels verifiable in the occasion of a nocturnal noise event. Requirement 5 confirms the necessity of treating noise emissions as any other emission in the life cycle. The flexibility (requirement 6) highlights what has been considered as a lack of already developed noise assessments available in the literature: in the future it should be possible to investigate, provided specific modelling adjustments, the impacts of noise on other organisms than humans.

The approach commonly in use in the context of LCA for chemical emissions can then be expanded to evaluate noise impacts, following the above-described requirements. In the procedure below, this parallel is described in detail using a multi-step approach, which takes into account the reviewed epidemiology of noise, the LCA and noise work previously analysed, and the theory described in the previous section of this paper.

3.3
Noise compared to emissions into the environment

For a comprehension of noise in the context of emissions it is fundamental to investigate useful areas of commonalities with, and distinction from, toxic compounds.

Given the physical nature of sound, noise obeys to the law of radiation, meaning that its intensity decreases as the distance from the source increases, with an effect localized in the immediate vicinity of the source itself, soon disappearing after the sound is produced (Muller-Wenk 2002). On the contrary, typical distances between an emission source of a compound and its location of deposition can amount to several hundreds of kilometres (Potting et al. 1998). Phenomena that are typical of other compounds, in fact, such as dispersion, dilution, accumulation/bio-accumulation, sedimentation and deposition, adsorption or degradation assume different characteristics in the case of noise. Moreover, besides the energy content of a specific sound emitted by a source, it is essential to ponder other important pieces of information, such as the frequency structure, the volume over time, and site-specific factors (e.g. presence of sensitive groups or keynote sounds) that can influence the impact and the magnitude of it. For toxic releases, the emission compartment is quite important. For noise, we can restrict the discussion to air in the case of human health impacts, although a further refinement of the air compartment into urban and rural will be made, and an additional temporal specification (e.g.: day, night) will be introduced. For a future extension to aquatic organisms (Anderson et al. 2011), we may need to include other compartments as well.

The LCA framework introduces a major break between inventory analysis and impact assessment. Inventory analysis looks at the elementary flows (or stressors or environmental interventions), i.e. the physical things taken from or introduced into the environment. It does so first on a per-unit-process basis, and later on aggregates them across the life cycle. In the context of toxics, the emission in kg per type of pollutant (phenol, benzene, etc.) per compartment (air, water, etc.) is what is specified here. Additional descriptors may then be needed (e.g., distinguishing Cr(III) and Cr(VI), or rural and urban emissions). In the context of noise, the physical intervention is the sound level (e.g., in dB, or in energy units), with a possible addition of other descriptors (day or night, rural or urban, high or low frequency,etc.).

The impact assessment takes the inventory results as a starting point. Typical methods for the assessment of human toxicity in impact assessment are based on a causality chain (Udo de Haes et al. 2002), used to depict the changes in the quality of a natural environment. In principle, the same type of chain can be applied to the evaluation of noise impacts.

Four phases are considered in human toxicology as parts of a full causality chain. As correctly suggested by Muller-Wenk (2002, 2004), the same scheme can be adapted for the use in the context of the evaluation of noise emissions:

- **Fate analysis** refers to the change in concentration of a specific pollutant caused by a given emission. In the context of noise impact evaluation, the purpose of the analysis is to determine the increase of sound pressure levels if one or more processes in the life cycle determine noise production.

- **Exposure analysis** investigates the number of individuals (humans or other target subjects) affected by the change in concentration identified in the fate analysis.

An increase in the sound pressure levels identified in the fate analysis has an impact on a quantifiable number of individuals.

- **Effect analysis** shows the effect of the increased concentration of a pollutant if humans (or other target subjects) are exposed to it for a given time lapse. The increase in the concentration of sound emissions (i.e. the marginal increase of sound levels above the background level) has various impacts on humans (or other target subjects), both psychologically and physiologically (see section 2), that are quantified at this stage of the analysis.

- **Damage analysis** describes the total measurable damage represented by the health effects considered in the previous analysis. The damages caused by the exposure to the noise sources/ noisy processes in the life cycle are in this phase evaluated to identify what type of diseases are identifiable on humans (or other target subjects).

3.4
General framework for sound emissions and noise impacts
Method overview

The framework here presented builds upon the considerations and the information commented in the previous sections. The breakdown of the various parts of the model starts by proposing a way in which sound can be dealt with in an inventory analysis, overcoming the issues of the common use of the logarithmic unit dB. A methodological proposal follows, which provides a theoretical way of calculating characterisation factors for the impact category noise, using a fate and effect factor (Pennington et al. 2004).

The methodology is based on the consideration of the variation of background sound levels at the emission compartment as a consequence of the presence of one -or more- sound emitting sources in the life cycle, which consequently determines a variation in the effect on humans at the exposure compartment where the sound propagates.

The inventory part for sound

The first question to address regards attaching sound to a unit process, in such a way that an aggregation across the life cycle can provide a starting point for the impact assessment. Even though sound is usually measured in dB, the sound pressure level is obviously not the right quantity to present, as it does not allow for an aggregation over the life cycle. Moreover, it lacks the aspect of duration of the sound.

Heijungs et al. (1992) stressed the necessity of translating a sound from dB into an additive scale and of incorporating the duration of the relative sound emission into an aggregate measure, and proposed the use of Pascals-squared-seconds. Similarly, in the field of occupational noise exposure, Drott and Bruce (2011) propose to use the Pascals-squared-seconds, or pasques. Pasques is an additive measure of sound exposure; therefore not suitable for the inventory of sound in a life cycle.

In common practice, a unit process is usually represented in number per unit output. This means that all data are related to that reference. When dealing with a permanently running steelworks which produces 500 kg/h steel and needs 600 kg/h iron, one typically converts the output of steel to 1 kg, thereby the input of iron is changed from 600 kg/h into 1.2 kg of iron. It must be observed that not only the numerical value changes, but the unit also changes from a flow (kg/h) into an amount (kg). If the process emits 10 kg/h of a pollutant, this converts into 0.02 kg, and when it covers 800 m^2, this converts into 1.6 m^2h. If the process in question produces a sound output of a certain frequency (say, 1 kHz) of 90 dB, it does not make sense to convert this into 90/500 = 0.18 dB h. Rather, the sound power level of the source must be calculated and then converted to a quantity that can be added.

The sound power level calculated in dB is obtained by applying the following Eq. (3):

$$Lw = 10\log\left(\frac{W}{W_0}\right) \tag{3}$$

where Lw is the sound power level in decibels, and W is the sound power in watt, produced by the source referred to a reference sound power (W_{ref}) of 1picowatt (10^{-12} watt; ISO 1996), which is normally considered as the lowest sound discernible by a person with a good hearing.

Thus, by back transforming the value of the sound power level in dB to the sound power, or more precisely to its energy per unit of time, it is possible to obtain an addable quantity. This proceeds by:

$$W = W_{ref} \times 10^{Lw/10} \tag{4}$$

The analysis of the sound power of a process commonly requires, with the intent of reducing the calculation and time efforts, and given the wide variety of frequencies the human ear is subject to (i.e. from about 20 Hz to 20 kHz), the selection of a scale of frequencies, from f_n to f_{n+1}, determining a set of values of W and Lw to be contemporaneously evaluated (e.g. $W_{fn...fn+1}$). A scale of octave bands, meaning a frequency band with each progressive band having double the bandwidth of the previous, is usually considered handy for the analysis of the sound power level and in general of noise levels. The centre frequencies assigned for the bands covering the full range of human hearing are commonly the frequencies from 63 Hz to 8KHz (ISO 1996), which can be conveniently numbered from 1 to 8. The assignment of frequencies to octave bands thus proceeds according to Table 1.

Octave band (i)	Centre frequency [Hz]	Frequency range [Hz]
1	63	44-88
2	125	88-177
3	250	177-354
4	500	354-707
5	1000	707-1414
6	2000	1414-2828
7	4000	2828-5656
8	8000	5656-11312

Table 1. Definition of the octave bands (Ford 1970).

Thus, back to the previous example, the steelworks produces energy per unit of time of 0.001J/s at, for instance, 1 kHz, so in octave band 5. Applying the conversion to the per-kg of steel, and then expressing it in joule further transforms this into:

$$\begin{aligned}
&(0.001\ J/s)/(500\ kg/hr) = \\
&= (0.001\ J/s)/(500\ kg\ /\ 3600\ s) = \\
&= ((0.001\ J)*3600)/(500\ kg) = \\
&= ((0.001/500)*3600)J = 7.20*10^{-3} J
\end{aligned}$$

Normal LCI routines are further applicable to scale these numbers to the functional unit, and to aggregate them for every unit process across the entire life cycle. This can be done for different categories of sound, e.g., for sound of high frequency during the night in an urban location, for sound of medium frequency during the evening in a forest, etc.

Thus, the inventory table contains sound items defined for the scale of eight frequency bands selected, expressed in J. Following the usual conventions in LCI, one can symbolise these by m1, m2, etc., where mi indicates the emitted amount of type i, or alternatively by m1,1, m1,2, m2,1, etc., where the first subscript refers to the type of emission (benzene, day-time frequency noise, etc.) and the second subscripts to the emission compartment (e.g. air, sea water, etc.), or further specify the sound items classifying the attributes considered (e.g. day, night, rural, etc., as in the example in Table 2).

Symbol	Name (i)	Specification (c)	Amount	Unit
m_1	SO_2	high population density air	23	kg
m_2	SO_2	low population density air	10	kg
m_3	Cr III	fresh water	0.5	kg
m_4	Octave 1	urban, day	$8.33*10^{-3}$	J
m_5	Octave 2	urban, day	$7.20*10^{-3}$	J
…				
m_8	Octave 5	urban, day	$7.20*10^{-3}$	J
...				
m_{11}	Octave1	rural, day	$5.50*10^{-3}$	J
m_{12}	Octave2	rural, day	$5.30*10^{-3}$	J
...	...			
m_{19}	Octave 1	rural, night	$3.20*10^{-3}$	J

Table 2. Example of an inventory table including also sound energy emissions in J per octave-band centre frequencies for a hypothetical life cycle.

The characterization factor

The characterization factor (CF) for the assessment of noise emissions can be calculated using a fate and effect factor, Eq. (1), according to the classical LCIA characterization scheme (Pennington et al. 2004), as in Eq. (5):

$$CF_{i,c} = \sum_f \left(FF_{i,c,f} \times EF_{i,f}\right) \quad (5)$$

where FF is the fate factor and EF the effect factor, i is the inventory item in compartment c, and f the final compartment after the fate step, where the target(s) is assumed to be exposed. Thus the fate factor FF models how inventory item i moves from compartment c to compartment f and the effect factor EF how serious the effect is for the population living at f and exposed to i.

Below, we elaborate the two steps of fate and effect for the conceptual sound-noise model.

The fate factor
In the context of toxics, the fate factor for a substance i is defined as the factor that measures how a change of continuous release to compartment c ($\varphi_{i,c}$) will result in a change of the steady-state concentration in compartment f ($C_{i,f}$):

4

$$\boldsymbol{F}_{i,c,f} = \frac{\partial C_{i,f}}{\partial \Phi_{i,c}} \quad (6)$$

Multi-media fate models, such as EUSES (Vermeire et al. 1997), contain expression for Ci,f($\varphi_{i,c}$). The fate factors will embody aspects of fugacity (how willing is a chemical to move from one compartment to another one) and degradability (how stable is a chemical in a specific compartment).

In the noise context, the development of theoretical models for the measurement of sound propagation from sources to receivers at various distance, impedances and contour characteristics (Boulanger et al. 1997; IMAGINE 2005,2007a, 2007b), and that of methods aiming at evaluating the attenuation of noise with distance (Delany et al. 1976), together with the specialist production in sound propagation manuals (see for instance Ford 1970) are a consolidated science of acoustics. For the purpose of LCA, ISO 9613-2 (ISO 1996) provides a more flexible and practical engineering method that can be used for predicting the long term average sound pressure level under defined conditions from a source of known sound power emission. Any source is defined as a point source or as an assembly of point sources, moving or stationary, making the standard suitable for overcoming methodological limitations in assessing noise impacts in LCA and able to follow the requirements defined (section 3.2). At this stage of the development, the ISO standard allows for the development of a generic structure that is able to encompass any situation of emission and propagation, be it determined by a single source or by an assembly of point sources each with directivity or propagation properties and in principle contributing to the overall sound emission. The model will be in the future supported, for the determination and calculation of specific variables and components (see Table 3), by findings of the international project IMAGINE (2007a, 2007b).

We propose, therefore, to use the long-term average sound pressure level (Lp) per octave-band i, as specified by ISO 9613-2, as a basis for the modelling of fate, adapting the notation when needed for disambiguation purposes. For the quantification of the Lp, in dB, we follow the procedure suggested by the ISO standard. We start by calculating the equivalent continuous octave-band sound pressure level at the final compartment f from Eq. (7):

$$Lp_{i,f} = Lw_{i,c} + D_{i,c,f} - A_{i,c,f} \tag{7}$$

Here, $Lw_{i,c}$ is the sound power level as described in Eq. (3). $D_{i,c,f}$ is the directivity correction, in decibels, that describes to what extent a deviation of sound pressure level occurs in a specified direction from the source of sound power level $Lw_{i,c}$. The directivity correction D is 0 dB for an omnidirectional sound emitting source. $A_{i,c,f}$ in Eq. (7) is the octave-band specific attenuation, in decibels, occurring during the propagation of sound from source to receiver and it is given by the contemporary consideration of several attenuation factors, which include geometrical divergence, atmospheric absorption, meteorological variation, presence of barriers, miscellaneous other effects, etc. The methodology can be adapted to be used for any generic source of sound, including that generated by transportation, with the introduction of transportation means-specific attenuation and propagation parameters. Given that Lp is expressed in dB a conversion will be needed to have the sound pressure expressed in pascal and therefore comparable with the sound power emission (W) gathered in the inventory phase. Recalling the definition of sound pressure level as presented in section 2.5, in Eq. (1), and that of sound power level in Eq. (3) we obtain:

$$\begin{aligned}
P_{i,f} &= P_{ref} \times 10^{Lp_{i,f}/20} = \\
&= P_{ref} \times 10^{\left(Lw_{i,c} + D_{i,c,f} - A_{1,c,f}\right)/20} = \\
&= P_{ref} \times 10^{\left(Lw_{i,c}\right)/20} \times 10^{\left(D_{i,c,f} - A_{1,c,f}\right)/20} = \\
&= P_{ref} \times \sqrt{\frac{W_{i,c}}{W_{ref}}} \times 10^{\left(D_{i,c,f} - A_{1,c,f}\right)/20} = \\
&= \frac{P_{ref}}{\sqrt{W_{ref}}} \times \sqrt{W_{i,c}} \times 10^{\left(D_{i,c,f} - A_{1,c,f}\right)/20}
\end{aligned} \tag{8}$$

Here $P_{i,f}$ is the sound pressure, in pascal, in octave band i at compartment f relative to a reference sound pressure, P_{ref}, of $2*10^{-5}$ pascal (ISO 1996), while $W_{i,c}$ is the sound power, in watt, in octave band i at compartment c. The factors $D_{i,c,f}$ and $A_{i,c,f}$ thus serve to translate how much sound power from a source at c reaches a target at f.

The fate factor is now defined as the marginal increase of the sound pressure at f due to a marginal increase of the sound power at c, evaluated at the background level $W_{i,c}=Wamb_{i,c}$:

$$FF_{i,c,f} = \left(\frac{\partial P_{i,f}}{\partial W_{i,c}} \right)_{W_{i,c}=Wamb_{i,c}} = \\ = \frac{P_{ref}}{\sqrt{W_{ref}}} \times \frac{1}{2\sqrt{Wamb_{i,c}}} \times 10^{\left(D_{i,c,f}-A_{i,c,f}\right)/20} \quad (9)$$

4

The fate factor is measured at c given the ambient condition before the functional unit under investigation is introduced into the system, therefore the fate factor reflects the marginal increase in the total ambient sound power at c.

As P_{ref} and W_{ref} are given, this reduces to

$$FF_{i,c,f} = \frac{C_{ref}}{\sqrt{Wamb_{i,c}}} \times 10^{\left(D_{i,c,f}-A_{i,c,f}\right)/20} \quad (10)$$

where C_{ref} is 20 $Pa*W^{-1/2}$. The unit of the fate factor is Pa/W: it brings about the conversion of a source sound power in W to a target sound pressure in Pa. Therefore a sound power "emitted" by a generic source in the life cycle at compartment c (e.g. rural day), being it a machine, a truck, a train, etc. or a combination of them is diffused into air and propagates through the medium and reaches compartment f, attenuated by the direction of emission from the source and by a series of attenuation factors (e.g. meteorological, physical, etc.) which determine a variation of sound pressure at f. It has to be noticed that the fate factor is a function of the sound power $Wamb_{i,c}$. This is not the case for the linear multi-media models that are used for toxicity assessment, but it is not strange in itself. Toxicity models in LCA often employ a non-linear dose-response relation for the effect factor (Huijbregts et al. 2011), but not for the fate factor. We should understand the Wambi,cas the background level to which a marginal change is added. So, it is not case-dependent, but it obviously depends on the compartment (location) of emission c, and on the octave band i. Background levels of sound pressure may be obtained from noise maps, where noise exposure data by different noise sources and noise assessment data at a European level have been collected for most European countries (EEA-ETC LUSI 2010).

The effect factor

In LCIA, the effect model transforms the results of the exposure step (the dose) into a measure of impact. For toxics a usual way to do so is to divide the dose for a chemical by a critical level, say the EC50 or HC5, of that chemical. In that way, different types of chemical are "normalized". This can be interpreted as a conversion step transforming the dose into an "effective" dose, where the intrinsic harmfulness of the chemical is used to establish the relative weight of a chemical.

For the effect step in the noise model, we do a similar thing. The effect of the exposure to noise depends on three aspects:

- the aspect of the frequency-dependency of perception by humans;

- the aspect of the time of the day of the exposure;

- the aspect of the number of humans that are exposed in the target area.

Because the effect indicator we develop corrects the sound levels at a target location into "effective" sound levels, the unit of the category indicator results will still be pascal-like, so looking like an exposure indicator, but in fact representing an effect indicator.

Following the specifications above, the sound pressure level in octave band i at compartment f, $Lp_{i,f}$, is perceived differently for different octave bands. The A-weighting provides standardized weighting factors for this (Fletcher and Munson 1933; ANSI 2001). The A-scale weighting factors for octave band i is denoted as α_i, and is added to $Lp_{i,f}$ to obtain the frequency-corrected sound pressure level $Lpf_{i,f}$, (for which the "unit" dB(A) is typically used):

$$Lpf = Lp_{i,f} + \alpha_i . \qquad (11)$$

To account for the fact that sound emissions influence the life of individuals differently according to the time of the day the emission takes place, the value of $Lpf_{i,f}$ is further corrected by a penalty that is zero for daytime and non-zero in the evening and at night (Ouis 2001; see section 2.5 of this article). Thus, Eq. (11) transforms as:

$$Lpft_{i,f} = Lp_{i,f} + \alpha_i + \beta_f \tag{12}$$

where β_f represents the time weighting of the sound. For the frequency-and time-corrected pressure, Pft, back transforming the dB into pascal applying the definition of sound pressure level, we thus obtain

$$\begin{aligned} Pft_{i,f} &= P_{ref} \times 10^{Lpft_{i,f}/20} = \\ &= P_{ref} \times 10^{\left(Lp_{i,f}+\alpha_i+\beta_f\right)/20} = \\ &= P_{ref} \times 10^{\left(Lp_{i,f}\right)/20} \times 10^{\left(\alpha_i+\beta_f\right)/20} \end{aligned} \tag{13}$$

The third aspect of the number of targets is introduced by multiplying the total value of Pft at f by the number of people living in compartment f, N_f:

$$\boldsymbol{P} \quad = \sum_f \left(N_f \times \sum_i Pft_{i,f} \right) \tag{14}$$

where PP is interpreted as the person-pressure of sound, which is measured in person-Pa.

The effect factor is introduced as the marginal change in person-pressure due to a marginal change in the sound pressure of octave band i at compartment f:

$$EF_{i,f} = \frac{\partial PP}{\partial P_{i,f}}. \tag{15}$$

As the complete formula for "dose-response" is

$$PP = \sum_f \left(N_f \times \sum_i \left(P_{ref} \times 10^{\left(Lp_{i,f}\right)/20} \times 10^{\left(\alpha_i+\beta_f\right)/20} \right) \right) \tag{16}$$

the effect factor becomes

$$EF_{i,f} = N_f \times 10^{\left(\alpha_i+\beta_f\right)/20}. \tag{17}$$

The effect factor is thus strikingly simple: it contains just the A-scale weighting for octave band i (α_i), the day/night weighting (β_f) and the number of people living in compartment f (N_f). The unit of the effect factor is person, thus it represents, given the population at f, the number of people that are exposed to a variation in sound pressure at compartment f corrected according to the sensitivity to the frequency composition of the emission and the time of the day of the exposure.

The midpoint characterization factor and its use in LCIA

For midpoint characterization, the usual structure applies. The characterization factor is

$$CF_{i,c} = \frac{C_{ref}}{\sqrt{Wamb_{i,c}}} \times \sum_{f} 10^{\left(D_{i,c,f} - A_{i,c,f}\right)/20} \times N_f \times 10^{\left(\alpha_i + \beta_f\right)/20} \quad (18)$$

The summation over the emission compartment f allows for the evaluation of the total impact of the sound emission on the target subjects living at f. The compartment can be spatially indentified and defined as urban, rural or off-shore, or, with a finer grain of definition, furtherly divided to incorporate a higher level of detail.

The unit of the characterization factor is person-Pa/W. It is applied in an LCA by means of

$$HN = \sum_{i} \sum_{c} CF_{i,c} \times m_{i,c} \quad (19)$$

where HN represents the noise impact to humans. As the sound emission mi,c is measured in J, the impact NH has the unit person-Pa/W*J = person-Pa*s. It can be interpreted as the number of people that are exposed to a certain sound pressure for a certain period of time.

The characterization factor looks complicated, so let us see what is needed to tabulate lists of such factors, as has been done for established impact categories, like global warming and toxicity. We need to specify the archetypical emission and exposure compartments c and f. For instance, one could choose here to define three spatial and three temporal situations: urban, rural and off-shore, and day, evening and night. For the frequencies i, we already chose for the eight frequency bands of Table 1. Six sets of numbers have to be listed; see Table 3.

Parameter	Value	Source
α_i	{-26.2, -16.1, -8.6, -3.2, 0.0, 1.2, 1.0, 1.1} [dB]	ANSI 2001
β_f	{0, 5, 10} [dB]	Ouis 2001
N_f	to be elaborated	Gridded population of the world, CIESIN 2011
$A_{i,c,f}$	to be elaborated	ISO9613-2(ISO 1996) IMAGINE (2007a; 2007b)
$D_{i,c,f}$	to be elaborated	ISO9613-2(ISO 1996) IMAGINE (2007a;2007b)
$Wamb_{i,c}$	to be elaborated	Noise maps, EEA-ETC LUSI 2010

Table 3. Values and possible sources for the parameters of the characterization factor.

Some of the data present in Table 3 requires the combination and gathering of various sources of information. Some of the data in question is usually available in the form of GIS maps with a variable level of grid mesh. This is the case of the number of people living at the exposure compartment, N_f, and of the background noise levels, $Wamb_{i,c}$ available in the form of noise maps. The values of $A_{i,c,f}$ and $D_{i,c,f}$ depend on the location of emission and exposure and can be derived from the application of the ISO9613-2 and of the findings of the IMAGINE project (2007a, 007b) to the archetypical compartments to be developed.

With a choice of three spatial and three temporal compartments and eight octave bands, there are no more than 72 characterization factors. In this way, applying the characterization step requires a simple and concise recipe.

4
Discussion and conclusion
4.1
Noise impact model development and future research agenda

The structural framework presented in section 3 represents the first step of a development process which will culminate in the creation of a working mathematical model, together with its elaboration and application to case studies, which will possibly allow for the determination of a noise footprint of a life cycle. The flexibility of the framework structure will allow for its expansion and adaptation for the incorporation of previous work and new contributions in the field, with particular attention to results obtained by international EU projects which have obtained significant results in proposing suitable methods for the measurement of sound propagation from various sources. The proposed model allows for the measurement of the sound emission from a single sound-emitting source or multiple sources present at the emission compartment. However, as in the case of models dealing with the combined emission of chemicals, the summation of multiple sources can lead to an extremely high noise concentration in the studied environment. At this stage of development, the model does not discriminate between possible synergistic, antagonistic, or interference effects of the emitting sources, but logarithmically treats their impacts.

The overall uncertainty of the model has not been tackled in this contribution, although it is of fundamental importance to deal with uncertainty in any LCA contribution. Given the complexity and the extension of such analysis, we reserve to conduct it in our follow up research. The use of techniques such as global or local sensitivity analysis (Heijungs and Huijbregts, 2004; Saltelli et al., 1999) can help to perfect the model performance and applicability. The study of the impact of the variation of the model input, considered the methodological, temporal and geographical variability of the model, will ensure to study how uncertainty of the input propagates to the variance of the model output and will allow to propose accurate characterisation factors for noise impacts. Similarly, the risk of underestimation of the impact, which applies to all data systems, will be taken into account in the characterization of noise. In the case of noise measurement, average values could portray a modelled system which in reality has a much higher impact on the health of the exposed population. Blast noises, for instance, which are common in the mining or construction sectors, are the result of sudden emissions which follow moment of silence. Therefore, averaging a value over time could underestimate the effective proportion of the impact.

For the noise impact on humans, in contrast to many traditional impact categories, we have not introduced a dimensionless potential, like the global warming potential (relative to CO2 to air) and the human toxicity potential (relative to, e.g., dichlorobenzene to air). For reasons of consistency, it would be reasonable to do the same and reformulate the characterization as

$$HNP_{i,c} = \frac{CF_{i,c}}{CF_{ref_i,ref_c}} \quad (20)$$

where HNP represents the human noise potential, related to a unit of sound emission in a predefined reference octave band and in a predefined reference compartment, for instance 1 kHz at urban day-time. The result of the characterization would in that case not be expressed in person-Pa*s, but in J-equivalent of the reference sound, just as the GWP yields a result in kg-equivalent of CO2.

Our idea at this moment is not to use the dimensionless potential for noise, but to use the (admittedly abstract) person-Pa/W for the characterization factors and the person-Pa*s for the characterization result.Furthermore, in order to develop a methodological solution for the quantification of noise impacts, it is fundamental to gather information about the background or ambient condition of the area where the sound event takes place. The importance of the specific location of exposure has been stressed in section 2.2, where auditory cognition concepts as soundmarks and keynote sounds have also been defined. Key elements of the location of emission (e.g. time of day) have to be defined to incorporate the subjective impact of noise in the analysis . The characterization factor developed allows for the evaluation of location-specific features of the emission. LCA tries to measure marginal changes, on a background situation subject to environmental interventions, even in circumstances in which they are relatively small and diminishing with increasing distance from the source (Verones et al. 2010). In our framework the fate factor is calculated considering that the emission compartment is already sonically perturbed and that the increase of pressure at exposure compartment is dependent on the increase of power at the emission compartment. As for the effect on humans, corrections have been applied to the sound pressure calculation to make it as adherent as possible to the human perception of sound/noise as identified in common epidemiological practise.

The calculation of the CF for noise impacts on human subjects allows for a midpoint characterization, though a possible extension of the framework from midpoint to endpoint level could be applied, with specificities to be further investigated with respect to the relationship between DALYs and the morbidities highlighted in the sections 2.3 and 2.4 of this article.

WHO (2011) selected (among the outcomes earlier reported) cardiovascular disorders, cognitive impairment, sleep disturbance, tinnitus and annoyance as consequences of noise to focus research on, giving details on appropriate measures and indexes to be used case by case and with detail of DALY estimates when possible. Estimated DALYs for western European countries were respectively: 60000 years for ischaemic heart disease, 45000 years for cognitive impairment of children, 903000 years for sleep disturbance, 21000 years for tinnitus and 587000 years for annoyance. All impacts in total ranged between 1.0 and 1.6 million DALYs. WHO data should be further analysed in details. If DALYs caused by environmental noise are compared with those from other pollutants, it is important to take into account the approximations and assumptions made in the calculation process. There are, in fact, several uncertainties, limitations and challenges which have to be taken into account for the selection of health effects. Unfortunately, the quality and the quantity of the evidence and data are not the same across the different health outcomes and derived from a limited pool of studies. Possible confounding factors should be taken into account in the analysis. These include age, gender, smoking, obesity, alcohol use, socioeconomic status, occupation, education, family status, military service, hereditary disease, use of medication, medical status, race and ethnicity, physical activity, noisy leisure activities, stress-reducing activities, diet and nutrition, housing condition and residential status (WHO 2011). Other stressors like air pollution and chemicals might be considered in the context of combined exposure with noise. A further point to consider with respect to variability is that psychoacoustical variations (see, for example, Moore 1989) should be taken into account for the analysis to be as much as possible reflective of the effective perception of noise by humans, and should possibly be included in future expansions of the framework. A-weighting and temporal corrections, in fact, do not fully cover the complete range of variations of human perception and relative response to a sonic event. Events with similar sonic features and similar sources that produce them can be perceived differently by different individuals and determine different stimuli and sensations (e.g. at equal contour conditions, a modern and fast train is pleasant, while an old and ugly one is unpleasant). The extent to which this is feasible is at this stage not clear.

As described in section 2.5 of this paper, dose-effect curves for a generic noise health effect supported by quantitative data are commonly available for effects attributable to Lp determined by transportation noise. Curves can be re-set and converted to Pa and variation of dose-effect relationships calculated per variation of sound pressures in Pa. Further research, also taking into account the precautions mentioned, is needed for other sources than transport related ones.

Given the stochastic nature of noise effects on humans, meaning that we have statistical evidence of the existence of some effects but we lack a deterministic link between severity/effect and exposure (Bare et al. 2002), uncertain estimates need to be made to move to an endpoint level. Potting, in Bare et al. (2002), suggests that a combination of "the spatial differentiated or site-dependent midpoint modelling with the site-generic endpoint modelling" would be desirable. In the context of noise the midpoint could then be translated, bearing in mind the introduction of extra uncertainty into the system, into an endpoint, requiring the calculation of a damage factor for human health, by using the DALY scale and a convenient health damage model.

Given the number of people, N, living at compartment f we can evaluate through PP the number of people who are exposed to a sound pressure in pascal. Individuals will be exposed to a different noise-related morbidity to which a year of life lost, or a fraction of it, can be associated. The morbidity could be intended as a statistically defined function linking the person-pascal at compartment f to the disability adjusted years given the composition of the population. At this stage the damage factor is just touched on and will be further developed in our future work.

Advancements in the modelling of noise impacts still require the development of research in some key fields. On the inventory side, there is a lack of sound emission data for unit processes outside the highly analysed transportation field. At a midpoint level impacts can already be highlighted through the framework, but dose-response curves need to be re-set. Furthermore, research should be oriented towards translating new epidemiological findings, where possible, into dose-response relationships, in turn translatable, if necessary, into the DALY scale. For the expansion of research to the evaluation of the impacts of noise on the quality of eco-systems and other subjects than humans, it would be necessary to incorporate in the analysis epidemiological data on ecosystems, which has not been systematically organised yet, in order to stress similarities and singularities of impacts on humans and impacts on ecosystems. As reported in section 2, on-going studies are already investigating the field with interesting results that could be incorporated in the model. In principle, the framework provided could be adapted with minor changes (e.g. different frequency correction) to non-human populations, providing the basis for future work in the field of LCA and noise impacts on the survival of ecosystems.

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Characterisation factors for life cycle impact assessment of sound emissions

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Abstract
Noise is a serious stressor affecting the health of millions of citizens. It has been suggested that disturbance by noise is responsible for a substantial part of the damage to human health. However, no recommended approach to address noise impacts was proposed by the handbook for life cycle assessment (LCA) of the European Commission, nor are characterisation factors (CFs) and appropriate inventory data available in commonly used databases. This contribution provides CFs to allow for the quantification of noise impacts on human health in the LCA framework. Noise propagation standards and international reports on acoustics and noise impacts were used to define the model parameters. Spatial data was used to calculate spatially-defined CFs in the form of 10-by-10-km maps. The results of this analysis were combined with data from the literature to select input data for representative archetypal situations of emission (e.g. urban day with a frequency of 63 hertz, rural night at 8000 hertz, etc.). A total of 32 spatial and 216 archetypal CFs were produced to evaluate noise impacts at a European level (i.e. EU27). The possibility of a user-defined characterisation factor was added to support the possibility of portraying the situation of full availability of information, as well as a highly-localised impact analysis. A Monte Carlo-based quantitative global sensitivity analysis method was applied to evaluate the importance of the input factors in determining the variance of the output. The factors produced are ready to be implemented in the available LCA databases and software. The spatial approach and archetypal approach may be combined and selected according to the amount of information available and the life cycle under study. The framework proposed and used for calculations is flexible enough to be expanded to account for impacts on other target subjects than humans and to other continents than Europe.

Keywords
Noise, noise impacts, life cycle, LCIA, LCA, annoyance, disturbance0F**

*** Index of abbreviations and symbols. i= frequency index; c= time index; f=location index; CF=Characterisation factor [number of people-Pa/W]; D=Directivity [dB]; EF=Effect factor [number of people]; FF=Fate factor [Pa/W]; Lw=Background sound power level [decibel]; Nf=Number of exposed subjects; AC= archetypal context; SC=Spatial context.*

1
Introduction
1.1
Scope
Life cycle assessment (LCA; ISO 14042, ISO, 2000) aims at quantifying in a holistic and integrated way how each phase of the life cycle of a product contributes to impacts such as climate change, eutrophication, and resource depletion among others (Rebitzer et al. 2004; Pennington et al. 2004). The necessity of quantifying the impact of noise emissions from any life cycle has been stressed since the first days of the formalisation of the methodology (Heijungs et al., 1992).

Noise has for long been recognised as a stressor. Scientific studies have shown that the impacts of noise are not limited to psychological effects, such as annoyance, but also to physiological effects, such as cardiovascular diseases (WHO, 2011; Babisch, 2006). As a result of traffic noise, one in three individuals in Europe is affected by environmental noise during the daytime, and one in five at night (WHO, 2011). It has been quantified that disturbance by noise is responsible for a substantial part of the damage to human health, when measured in disability-adjusted life years (DALY; Muller-Wenk, 2004).

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The LCA handbook of the European Commission (ILCD, 2010) included noise as one of the impact categories with high priority for methodological development, because no recommended approach to address noise impacts could be proposed by the handbook. To date all practical applications of LCA (case studies, databases, software) do not include noise as an impact category. To a large extent this is due to a lack of a good method and to a limited investigation of the relevant literature in acoustics and impact assessment of sound. Cucurachi et al. (2012), after an analysis of epidemiological data and a study of the LCA literature on noise, proposed a new theoretical framework. It aimed at presenting a rigorous formal way of characterisation of noise impacts, which is in line with the characterisation model and the overall theoretical structure used for other impact categories in LCA.

1.2
Problem definition
Sound and noise are two categories of the same physical phenomenon. However, sound emissions are not necessarily determining noise. Noise is the result of unwanted or intolerable sound, to which one is not voluntarily exposed. From a physical point of view, sound emissions are associated with a momentary compression and decompression of sound waves through a medium, which leads to a change of pressure and a shifting of

molecules in the medium. Thus, sound emissions are temporary and expire in a limited amount of time. Sound propagates and dissipates while it travels through air (i.e. the only medium considered by this contribution).

Several factors (e.g. meteorological conditions) intervene in and attenuate sound emissions, while other factors (e.g., directivity) orientate them. In the work of Cucurachi et al. (2012), such factors were included in the theoretical framework indicated for the calculation of the fate of and the effect factor for noise impacts. However, the framework provided only a theoretical model, with model parameters to be filled in. The aim of this new contribution is to operationalize the model, implement these factors and use them for the calculation of characterisation factors for noise impacts.

The environmental mechanisms involved in the propagation and attenuation of sound emission, and the relative noise impact are complex, non-linear and highly dependent upon local circumstances. The acoustic phenomena and parameters which are relevant in the proposed framework are, in fact, strictly related to a particular topography and to specific local conditions. To reach greater accuracy, propagation of sound is usually calculated either taking a fully empirical approach, or assuming specific conditions of propagation (e.g. a flat area with short grass). In an ideal world, LCA should be able to portray any possible context of (sound) emission and to account for the effects of those emissions on the target subjects. In practice, sound levels need to be predicted for different heights above ground, various types of foliage (e.g. tree belts), walls, houses, etc. For a fully-empirical local noise assessment, this can be done. In LCA, however, a life cycle typically spans thousands of locations, so a site-specific assessment is not feasible. This puts the modeller to face a situation in which one has to choose between the use of highly-specific spatially-defined data, or a situation in which it is necessary to assume representative conditions for the archetypal compartments of emission. Even though the level of accuracy may be greater when location-specific data is considered, spatially-defined variables are not uncertainty-free, nor is the amount of information available to practitioners sufficient to use it to describe the specific life cycle under consideration.

1.3
Research focus

The method described in the following sections is based on the established standards of propagation of sound from static or moving sources, such as ISO 9613-1, ISO 9613-2 (ISO, 1993; ISO, 1996), as well as on the recommended approach for the calculation of sound emission and propagation at a European level (European Commission, 2012). Data was processed and scaled to allow for the calculation of characterisation factors for noise, both in the form of ready-to-be-used maps at a European scale, and in the form of archetypal dimensions of emissions. The special case of indoor "occupational" sound emissions was defined only as an archetypal situation of emission. It was decided to use spatially-defined parameters (i.e. GIS map or raster data) to compile characterisation factors in the form of maps in a spatially-defined context. The outcome of this process was used to define archetypal situations of emissions, which used central nominal values for calculations. The use of spatially-defined CFs allowed for the selection of central values in the most appropriate range.

This contribution fills the gap of the absence of noise as an impact category in LCA and presents CFs for noise impacts at a European level (i.e. EU27), which can be used by practitioners, provided the inventory (i.e., sound emission) data are available. The factors produced are, in fact, ready to be implemented in the available LCIA databases and software. The framework proposed and used for calculations is flexible enough to be expanded to account for impacts on other target subjects than humans and to other continents than Europe.

In the following section, the model is described in detail. The results of the modelling decisions are shown in section 3 and discussed in section 4. The Supplementary Material of this contribution provides a detailed description of the equations and modelling choices (Supplementary Material 1), and their results (Supplementary Material 2, 3 and 4).

2
The noise impact assessment model: elaboration of the framework

2.1
The background model and the life cycle inventory phase

Most sounds emitted by a source are complex and fluctuate in amplitude and frequency. The relationships between sound energy level and frequency are required for the meaningful analysis of a sound spectrum. Cucurachi et al. (2012) propose to analyse the sound emitted by a source according to the one-third octave bands centre frequencies in which its spectrum can be split into. The distinction among frequencies allows to depict and follow the ability of our hearing system to perceive the frequency composition of a sound, but also allows accommodating any context of emission. If certain centre-frequency bands are dominant for a specific source, or limited information is available, selected centre-frequency bands may be chosen instead of others (e.g. 63 to 500 hertz, instead of 2000 to 8000 hertz). Similarly, if the model had to be expanded for the consideration of impacts on other target systems than humans, the centre-frequency ranges of interest may be chosen. No differentiation among sources (e.g. static or moving) was proposed in Cucurachi et al. (2012), but it was recommended to differentiate the emissions at the inventory level according to frequency of emission (e.g. 63 Hz), the location (e.g. rural and urban), and the time of the day (i.e. day, evening, and night. The characterisation of the frequency, the time, and the location of the sound emission are also crucial in the later impact assessment of the relative noise perceived by the target subjects.

In Cucurachi et al. (2012), 8 centre-octave frequency bands are considered in line with the ISO 9613-2 (1996) standard on the attenuation of sound during propagation outdoors. As for the location of emission, they were defined by analysing the result of the spatial analysis described in following section 2.2, and in accordance with the literature on the determination of archetypal situations of emission (Jolliet et al. 2005; Curran 2012;). Time specifications refer to the common practice of distinguishing between day, evening, and night time of sound emissions that are commonly used to allow for a different perception of sound by human according to the time of the exposure. The case of the undefined compartment of emission (e.g., time or otherwise) was introduced in all cases to account for a limited information in the hand of the practitioner who would have to use the CFs.

The sound emission is not only spatially differentiated as is common for many impact categories in LCA, but also temporally and physically differentiated. The collection of information during the inventory phase can allow for a better characterisation of sound, thus potentially a better quantification of the relative noise impacts. At the inventory level, Cucurachi et al. (2012) prescribe to take into account the sound power level of each source and to convert it into sound energy, using the physical properties of sound. International standards (e.g. ISO 9613-2; ISO, 1996) and reports (e.g. WHO, 2001) provide suitable and readily-usable information to calculate the sound power level of any source, be it static or mobile. An accurate reference is the CNOSSOS reference report (European Commission, 2012) which provides indications on how to calculate the sound power emission of any type of source, discriminating among noise caused by the so-called road traffic (e.g. light motor vehicles, medium motor vehicles, etc.), railway traffic, air traffic, and industrial sources.

Following ISO9614-1 (ISO, 1993b), in CNOSSOS the sound power level is defined as "in-situ" or in "semi-free field". Sound power includes effects of reflections and other specifications in the immediate vicinity of the source (e.g. the surface under the source). The parameters are specified per class of sources and also for combinations of similar sources (e.g. traffic conditions). Sound power level (in decibel, dB) can be back-transformed to the relative sound power using the reference value of 10^{-12} watt (W), and then the relative sound energy to be reported in the inventory table can be calculated by applying the methodology reported by Cucurachi et al. (2012).

The time a source is active in a life cycle can be calculated based on the production rate of the system (i.e. kg/s) and the relative output (i.e. kg). Similarly, for a life cycle involving a transportation stage the production rate would be the speed in km/hr, and the output the number of km driven relatively to the functional unit under consideration. The formula for the calculation of the LCI item $m_{i,c,f}$ is

$$m_{i,c,f} = W_{i,c,f} \times time_{c,f} \quad (1)$$

Where i is the centre-frequency band, c indicates the time , f the location, $W_{i,c,f}$ in joule/second is the sound power of the source under consideration calculated according to the indication of the CNOSSOS reference report, and $time_{c,f}$ is the time calculated as a function of the production rate of the system and the relative output.

A didactic example may be here of help. If the system under study has to produce e.g. 1 ton of product, and the relative production rate is, e.g., 1000 ton/year, the production rate of the system would be of 3.17E-5 ton/sec. The value of timec,f would be in total of 31536 seconds (i.e., as a ration between the functional unit and the production rate), to be further specified in terms of time and location. For the time, it should be considered that, for a system at continuous production, the emission would take place during the day for 12/24 of the time, in the evening for 4/24 of the time, and at night for 8/24 of the time. Alternative production rates or production systems with shifts may be used. Time can be similarly apportioned to different locations (i.e. archetypal or geographical).

Let us consider the case of a sound power level of 60 dB at a centre-band frequency of 1000 hertz, as calculated following the indications of CNOSSOS (2012). Similarly, we could calculate sound power levels at other centre-band frequencies. For a matter of simplicity of this didactic example, the value of the sound power level has not any further specification than the frequency specification i. In real applications, further local conditions of time and locations may be considered if necessary. We can back convert the sound power level of 60 dB to a sound power in joule/second, using the reference sound power level of 10^{-12} dB (ISO 9613-1, 1993). Applying the formula reported in Eq.1 we can calculate the inventory items mi,c,f in joule that will function as inventory item in the inventory table relative to the example under study. The items to be inventoried would be 0.015768 joule for the day, 0.005256 joule for the evening, and 0.010512 for the night. As we will see in the next section, these values will be multiplied by the appropriate CFs, to calculate the human noise impact at a midpoint level.

2.2
Definition of spatial parameters and archetypal situations of emission

The environmental mechanisms involved in the propagation and attenuation of sound emissions, and the relative noise impacts are typically complex, non-linear and highly-dependent upon local circumstances. In order to operationalize the impact assessment model described in Cucurachi et al. (2012) in line with ISO 9613-1 and ISO 9613-2 (ISO, 1993;1996) and the CNOSSOS reference report (European Commission 2012), this contribution introduces a series of input parameters, constants and variables (see Table 2.1) that will be detailed in the next sections and in the Supplementary Material 1.

Table 2.1. Parameters and variables used in the model

Input parameter [a]	Description [b]	Unit/Expression [c]
Lw	Background sound power level	dB
T	Temperature	°C
Rh	Relative humidity	%
P	Local pressure	Pa
h	Height of propagation	m
d	Distance from source to receiver	m
S	Surface of propagation	m^2
Nf	Population	number [d]
ρ	Population density	number
$Wamb$	Background Sound Power	W
Pr	Attenuation factor for protective measures	dB
ψ	Rate of use of protective measures	%
αm	Room absorption parameter	number
C_{ref}	Ratio of conversion factors	number
D	Directivity of sound propagation	dB
C	Constant transformation factor dB to Watt	W
P_{ref}	Reference ambient pressure	Pa
P_{rel}	Relative pressure	number
Kelvin	Conversion factor from °C to°K	number
T_{ref}	Reference ambient temperature	°C
T_{kel}	Local temperature in Kelvin	°K

T_{rel}	Relative temperature	number
T01	Triple-point isotherm temperature	°K
H	Molar concentration of water vapour	number
fro	Nitrogen relaxation frequency as in ISO 9613-1	Hz
frn	Oxygen Relaxation Frequency as in ISO 9613-1	Hz
αatm	Attenuation factor due to atmospheric conditions	dB/m
rc	Sound absorbing characteristics of a room	m^2
R	Sound absorbing characteristics of a room	dB
α	Frequency penalty	dB
β	Time penalty	dB
Aatm	Attenuation due to atmospheric conditions	dB
Adiv	Attenuation due to divergence	dB
Aground	Attenuation due to ground conditions	dB
Apr	Attenuation due to the use of protective measures	dB
Aextra	Attenuation due to other factors	dB

The parameters defined in Cucurachi et al. (2012) were firstly spatially-defined in raster maps (see Supplementary Material 1), which were meaningfully combined to obtain spatially-explicit CFs for EU27 (Eurostat, 2007) using ArcGIS 10 (ESRI, 2011).

The following dimensions were defined:

- **octave**: 63 Hz (44 to 88 Hz), 125 Hz (88 to 177 Hz), 250 Hz (177 to 354 Hz), 500 Hz (354 to 707 Hz), 1000 Hz (707 to 1414 Hz), 2000 (1414 to 2828 Hz), 4000 Hz (2828 to 5656 Hz), 8000 Hz (5656 to 11312 Hz);

- **time**: day (7 am to 7 pm), evening (7 pm to 11 pm), night (11 pm to 7 am), and unspecified.

CFs in the spatial format were calculated using ArcGIS 10 (ESRI, 2011). A total of 32 CFs were produced. The resulting raster maps are provided as Supplementary Material 1 to this contribution.

Single parameters were obtained from various sources (see Table 2.1), and adapted for the calculations described in the next sections.

Table 2.2. Specific parameters and resolution used in the spatial context

Parameter	Source of the data	Spatial resolution
Ambient sound level [dB]	EASA, 2009	10 km
Temperature [°C]	Hijmans, 2005	1 km ca.
Relative hum idity at 2 metres [%]	Saha et al., 2010	38 km ca.
Ambient pressure [kPa]	ISO, 1993a; 1996a	Set to 10 km
Average propagation height [m]	This report	Set to 10 km
Distance [m]	This report	Set to 10 km
Number of exposed subjects [number]	EASA, 2009	10 km
Elevation [m]	Jarvis et al., 2008	30 m

The ETRS89 Lambert Azimuthal Equal Area (Annoni et al., 2003) was defined for all raster layers and a cell size of 10 kilometres was selected in line with the available data. Given the different origin of all sources, processing tools in ArcGIS were used to obtain raster maps with the suitable level of spatial definition. Map algebra (Burrough et al., 1998) was, then, used to implement the calculations defined in the Supplementary Material. For those parameters whose value would not change at different locations, a constant raster was defined and used as an input for calculations.

The results obtained were used to elaborate archetypal situations of emissions, i.e. urban, suburban, rural, industrial and indoor. Statistical data was used for the definition and differentiation of parameters amongst the defined dimensions. In all the cases when it was not possible to find suitable statistical support, the data available in a map format and spatially-defined was analysed and provided a sufficient basis upon which to develop calculations. The sources of the data are reported in Table 2.2. The parameters used for the protective measures and the rate of use of protective measures were defined only in the case of indoor emissions.

Table 2.3. Specific parameters and sources used in the archetypal context

Parameter	Source of the data (elaboration from)
Ambient sound level [dB]	EASA, 2009;King et al., 2012
Temperature [°C]	Hijmans et al., 2005
Humidity [%]	Saha et al., 2010
Ambient pressure [kPa]	ISO, 1993a
Average propagation height [m]	This report
Distance [m]	This report

Population density [people/km^2]	Eurostat, 2012; Analysis of spatially-defined data in the spatial context
Reference area [km^2]	Eurostat, 2007; Analysis of spatially-defined data in the spatial context
Number of exposed subjects	Eurostat, 2007; Analysis of spatially-defined data in the spatial context
Use of protective measures	Concha-Barrientos et al., 2004
Rate of use of protective measures	Concha-Barrientos et al., 2004

Parameters and constants were combined together in a spreadsheet compiled using Microsoft Excel (see Supporting Information 3 of the original publication).

The following dimensions were defined for this context:

- **octave**: i.e.,bands are the set of frequencies by which the frequency range may be divided; a frequency is said to be an octave in width when the upper band frequency is twice the lower band frequency. Thus, we may define the following octave-bands frequencies: 63 Hz (44 to 88 Hz), 125 Hz (88 to 177 Hz), 250 Hz (177 to 354 Hz), 500 Hz (354 to 707 Hz), 1000 Hz (707 to 1414 Hz), 2000 (1414 to 2828 Hz), 4000 Hz (2828 to 5656 Hz), 8000 Hz (5656 to 11312 Hz);

- **location**: i.e., the spatial context in which the emission takes place. The following archetypes were identified: urban area, suburban (i.e. residential)area with no nearby traffic concern, rural area with no nearby traffic, industrial or commercial area, indoor, and unspecified;

- **time:** i.e., the temporal context of the emission. The following archetypes were identified: day, evening, night, and unspecified.

Section 3 and the Supplementary Material (see Supplementary Material 2 and 3) provide the full set of factors for the defined dimensions in both spatial and archetypal contexts.

2.3
Background conditions of exposure

The degree to which environmental noise affects humans (and other species) depends on the ambient background conditions of the soundscape they are used to, as well as, to a certain extent, on the sensitivity of each individual to sound changes above the background. It can be demonstrated that human activities generate sound at growing intensities with growing population levels (US-EPA, 1974; Stewart et al. 1999). Sound emissions are usually quantified in terms of a pressure level in dB or scaled to the sensitivity to sound of the human hearing system (in dBA). Alternatively, the sound pressure may be denoted by a physical natural quantity (i.e. measured in pascal).

The background sound environment of a specific location may be also measured by its sound power level. Availability of data in both cases is limited. We use the sound power to indicate the physical natural quantity (i.e. measured in watt), while sound power level here denotes the sound power ratio (in dB) to a reference quantity of 1 picowatt (pW).

A study by EASA (2009) reports sound pressure level using yet another measure: L95, in dBA, for day, evening, and night. L95 defines the sound pressure level exceeded for 95% of the time at a given location (i.e. only in 5% of the time the sound pressure level was less than L95). Background sound pressure levels, as calculated by EASA, may be defined as the sound pressure level at a location from a number of more or less identifiable sound sources when the direct sound from prominent sources is excluded (EASA, 2009).

In the context of acoustic ecology it would be defined as the reference soundscape of a specific location. Using a more appropriate LCA terminology, the background sound pressure level may be defined as the background sound of a location which was not yet perturbed by the functional unit under study, whose sound power has been inventoried in the LCI (i.e. life cycle inventory) table.

L95 represents a sound pressure level in dBA, which may be transformed to a sound power in W. We are, in fact, interested in the sound power of the environment under study. In other terms, we assume that the environment where the emission takes place is itself a source of sound emission with a certain sound power. This "theoretical" source is a composition of sources already perturbing the environment before the functional unit is active in it. The value of the background sound power is in reality different across different centre-frequency ranges, as it was the sound power inventoried in the LCI. Due to the limited availability of data, we considered the value of the background sound environment as equal across all centre-frequency bands. For the details of the calculation of the L95 value we refer to the full BANOERAC report (EASA, 2009).

The CFs for midpoint noise impacts were defined in Cucurachi et al. (2012) according to the classical LCIA characterisation scheme (Pennington et al. 2004), as shown in Eq. (2):

$$CF_{i,c,f} = \sum_{i,c,f} \left(FF_{i,c,f} \times EF_{i,c,f} \right), \tag{2}$$

Thus, the CFs for each of the defined spatial and archetypal situations of emission were calculated by multiplying the FF and the EF at a certain centre-frequency (i), time (c), and location (f). The quantity which expresses the CF is personx Pa/W, which would correspond to $s*m^{-3}$ using the SI standard units (Heijungs, 2005). If we consider that a sound emission, i.e. $m_{i,c,f}$, is inventoried in units of sound energy (in J), the noise impact on humans (HN) can be expressed by the quantity person x Pa x s, or using the SI unit kg/m x s.

The background conditions of a situation of exposure constitute the basis for the calculation of the fate factor (FF) described in Cucurachi et al. (2012):

$$FF_{i,c,f} = \frac{C_{ref}}{\sqrt{Wamb_{c,f}}} \times 10^{\left(D_{c,f} - A_{i,c,f}\right)/20} \quad (3)$$

The FF is measured in Pa/W and defines the conversion of a source sound power in watt (W) to a target sound pressure in pascal (Pa). The fate factor reflects a marginal increase in the total ambient sound power of octave-band i at time c, and at location f due to the fact that a functional unit was introduced into the system, evaluated at the background level $Wamb_{c,f}$, taken into consideration the directivity of sound ($D_{c,f}$) and the various possible attenuations $A_{i,c,f}$. No differentiation for centre-octave band was considered for the background, due to a limited availability of suitably differentiated data. The detailed elaboration of the calculations of the parameters considered for the FF, including the background sound power, is provided in section 2 of the Supplementary Material 1 of this contribution.

The effect factor was defined by Cucurachi et al. (2012) as:

$$EF_{i,c,f} = N_f \times 10^{(\alpha_i + \beta_c)/20} \quad (4)$$

The unit of the effect factor is person. N_f represents the population size at the exposure compartment f at a certain time of the day c, α_i is the penalty (in dB) to be added to account for the A-level scale (ISO, 1996a), β_c represents the weighting of the sound emission (in dB) for the time of the day the emission took place. All parameters and modelling choices are described in Supporting Material 1 to this contribution.

2.4
Indoor/localised occupational sound emissions

The CF defined for the calculation of outdoor emissions was extended to the case of sound emissions taking place indoor (see section 3 of the Supplementary Material 1). The expansion refers to the definition of an indoor/localised occupational compartment of sound emissions (indoor compartment, from now on). It models the exposure to sound emissions which take place in an indoor environment (e.g. a print shop, a production line in a factory) or to sound emissions which are localised at a specific site (e.g. a construction site). The sound emissions considered here can be defined as "occupational". Therefore, they are specifically oriented at investigating the effects of sound emissions (and noise) on, e.g., operators of plants, builders, musicians and, in general, all the categories of workers operating with equipment which produces a sound energy of constant or variable intensity and which are subject to serious health burdens (Concha-Barrientos et al., 2004; Stewart et al., 2011).

We extended the fate factor described in Cucurachi et al. (2012) to the indoor compartment with the introduction of a term R, which represents the refraction of sound indoor. The fate factor may be re-written as:

$$FF_{i,c,f} = \frac{C_{ref}}{\sqrt{Wamb_{c,f}}} \times 10^{\left[D_{c,f} + R_{i,f} - A_{i,c,f}\right]/20} \qquad (5)$$

The unit of the fate factor is Pa/W and maintains the exact same meaning as described in section 3. R represents the reverberant component of sound in a space (i.e. room or localised site), measured in dB. It expresses the acoustic properties of a room (or site), as a function of its specific absorption properties and its surface (Schroeder, 2007).

The effect factor defined by Cucurachi et al. (2012) still holds for the indoor compartment of emissions. In this case, the main difference is the interpretation of the day/evening/night penalty β_c. In the indoor compartment, in fact, it does not refer to the sleep disturbance of individuals, since they are at work and typically not asleep. The penalty here refers to the disruption of the regular biological clock as determined by evening and night working hours (WHO, 2001). The value of Nf reported in the formula for the effect factor (see section 2.3.4) represents in the indoor case the number of workers exposed to the sound emission.

3
Results: Characterisation factors and sensitivity analysis
3.1
Definition and quantification of characterisation factors for noise impacts on humans

A total of 248 CFs was calculated for the defined archetypal and spatial contexts, based on the modelling decisions previously described and detailed in the Supplementary

Material 1 to this contribution. The CFs are representative of a vast array of possible conditions of emission.

To support also the needs of a practitioner that would have complete information on all sound emissions in a life cycle, we introduced an extra CF in the system, in order to leave the user the possibility of defining a "user-defined" context of emission. If enough information is available, one could directly input the location-specific parameters into the model, and have a customised characterisation factor as a result. According to the information available, the practitioner may choose to use 10-by-10-km maps and/or archetypes for different phases of a life cycle, or, alternatively, define site-specific customised conditions. The calculation sheet for the development of localised user-defined CFs is provided in the Supplementary Material 4.

3.1.1
CFs under archetypal conditions

The fixed parameters reported in Table 3.1, allowed for the calculation of all the archetypal CFs, and are representative of the full set of dimensions defined in section 2.1. The case of either unspecified frequency ranges, or unspecified time, or unspecified space, and all possible permutations of the three cases also needed to be defined. In some cases it was decided to take a regular mean or a weighted (i.e. with a probability index) value of parameters across dimensions. Given the impossibility of averaging several values of the background sound power level across different dimensions, due to the logarithmic scale used for the measurement of the parameters, a pessimistic approach was considered and the maximum value in all cases was selected. The underlying assumption is that the protection of the health of the target should be paramount also at the modelling phase, thus the background levels shall be in all cases the worst among day, evening and night conditions.

Table 3.1. Parameters defined for the archetypal case

place	time	Wamb [dB]	T [°C]	Rh [%]	P [Pa]	h [m]	d [m]	ρ[person/m²]	S [m²]	Nf [people]	Pr [dB]	ψ	αm
urban	day	77	20	30	101325	3	10	200	20	4000	-	-	-
urban	evening	82	16	60	101325	3	10	375	20	7500	-	-	-
urban	night	84	12.8	60	101325	3	10	450	20	9000	-	-	-
urban	unspecified	84	15.2	54	101325	3	10	377	20	7550	-	-	-
suburban	day	69	20	30	101.325	3	10	67	30	2000	-	-	-
suburban	evening	75	16	60	101.325	3	10	133	30	4000	-	-	-
suburban	night	75	12.8	60	101.325	3	10	133	30	4000	-	-	-
suburban	unspecified	75	15.2	54	101.325	3	10	120	30	3600	-	-	-
rural	day	62	20	40	101325	3	100	50	10	500	-	-	-
rural	evening	68	16	70	101325	3	100	100	10	1000	-	-	-
rural	night	68	12.8	70	101325	3	100	100	10	1000	-	-	-
rural	unspecified	68	15.2	64	101325	3	100	90	10	900	-	-	-
industrial	day	84	20	30	101325	3	10	67	30	2000	-	-	-
industrial	evening	82	16	60	101325	3	10	50	30	1500	-	-	-
industrial	night	78	12.8	60	101325	3	10	33.4	30	1000	-	-	-
industrial	unspecified	84	15.2	54	101325	3	10	45	30	1350	-	-	-
indoor	day	63	25	40	101325	3	1	0.033333	300	10	5	0.3	0.05
indoor	evening	61	25	40	101325	3	1	0.026667	300	8	5	0.3	0.05
indoor	night	58	25	40	101325	3	1	0.02	300	6	5	0.3	0.05
indoor	unspecified	63	25	40	101,325	-	1	0.024667	300	10	5	0.,3	0.05
unspecified	day	84	20	32.5	101325	3	32.5	95	22.5	2125	-	-	-
unspecified	evening	82	16	62.5	101325	3	32.5	156	22.5	3500	-	-	-
unspecified	night	84	12.8	62.5	101325	3	32.5	167	22.5	3750	-	-	-
unspecified	unspecified	84	15.2	52.5	101325	3	32.5	139	22.5	3125			

The following assumptions were made:

- Unspecified frequency: in this case, the central 1000 Hz frequency was selected for the calculations as it is the central frequency range for which no extra penalty has to be added in the calculation of sound emissions in dBA (ISO, 1996a). This frequency band is central in the sound spectrum and provides a sufficient representation of a sound, if unspecified. Input parameters for time and place did not change.

- Unspecified time: an average value of 7.5 decibel was considered for the penalty β for day, evening and night emissions. For the calculation of the other parameters, values were dimensioned according to the probability of emissions taking place during different parts of the day. It was decided to adopt a pessimistic view over reality, and therefore the highest probability-weight was attached to "night-parameters", then to "evening parameters", and a lower weight was assigned to "day-parameters". The maximum background sound power level was chosen. It was, in fact, decided to adopt a pessimistic view on input parameters for frequency and place remained equal.

- Unspecified place: the values of the system parameters were averaged across the 4 different outdoor places of emissions, differentiated per day, evening and night, with unaltered values for the frequency. The maximum background sound power level was chosen.

- Unspecified time and place: the values of the system parameters were averaged, without any additional weight, across places and times of sound emission considering the 12 different outdoor contexts of emissions. Emissions across places and time were assumed to be equally probable. Emissions taking place indoor were excluded from the calculations, in light of the definition given of the indoor compartment in section 2.3.8. The maximum background sound power level was chosen across the 12 different outdoor contexts.

- Unspecified frequency and time: the values of the system parameters were averaged across day, evening and night for each of the defined places of emission. The maximum background sound power level across day, evening, and night was chosen.

- Unspecified frequency and unspecified space: the central 1000 Hz frequency was selected for the frequency, together with an average of all-day, all-evening and all-night values respectively. The maximum background sound power level of all-day, all-evening and all-night values, respectively, was chosen.

• Unspecified frequency, unspecified time and unspecified space: the central 1000 Hz frequency was selected for the frequency, and the values of all other parameters were averaged across 12 outdoor possible combinations of dimensions. The maximum sound power level across all the possible outdoor combinations was chosen.

The results of the calculations of the CFs for the 248 possible combinations of the dimensions of sound emissions are reported in the Supplementary Material 3 to this contribution.

If we focus on sound emissions at the central frequency of 1000 Hz (in Figure 3.1), it is possible to notice that the highest impact relates to emissions taking place indoor, and at night, while those taking place during the day in a rural area are the least impacting. The case of unspecified emissions at an unspecified time scores lower than emissions taking place during the day.

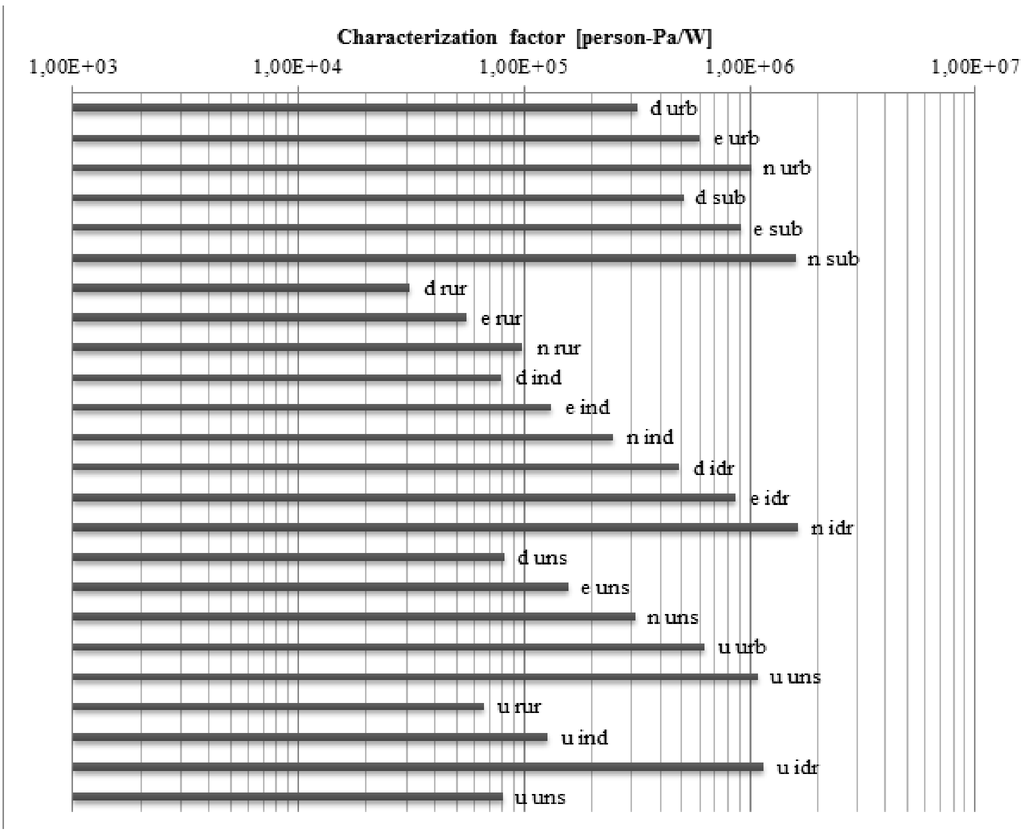

Figure 3.1. Characterisation factor (in personxPa/W) at 1000 Hz. In the figure: urb=urban; sub=suburban; rur=rural; ind=industrial; idr=indoor; u=unspecified; d=day; e=evening; n=night

The trends reported for the lowest available octave band of 63 Hz follow a similar trend as described above for emissions at 1000 Hz. Figure 3.2 reports the CFs for emissions in all archetypal compartments at 63Hz.

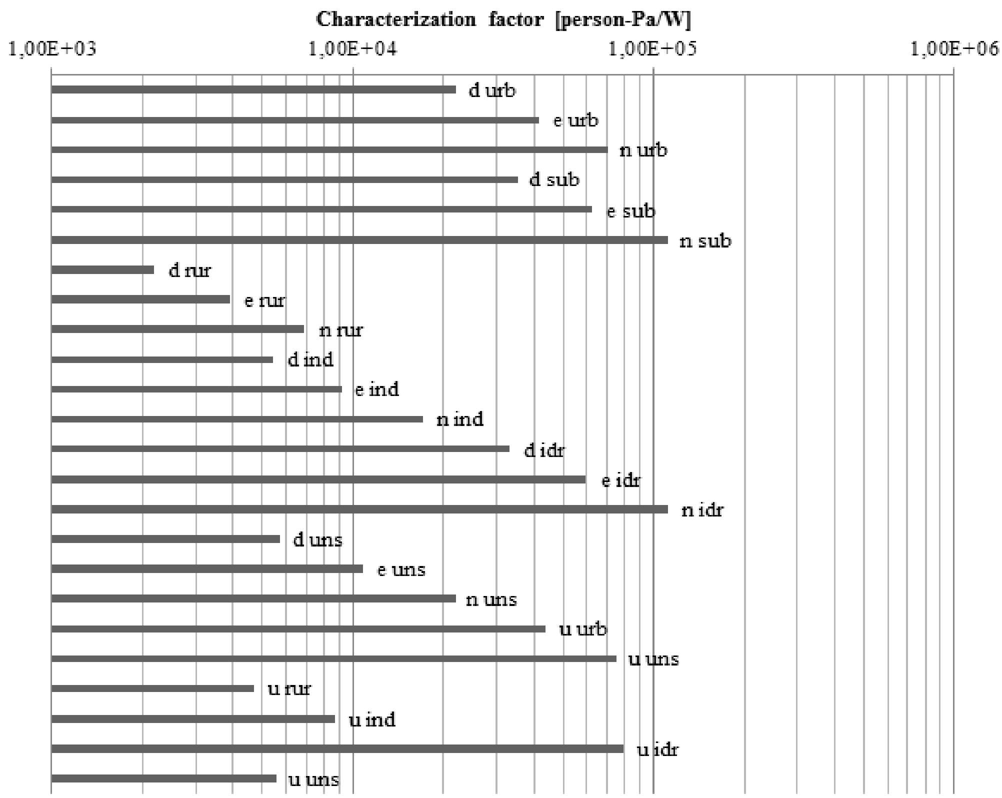

Figure 3.2. Characterisation factor (in personxPa/W) at 63 Hz. In the figure: urb=urban; sub=suburban; rur=rural; ind=industrial; idr=indoor; u=unspecified; d=day; e=evening; n=night

At urban locations and at day time the CFs change at varying frequencies (Figure 3.3), and the highest impact results at 2000 Hz.

5

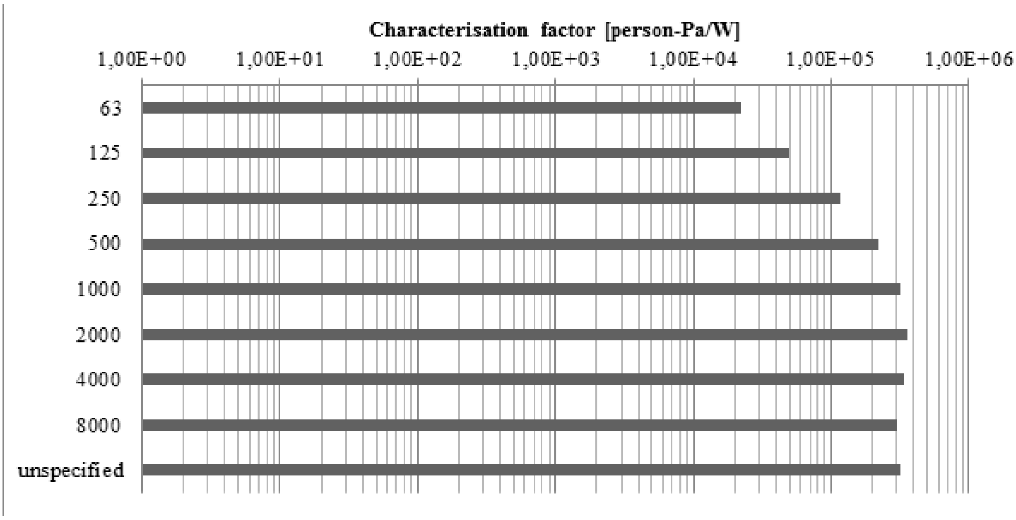

Figure 3.3. Characterisation factor (in personxPa/W) in a urban area during day time at eight centre-octaves and unspecified frequency

3.1.2
Maps of CFs for EU27

In the spatial context, 32 maps of CFs with a 10-km^2 grid were produced (see Supplementary Material 1). They refer to emissions taking place in EU27. Raster data was collected and analysed for all the defined parameters. CFs are provided for eight centre-frequencies (i.e. from 63 to 8000 Hz) for day, evening, night and unspecified time. In this case, the value of Wamb for the unspecified case was calculated as a mean of the Wamb value for day, evening, and night.

For the case of unspecified frequency of emission, we recommend to consider the use of the CFs calculated at the central frequency of 1000 Hz.

We will focus the analysis on emissions at 63 Hz and compare those taking place during day, evening, night or during an unspecified time (Figure 3.4). Following the colouring scale, the least affected areas are shown in green, while the most affected are represented in dark red. From the comparison of the maps it is clear that metropolitan areas are the most sound-intensive locations, regardless of the time of the emission.

Areas around bigger cities (e.g. Great London area) are the ones which show the highest values of CFs. Areas with CFs values close to zero, or equal to zero, correspond to areas where attenuations are so dominant to attenuate any effect of the sound emission.

The model adopted shows to be sensitive in changes in emissions at different centre-frequency ranges. The mean for CFs at 63 Hz during day time is 1757personxPa/W, with a standard deviation of 2635 personxPa/W. CFs for emissions taking place at night have the highest impact, with an average of 7099 person x Pa/W and a standard deviation of 9134 person x Pa/W. During the evening the CFs at 63 Hz have a mean of 2070person x Pa/W and a standard deviation of 2828 person x Pa/W. In the case of unspecified time of emission, a mean of 2651 person x Pa/W was calculated, with a standard deviation of 3633 person x Pa/W.

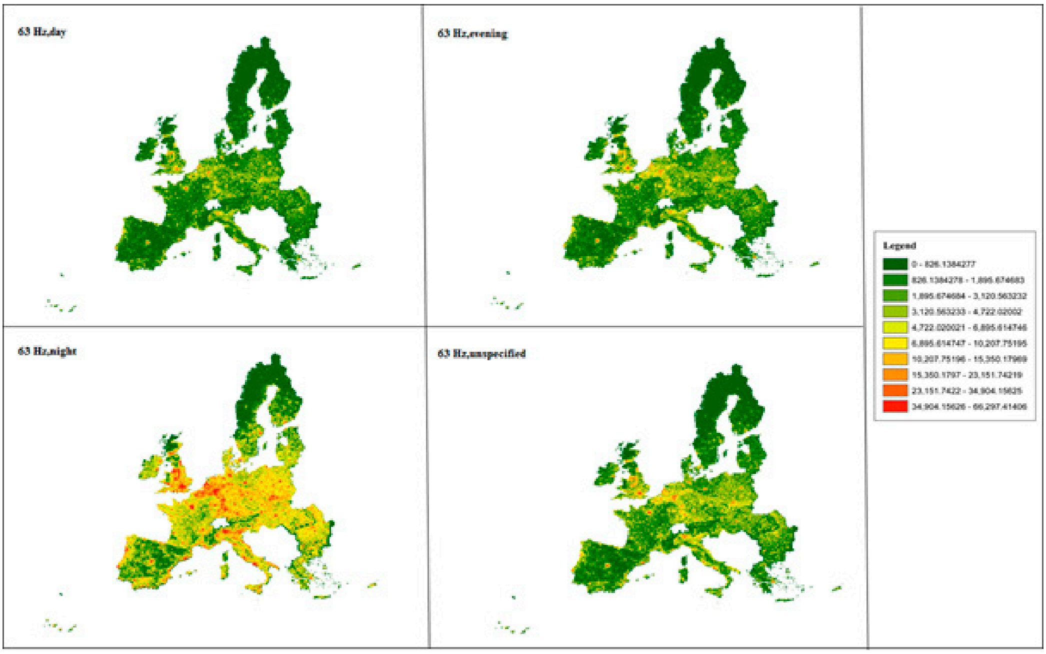

Figure 3.4. Characterisation factor in map at 63 hertz for day, evening, night and unspecified time, at 63 Hz for EU27

At the same frequency, i.e. 63 Hz, CFs for day and evening have in all cases a lower value than CFs for night and unspecified time. In Figure 3.5 the difference is shown graphically. The highest differences are visible (in red) around areas with higher population density and higher background sound levels.

5

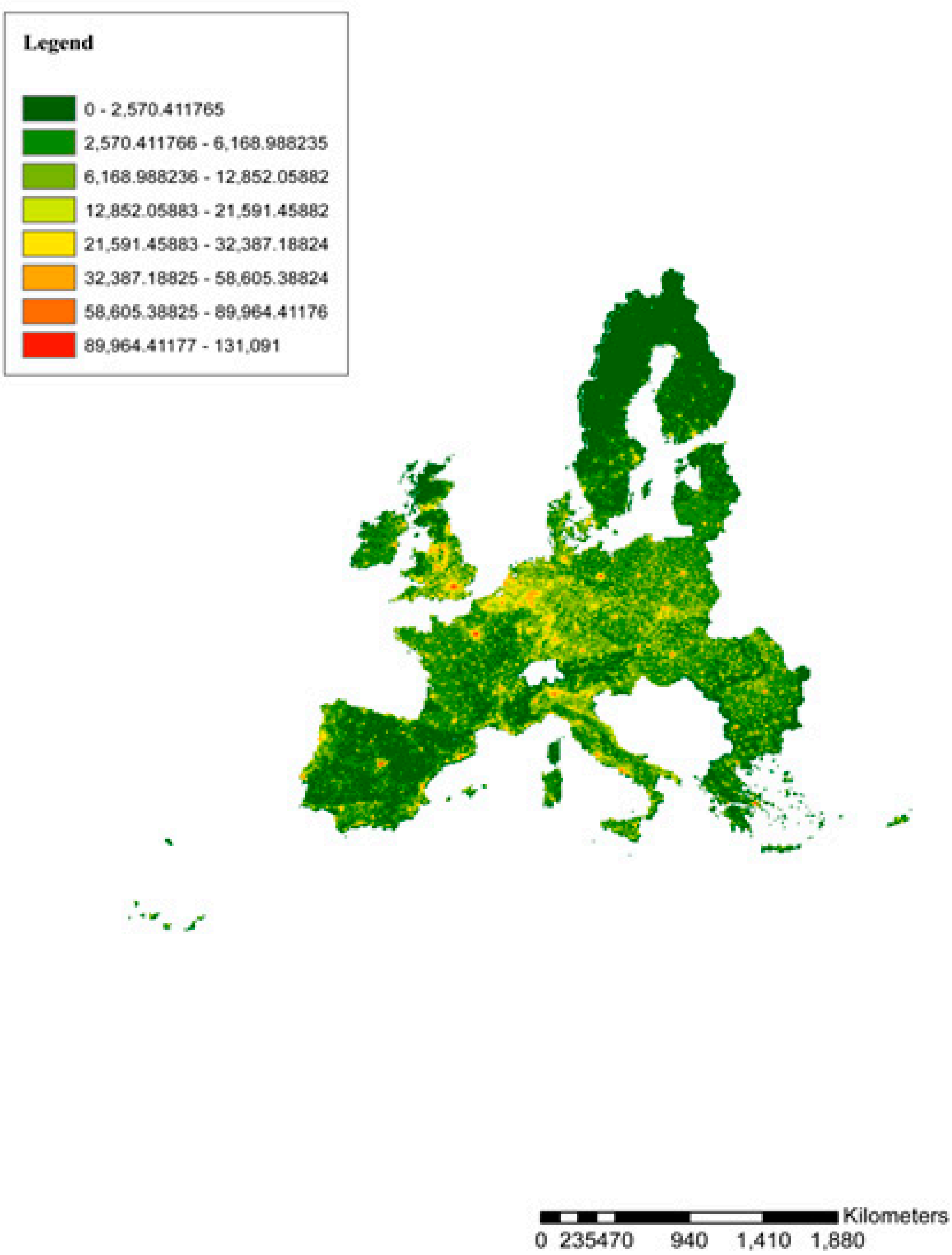

Figure 3.5. Difference between CF at 63 Hz night and CF at 63 Hz unspecified

3.2
Global sensitivity analysis applied to the noise impact model

For the calculation of CFs in both archetypal and spatial cases, it was necessary to fix factors to a central value, either using data from the literature or extrapolating data from the spatial analysis. We are conscious that this decision introduces extra uncertainty into the overall model. While it can be accepted that uncertainty is an intrinsic feature of complex models (Couclelis, 2003), it does not exclude that much can be done to manage and resolve uncertainties where possible. As stated before in this report, spatial calculations are also the results of assumptions and of the extension of characteristics defined for a specific area to a greater or smaller area of reference. Therefore, they are also uncertain.

We decided to corroborate the proposed model and calculations by applying global sensitivity analysis (i.e. considering at once the full range of input factors). For each parameter a sample distribution was chosen as shown below (Table 3.2). We used the Monte Carlo method (Caflisch, 1998) with quasi-random sampling to calculate 1000 samples of each of the thirteen uncertain input factors considered in the noise LCIA model. The sampling technique was selected to avoid clusters and gaps, which may occur in samples generated randomly (Saltelli et al., 2008). The quasi-random samples are random in the sense that they are distributed uniformly across the entire sample space, but the selection algorithm keeps the newly selected points away from the already-selected ones, thus avoiding the phenomenon of discrepancy (i.e. the lumpiness of a sequence of points in a multidimensional space; Saltelli et al., 2008).

Table 3.2. Description of uncertain input factors

Statistical definition of parameters				
Parameter [unit]	**Symbol**	**Distribution**	**Mean [a] or left bound [b] or discrete values [c]**	**Standard deviation [a] or right bound [b] or discrete values [c]**
Ambient sound power level [dB]	Lw	Normal	20	10
Frequency [Hz]	fm	Discrete (equiprobable)	[63;125;250;500;1000;2000;4000;8000]	[0.1;0.1;0.15;0.15;0.15;0.15;0.1;0.1]
Temperature [deg]	T	Uniform	0	25
Relative Humidity [%]	Rh	Uniform	10	90
Pressure [kPa]	P	Uniform	10	101325
Average propagation height [m]	h	LogUniform	2	8
Distance [m]	d	LogUniform	5	50
Reference area [km2]	S	LogUniform	5	30
Number of people	Nf	Normal	1000	300
Directivity [dB]	D	Discrete	[3;6;9]	[0.7;0.15;0.15]
Frequency penalty [dB]	α	Discrete	[-26.2;-16.1;-8.6;-3.2;0;1.2;1;1.1]	[0.1;0.1;0.15;0.15;0.15;0.15;0.1;0.1]
Time penalty [dB]	β	Triangular [d]	[0;5;10]	-
Ground composition coefficient	G	Uniform	0	1

Sensitivity analysis was conducted and the noise impact framework was implemented in the software SIMLAB (Saltelli et al., 2004). The variance-based method extended Fourier amplitude sensitivity testing (eFAST, Saltelli et al., 2002, 2008 pp.164-166) was used to study how the variance of the output of the proposed model would depend on the uncertain input factors (Saltelli et al., 2008). Variance-based methods are based on the decomposition of the variance of a model output such as $V(Y) = V[E(Y|X_j)] + E[V(Y|X_j)]$, for any generic input variable X_j (Tarantola et al. 2002). For every input variable, eFAST provides both the first-order sensitivity index (S_j , i.e. the direct contribution to the variance of each parameter) and the total-order sensitivity index of each input parameter (S_{Tj}, i.e. the sum of all the sensitivity indices, including all the interaction effects, involving that parameter). Table 3.3 shows the first and total order indices for the noise impact model calculated using eFAST. Each of the first order indices, i.e. S_j, indicates by how much the output variance could be reduced if any input X_j could be fixed to a nominal value (Saltelli et al. 2008), thus it is equal to $V[E(Y|X_j)] / V(Y)$. The total sensitivity index S_{Tj} is a measure of the overall effect of factor X_j on the output, including also all the interactions. It corresponds to the expected variance that is left when all factors are fixed (Saltelli et al. 2008); thus, $S_{Tj} = V[E(Y|X_{-j})] / V(Y)$, where X_{-j} indicates that all factors are considered but X_j (Tarantola et al. 2002). The calculation of S_{Tj} allows to identify non-influential factors in a model, rather than prioritising the most influential ones.

	First order indices (S_i)			Total order indices (S_{Ti})		
Input variable (X_i)/Model output (Y)	**EF**	**FF**	**CF**	**EF**	**FF**	**CF**
Lw	0.050	0.129	0.118	0.436	0.804	0.746
Freq	0.092	0.005	0.106	0.791	0.102	0.874
T	0.075	0.071	0.032	0.689	0.655	0.354
P	0.035	0.077	0.091	0.406	0.761	0.778
Rh	0.083	0.045	0.042	0.750	0.477	0.460
h	0.066	0.017	0.067	0.625	0.243	0.626
d	0.061	0.103	0.108	0.554	0.857	0.882
S	0.080	0.042	0.059	0.719	0.330	0.584
Nf	0.035	0.023	0.084	0.404	0.325	0.723
D	0.075	0.248	0.113	0.600	0.907	0.891
α	0.099	0.088	0.002	0.814	0.768	0.799
β	0.217	0.009	0.108	0.911	0.217	0.883
G	0.033	0.028	0.048	0.386	0.329	0.477

The indices were calculated both for the final CFs but also for the EF and FF. For the EF, the penalty β has the highest S index. For instance, the result would suggest that the size of the penalty matters in the overall result, therefore the model is sensitive to the extra values in dB added to day, evening and night emissions. The directivity of sound (D), the background sound power (Lw), and the distance from source to receiver (d) and contribute to most of the variance of the FF. The uncertainty of the attenuation factor included in the model could be reduced if the direction of propagation of sound, the actual background sound power at the location, and the actual distance were known. In this case, the sum of the S_js does not equal to 1, which suggests higher order interactions among parameters, which suggests that the model is non-additive and non-linear (Saltelli et al., 2008).

As for the CF, which is a product of the FF and the EF, a similar set of parameters resulted to be statistically important, with the addition of the frequency of emissions (Freq) appear to be the most relevant values.

The S_{Ti} (Table 3.3) confirms that higher-order interactions are present and need to be taken into account for the complete understanding of the model. As Saltelli et al. (1997) propose, a set of input parameters with total sensitivity index greater than 0.8 can be regarded as `very important', between 0.5 and 0.8 as `important', between 0.5 and 0.3 as `unimportant', and less than 0.3 `irrelevant'. In the case of our model, interactions highlight how all the included parameters are important, because of the higher order interactions between them. The distance d from the source to the receiver is still the most influential value, together with the directivity index D and the penalty β (i.e. S_{Ti}=0.89). The frequency of the sound emission comes right after with a S_T of 0.88.

3.3
A possible transition to the endpoint

So far we have dealt with a model that stops at the midpoint of the impact pathway. Sound emissions have been characterised using the impact assessment model detailed in Cucurachi et al. (2012). The results relate to the sound pressure that, for the time the functional unit under study is active in the product system under study, each individual experiences at a certain location, time of the day, and with a certain frequency of emission, (see Heijungs and Suh, 2002 on the computational structure of LCA). In order to more easily compare the impacts from sound emissions to those of other emissions, it may be interesting to move to the endpoint level.

The human noise midpoint, $HN_{midpoint}$, may be defined as:

$$HN_{\text{midpoint}} = \sum_i \sum_c \sum_f m_{i,c,f} \times CF_{i,c,f} \quad (6)$$

where $m_{i,c,f}$ represents the inventory quantity in joule as calculated in section 2.1, and $CF_{i,c,f}$ refer to the characterisation factors, in person x pascal x second, for the relative specific i, c, and f conditions of emission/exposure, as calculated and detailed in the previous sections.

In order to move to the endpoint, it is necessary to find the suitable conversion factor that converts the $HN_{midpoint}$ in person x Pa x sec, to a quantity in a unit, such as the DALY scale, which would allow for the comparison of noise impacts to other impacts to the human health area of protection. Hence, the human health endpoint in DALYs, $HH_{endpoint}$, may be calculated using a certain mid to end conversion factor, in DALY/person x Pa x sec, as

$$HH_{\text{endpoint}} = HN_{\text{midpoint}} \times mid\_to\_end \qquad (7)$$

and, consequently,

$$mid\_to\_end = \frac{HH_{\text{endpoint}}}{HN_{\text{midpoint}}} \qquad (8)$$

In order to quantify the mid_to_end conversion factor, it is necessary to refer to studies that have calculated the $HH_{endpoint}$ for a certain geographical extent for which enough data is available, using a certain disability weight. A study from WHO (2011) on the burdens of disease from noise calculated the impact from environmental noise in DALYs from a considerable part of the EU, with some exceptions due to lack of exposure data. The study provides sufficient data for the Netherlands that can be used for the purpose of this contribution to quantify the conversion factor from midpoint human noise to endpoint human health. A total of 25000 DALYs was calculated for the sole nocturnal exposure to noise with a disability weight of 0.07. For the Netherlands, De Hollander et al. (1999) calculate the burden from environmental noise using a disability weight of 0.01 for severe annoyance and sleep disturbance. The study calculates a total of 28690 DALYs lost due to residential noise as a function of the two combined environmental factors.

In order to calculate the mid_to_end conversion factor for the case of the Netherlands, the $HN_{midpoint}$ needs to be calculated. To this end, we resorted to the spatially-explicit CFs described and calculated in sections 2 and 3 of this contribution. By means of ArcGIS (ESRI 2012), we calculated the $HN_{midpoint}$ as a function of the background sound pressure L95 provided by EASA (2009). Due to data limitations, we considered the sound pressure level L95 as unspecified in terms of frequency, but differentiated per time (i.e. day, evening, night), and location (i.e. The Netherlands). The corresponding background sound power level was calculated as described in the Supplementary Material 1 of this contribution, and converted to a quantity in joule considered a time frame of 1 year. We did not consider here any specific functional unit or life cycle, but the sound power background level as calculated for the Netherlands as a function of all active static and moving sources of sound emissions, and normalised of a 1 year time frame.

A total of 7.82E+8 person x Pa x sec was calculated: respectively, 3.18E+8 for day, 2.67E+08 for evening, and 1.96E+8 for night emissions. For a matter of comparison, we calculated the value of mid_to_end applying Eq.7 and using both the DALYs totals as calculated by De Hollander et al. (1999) for day evening and night emissions, and the DALYs calculated by the WHO (2011) for the same geographical extent. The mid_to_end conversion factor as calculated using De Hollander et al. (1999) amount to 2.9061E-5 DALY/person x Pa x sec. Alternatively, a value of 2.13E-4 DALY/person x Pa x sec was found applying the WHO (2011) assumptions for the evening condition.

4
Conclusions, future agenda and potential expansion of the model

This contribution proposes CFs which are immediately usable for the calculation of the impact of noise on humans at a midpoint level for any sound-emitting source, or combination of emitting sources. The methodology can be also applied with minor adjustments (e.g. frequency of interest, number of exposed subjects) to target systems other than human beings. The provided CFs can be implemented in any of the available LCA databases for impact-assessment systems.

The calculations are based on the assumption that the level of detail of CFs may be more or less of interest for practitioners and researchers, based on to the amount of information that is available to them in a specific case. In total, 248 potential CFs were calculated (i.e. 32 spatial and 216 archetypal). Most life cycles will require the use of multiple CFs and even the combination of both spatial and non-spatial factors, based on the amount of data that is available and on the complexity of the system under study. The additional possibility of using user-defined values as input is allowed for the expansion of contexts of emissions and their adaptation to the specific needs.

The CFs are applicable to life-cycle aggregated sound emissions, measured in joule. The goal of the methodology is not support the quantification of noise emissions in a life cycle of a complex product system. The procedure for obtaining these frequency-, time-, and location-specific data from dB that belong to individual unit processes has been described by Cucurachi et al. (2012). The standard databases with process data for LCA do not contain noise emissions, thus more investigations are needed at the inventory level to use the characterisation factors as elaborated in the present work. The literature provides already enough information to analyse specific cases, such as the proposed CNOSSOS report (European Commission, 2012). Nevertheless, we will demonstrate the use of the CFs in a future case study.

The CFs provided are in person x pascal/watt, or $s*m^{-3}$. The measure provides a midpoint characterisation factor for the impact of noise on humans. The quantification of the amount of DALYs that are associated to the quantity expressed by the midpoint CFs may be used to provide a measure of the noise impacts at an endpoint level. The calculation of the DALYs associated with noise has been extrapolated from past studies by studying data from surveys on noise annoyance and level of disturbances (Miedema and Vos, 1998; Muller Wenk, 2004; WHO, 2011). The conversion of person x pascal x second in the DALY scale was proposed with reference to the case of the Netherlands, for which sufficient information was available. Itsubo and Inaba (2008) developed a damage function for noise impacts associating the corresponding value in DALYs to a sound energy emission in joule for Japan. These results may provide an interesting basis of comparison, once suitable inventory data is available at the right level of geographical specification also for Japan. We intend to go towards this direction, also making use of the results available in the literature of the impacts of noise on health (see for instance, Fyhri and Klæboe, 2009; Pirrera et al., 2010). The assumption of linearity allowed for the quantification of a conversion factor, but may introduce uncertainty that need to be further investigated into the calculations. The comparison of results in a complete case study involving also the study of other environmental impacts in a complete product system in under development within the LC-IMPACT project of the EU (www.lc-impact.eu) and will certainly be a test bed for our methodology.

The result of the global sensitivity analysis allowed for a better comprehension of the model structure when parameters are independent. The first order and total order sensitivity indices that we calculated already provide an idea of the areas where investments may be made to reduce uncertainty. We saw, in fact, that it is risky to fix some values to a central value without carefully thinking over their contribution to the variance of the output and the high-order interactions between a parameter and the others. The results provide a good basis on which to expand the analysis of the framework and through which to improve data collection. The limited availability of data (e.g. only one trustable source for background sound levels) and the highly-localised nature of the impacts may pose a challenge to the collection of information for some of the parameters. As stated in Borgonovo et al. (2012), without a proper sensitivity analysis one is exposed to the so-called black-box effect, namely the risk of not fully understanding the behaviour of the model on which analyses and decisions are based. The use of global sensitivity analysis techniques should become standard practice also in the LCIA development. Several applications of sensitivity analysis techniques have, in fact, improved the understanding and the performance of complex environmental systems (see, for instance, Fassó et al. 2003, and Borgonovo et al. 2012). As it was shown in the case of noise, the development of spatially-explicit CFs does not statim reduce uncertainties. In our case, the lack of data did not allow us to go to a finer resolution than 10 km2. In order to also evaluate the right scale of spatial definition for the development of maps of CFs, a global sensitivity analysis should be conducted. The application of sensitivity analysis to environmental risks and impacts may have to handle a large set of input data, especially in the case of spatially and temporally-variable systems. Techniques have been developed to overcome such issues through the use of meta-models (Marrell et al. 2011). In this context, a Gaussian process model as developed by Marrell et al. (2011) can and should be used to calculate sensitivity indices (or index maps) and process uncertainties also in the case of high dimensional output of a model, as are characterisation maps in LCIA.

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6

A protocol for the global sensitivity analysis of impact assessment models in LCA

A protocol for the global sensitivity analysis of impact assessment models in LCA

Based on:
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Abstract
The Life Cycle Assessment (LCA) framework has established itself as the leading tool for the assessment of the environmental impact of products. It has been claimed that more attention should be paid to quantifying the uncertainties present in the various phases of LCA. Though the topic has been attracting increasing attention of practitioners and experts in LCA, there is still a lack of understanding and a limited use of the available statistical tools. In this work, we introduce a protocol to conduct global sensitivity analysis in LCA. The article focuses on the Life Cycle Impact Assessment (LCIA), and particularly on the relevance of global techniques for the development of trustable impact assessment models. We use a novel characterization model developed for the quantification of the impacts of noise on humans as a test case. We show that global SA is fundamental to guarantee that the modeler has a complete understanding of: (i) the structure of the model; (ii) the importance of uncertain model inputs and the interaction among them.

Keywords
Life Cycle Assessment; LCIA; Global Sensitivity Analysis; Uncertainty importance

1
Introduction

In over thirty years of developments and refinements, Life Cycle Assessment (LCA) has become the reference framework in the sustainability assessment of products and services (EC-JRC 2011). At a policy level, LCA studies are now recommended in a growing number of countries around the world and performed on a vast array of complex product systems (Guinée et al. 2011). As the interest in the methodology has grown, so has done the attention to the trustworthiness of the results of LCA studies.

Results of LCA studies are increasingly used by policy makers. Typical problems are the selection of energy systems for optimal planning, or the discrimination between the environmental performances of products, so that the legislator can establish if any of these products has to be outlawed. A difficulty associated with LCA is cross-comparison and validation of the results obtained. Outcomes are in all cases the result of a modelling process that involves modelling assumptions and uncertain or variable data, which need to be analysed and interpreted in the specific context in which they were made. Since the early days of the methodology, concerns have been expressed about the accuracy and credibility of results, due to the great variability in impacts results also for comparable systems. Even studies compliant with the standard on (ISO. 2006) and dealing with identical systems showed large differences in the assessed impacts (Henriksson et al. 2013). The cross-validation of LCA results is not always straightforward, because assumptions are system- and context- specific. Therefore, there is an urgent need for the LCA community to deploy statistical tools to deal with variability of results and to increase the possibility of objectively evaluate systems.

Sources of variability (e.g. limited data quality, geographic representativeness) need to be reported and analysed to guarantee the reliability of the results of LCA studies. Important for the credibility of LCA is that results are accompanied by adequate uncertainty quantification(Björklund 2002), so to best inform the decision-process(Huijbregts 1998). Reap et al. (Reap et al. 2008a, 2008b) claim that sensitivity and uncertainty analysis tools would improve the representativeness of the whole framework. The importance of sensitivity analysis (SA) has been agreed upon since the beginnings of the development of LCA [e.g. (Heijungs 1996)], and required by the ISO standard (ISO. 2006). The ISO 14044 standard defines SA as "the systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study" (ISO. 2006). In practice, SA has been alternatively interpreted generically as the activity of studying how the output results are sensitive to the variation of the input data, or as a synonym of uncertainty analysis, or as the break-down of output uncertainty in terms of input uncertainties (Heijungs and Huijbregts 2004; Lloyd and Ries 2007). While in the field of LCA there seems to be an overlapping of concepts falling under the definition of SA, in the risk analysis literature the concept has been formalised and a variety of rigorous statistical techniques have been introduced (Borgonovo 2006; Frey and Patil 2002; Helton and Davis 2002; Helton 1994; Iman and Helton 1988, 1991; Iman and Hora 1990; Patil and Frey 2004; Saltelli 2002).

Internationally, several agencies prescribe sensitivity and uncertainty analysis as part of best practices in the utilization of scientific codes to support decision and policy making. The US EPA [(US - EPA 2009); Appendix D], the European Commission [(European Commission 2009)-section 5.4], the Florida Commission on Hurricane Loss Projection Methodology (FCHLPM)(Iman, Johnson, and Watson 2005), National Institute for Health and Care Excellence in the Great Britain [(Nice 2008); section 5.7], and the "Guidelines for Economic Evaluation of Pharmaceuticals" in Canada [(Canadian Health 2006); section 2.2.6] are just a few examples.

Rabitz [(Rabitz 1989); p.221] observes that *the judicious use of SA techniques appears to be the key ingredient needed to draw out the maximum capabilities of mathematical modelling*. Helton and Oberkampf (Helton and Oberkampf 2004) note that SA should be a fundamental part of any analysis that involves the assessment and propagation of uncertainty.

Characterisation (or impact assessment) models that are used in LCIA can be considered as a specific class of complex integrated assessment models (IAMs). Characterization models are used to calculate science-based conversion factors (characterization factors) to obtain the potential human health and environmental impacts of the resources and releases across a life cycle for a certain stressor [i.e. a set of conditions that may lead to the impact] (EPA 2006; ISO. 2006). Indeed, such models deal with intricate complex phenomena, need to capture elements that vary in different time and space scales, and involve both physical laws and socio-economic aspects (Anderson et al. 2014). Global SA techniques enable us to study the structure of IAMs and their dependence upon the uncertain model inputs, and also to understand which model inputs require additional investigation improve our confidence in the results (Kioutsioukis et al. 2004; Saltelli et al. 2008).

Thus, the provisions concerning the use of global SA that apply in other fields, should also apply for decisions based upon characterization models. However, no shared protocol for the performance of uncertainty and global SA in LCA and, in particular, for the integration of global SA techniques in the process is available to date (Padey et al. 2013). A possible reason is computational burden, with a high number of model runs required to accurately estimate these sensitivity measures. However, several recent advances have contributed in abating such computational cost, making the techniques, in principle, applicable to a vast class of models. In particular, developments in the post processing or given data directions (Lewandowski, Cooke, and Duintjer Tebbens 2007; Plischke, Borgonovo, and Smith 2013; Storlie et al. 2009) allow analysts to compute global sensitivity measures directly from a Monte Carlo (MC) sample of the model inputs, without the need of a specific design. Then, because several software tools available for LCA studies already include MC subroutines, no additional computational burden with respect to current practice is imposed by post processing schemes.

In this article, we construct a protocol on how to regularly conduct a global SA in impact assessment modelling. We proceed as follows. We cast global SA techniques in the context of LCA characterisation models. We clarify the conceptual differences between SA tools, relating them to the tools that are used in current LCA practice. We introduce sensitivity analysis settings (Andrea Saltelli 2002) in the LCA context. We then define a multi-step protocol for the application of global SA methods to LCIA models. The protocol starts from the identification of the relevant uncertainties and the assignment of distributions, continues with the definition of SA settings and ends with the assessment of the decision-maker's confidence in the estimates.

We illustrate the application of the protocol to a recent LCA model developed to quantify the impact on humans of sound emissions (Cucurachi, Heijungs, and Ohlau 2012; Cucurachi and Heijungs 2014). Two alternative configurations of the same model, at a different level of complexity are analysed using an ensemble of global sensitivity analysis techniques. Numerical findings are discussed in detail. Before concluding, we offer a critical discussion about the proposed protocol, discussion which is also aimed at highlighting the lessons learned and the insights and limitations of the approach that apply within the LCA framework, but also outside it as well.

The remainder of the paper is organised as follows. Section 2 provides an overview of the available SA techniques and gives some insight on the way SA is defined and used in the field of LCA. In section 3, the settings are defined for a global SA design in the context of LCIA. The structure of the noise LCIA model is here analysed together with the importance of its inputs. Section 4 discusses the contribution of global SA for the LCA community. Concluding remarks regarding the empowerment of LCIA models close the article.

2
Literature review: sensitivity analysis and its use in LCA
2.1
The sensitivity analysis setup

The SA standard setup is as follows. One considers the relationship between a quantity of interest (y) [model output] and a set of independent variables (x)

$$y = g(\mathbf{x}), \quad g : \Omega_{\mathbf{X}} \to \mathrm{R} \tag{1}$$

where $\Omega_{\mathbf{X}} \subseteq \mathrm{R}^k$, with k denoting the number of model inputs (i.e., the size of x). $\Omega_{\mathbf{X}}$ is the k-dimensional domain of g and it is the Cartesian product of the individual subsets of $\mathbb{R}$ over which each model input is allowed to vary. The model is usually implemented as a scientific code and helps the analyst to forecast the behaviour of y given the values of the model inputs x.

In a local sensitivity analysis, the analyst is interested in obtaining the response of the output around one point of interest in the model input space $\Omega_{\mathbf{X}}$. Typically, local sensitivity is performed varying one model input at a time (referred to also as OFAT), while the remaining model inputs are kept at a nominal (or base case) value (Saltelli, Tarantola, and Chan 1999). The perturbations of the model inputs can be finite in Tornado diagrams (Eschenbach 1992) and finite change sensitivity indices (Borgonovo and Smith 2011; Borgonovo 2010) or infinitesimal, in differentiation-based methods (Griewank 1995, 2000; Sobol' and Kucherenko 2009). A sensitivity index S_i is calculated through the use of a set of partial derivatives of the output y, with respect to each input X_I :

$$S_i = \left. \frac{\partial g(\mathbf{x})}{\partial x} \right|_{\mathbf{x}=\mathbf{x}^0} . \tag{2}$$

In Helton (Helton 1993), partial derivatives are normalized by the nominal value of the factor or by its standard deviation. For instance, if one writes

$$S_i = \frac{\partial y}{\partial x_i} = \frac{\partial y}{\partial x_i} \frac{x_i^0}{y^0}, \tag{3}$$

one obtains the elasticity of the model output with respect to X_I. These two sensitivity measures are particular cases of the differential importance measure [see (Borgonovo 2008) for details].

Differentiation-based approaches compute a value for the sensitivity index S around a fixed nominal point $x^0 = \left(x_1^0, x_2^0, \ldots, x_k^0\right)$ (Saltelli, Tarantola, and Campolongo 2000). Thus, they provide a very limited exploration of the input-output space, if the analysis is limited at a point of interest. Additionally, they ignore probabilistic information in the presence of uncertainty. More generally, because they are OFAT approaches, they are not capable of quantifying the relevance of potential interactions among model inputs (Anderson et al. 2014; Saltelli et al. 2008). However, differentiation-based methods remain appropriate in applications in which the analyst wishes to study how small changes in the input x_i affect the model output around one or more points of interest. When a better exploration of the model input space is sought, then global sensitivity methods are appropriate.

2.2
Global Sensitivity Methods

Global SA methods are used to investigate which model inputs are the most influential in determining the uncertainty of the output of a model, and, after uncertainty analysis, to obtain additional information about the input–output mapping (Anderson et al. 2014). Global SA methods allow analysts to consider the behaviour of the model $g(x)$ in the entire k-dimensional domain, as well as the probability distributions specified to address the variation of the model inputs. Thus, the formal setting sees the enrichment of the model input space Ω_x with the probability space $(\Omega_x, B(\Omega_x), P_x)$, where 1) the capital X denotes that the model inputs are now random variables, 2) P_x denotes the probability distribution that characterizes the analyst's state of knowledge about the model inputs and $B(\Omega_x)$ is a Borel σ-algebra.

Global SA methods have become the golden standard of sensitivity analysis under uncertainty (Saltelli et al. 2008). A number of global SA techniques have been developed. Due to space limitations, we cannot provide a detailed overview of all methods. For broad reviews, we refer to (Borgonovo 2006; Saltelli et al. 2005, 2012). For details on screening methods, we refer to (Campolongo, Saltelli, and Cariboni 2011; Morris 1991), on non-parametric methods to (Helton and Sallaberry 2009; Helton et al. 2006; Storlie et al. 2009), on expected value of information-based methods to (Felli and Hazen 1998; Oakley 2009; Strong and Oakley 2013). We analyze here in detail the sensitivity measures we are to use in this work, namely, variance-based and distribution-based methods.

As for variance-based techniques, assuming that $g(x)$ in eq. (1) as an integrable function on $(\Omega_x, B(\Omega_x), P_x)$, and if P_x is a product measures, (i.e., we assume that the model inputs are independent), then the following expansion of g(x) holds (Efron and Stein 1981):

$$y = g(\mathbf{x}) = g_0 + \sum_{i=1}^{n} g_i(x_i) + \sum_{i<j}^{n} g_{i,j}(x_i, x_j) + \ldots + g_{1,2,\ldots,k}(x_1, x_2, \ldots, x_k) \quad (4)$$

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where

$$\begin{cases} g_0 = \int \ldots \int\limits_{\Omega_X} g(\mathbf{x}) dP_X = \mathbb{E}[g(x)] \\ g_i(x_i) = \mathbb{E}[g(\mathbf{x}) \mid X_i = x_i] - g_0 \\ g_{i,j}(x_i, x_j) = \mathbb{E}[g(\mathbf{x}) \mid X_i = x_i, X_j = x_j] - g_i(x_i) - g_j(x_j) - g_0 \\ \ldots \end{cases} \tag{5}$$

In the above equalities, the univariate functions $g_i(x_i)$ represent the first order effects, namely, the part of the response of $g(x)$ due to the individual variation of x_i. Similarly, the $g_{i,j}(x_i, x_j)$ functions account for the residual interaction between pair of variables; etc. [see (Saltelli et al. 2008)].

If, in addition, we assume that $g(x)$ is square integrable, by the orthogonality of the functions in eq. (5), we obtain the complete ANOVA decomposition of the variance of $g(x)$ (Efron and Stein 1981):

$$V[y] = \sum_{s=1}^{n} \sum_{i_1 < i_2 \ldots < i_s}^{n} V_{i_1,\ldots,i_S}. \tag{6}$$

where

$$\begin{aligned} V &= \int g^2(\boldsymbol{x}) dx - g_0{}^2, \\ V_{i_1,\ldots,i_S} &= \int g^2{}_{i_1,\ldots,i_S}\left(x_{i_1}, x_{i_2}, \ldots, x_{i_s}\right) dx_{i_1} \ldots dx_{i_s}, \end{aligned} \tag{7}$$

Of particular interest are the first and total order sensitivity measures. The first order indices are defined, independently in (Iman and Hora 1990; Sobol' 1993; Wagner 1995):

$$S_i^{FIRST} = \frac{V_i}{V[y]} = \frac{(V[\mathbb{E}(y|x_l)])}{V[y]} \tag{8}$$

They account for expected reduction in variance of the model output when $X_i = x_i$.

We note that if the model output is additive, that is, if $g(\mathbf{x}) = \sum_{j=1}^{k} h_j(x_j)$, where $h_j(x_j)$ is a univariate function of X_j , then

$$\sum_{j=1}^{k} V_j = 1 \tag{9}$$

that is, a model is additive if the sum of the first order sensitivity indices is unity. The total order sensitivity indices are defined by

$$S_i^{TOTAL} = \frac{(\mathbb{E}[V(y|x_{-i})])}{V[y]} \tag{10}$$

with the symbol x_{-i} denoting the fact that all variables are fixed but x_{-i}. S_i^{TOTAL} represents the portion of the variance of the model output contributed by X_i individually and through all its interactions with the remaining model inputs.

The presence of interactions indicates that the model is non-additive, that is, its response is not the direct sum of the effects of the individual model input variations. In that case, the total order sensitivity indices equal the first order indices. Knowledge of the first and total order indices allows analysts to obtain information about a structural feature of the model input output mapping.

One of the key assumptions for eqs. (4), (5), (6), and (7) is that the model inputs are independent random variables. Under correlations, the interpretation of V_i remains as the percentage of model output variance that is reduced when we fix X_i, although this does not correspond anymore to the functional contribution of X_i. If correlations are present, Bedford (Bedford 1998) shows that the variance decomposition loses uniqueness and the value of the sensitivity indices becomes dependent on the lexicographical ordering of the variables. Oakley and O'Hagan (Oakley and O'Hagan 2004) highlight that the tidy correspondence of the functional and variance decompositions is lost. This has led authors to introduce sensitivity measures that, while looking at the entire domain, naturally accommodate correlations among model inputs. We consider here moment-independent (also called distribution-based) sensitivity measures. The key-intuition of distribution-based sensitivity measures is to measure the discrepancy between a) $F_Y(y)$, that represents the degree of belief about Y, and b) $F_{Y|X_i=x_i}(y)$ that represents the degree of belief about Y when we receive information that $X_i = x_i$. Then, one can consider the quantity:

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$$\delta_i = \mathbb{E}[d\left\{F_Y(y), F_{Y|X_i}(y)\right\}] \tag{11}$$

where $d\left\{F_Y(y), F_{Y|X_i}(y)\right\}$ is a chosen separation measurement between the conditional and unconditional model output distribution. $d\{\cdot,\cdot\}$ determines the so-called inner statistic of the global sensitivity measure (Borgonovo et al. 2013).

Depending on the chosen separation measurement, $d\{\cdot,\cdot\}$, one obtains a specific sensitivity measure. For instance, for first order variance-based sensitivity measures, the inner statistics is obtained setting

$$d\left\{F_Y(y), F_{Y|X_i}(y)\right\} = \mathbb{E}[(Y-\mu_Y)^2 \mid X_i = x_i] - \mathbb{E}[(Y-\mu_{Y|X_i})^2 \mid X_i = x_i] \qquad (12)$$

where $\mu_Y, \mu_{Y|X_i}$ are respectively the mean and conditional mean of the model output.

Setting:

$$d\left\{F_Y(y), F_{Y|X_i}(y)\right\} = \frac{1}{2}\int_{\Omega_Y} | f_Y(y) - f_{Y|X_i}(y) | \, dy \qquad (13)$$

And averaging over the marginal distribution of X_i, we obtain the δ^B importance measure (Borgonovo 2007):

$$\delta_i^B = \frac{1}{2}\mathbb{E}\left[\frac{1}{2}\int_{\Omega_Y} | f_Y(y) - f_{Y|X_i}(y) | \, dy\right] \qquad (14)$$

By setting

$$\delta_i^{KS} = \mathbb{E}\left\{\sup_y \left|F_Y(y) - F_{(Y|X_i)}(y)\right|\right\}, \qquad (15)$$

and

$$\delta_i^{KU} = \mathbb{E}\left\{\sup_y \left|F_Y(y) - F_{(Y|X_i)}(y)\right| + \sup_y \left|F_{(Y|X_i)}(y) - F_Y(y)\right|\right\}, \qquad (16)$$

one sensitivity measures that measure separation between cumulative distribution functions using the Kolmogorov-Smirnov and Kuiper metrics. For the interpretations of these measures, we refer to Baucells and Borgonovo (Baucells and Borgonovo 2013). These three sensitivity measures share the following properties: 1) they are well posed in the presence of correlations; 2) they do not depend on a particular moment of the model output distribution; 3) they are normalized between 0 and 1, 4) they are equal to zero if and only if Y is independent of X_i and 5) they are invariant to monotonic transformation of the output. This last property is particularly convenient when estimation is of concern (Borgonovo et al. 2013).

2.3
Estimation and Global Sensitivity Analysis Settings

The computational cost for computing all $V_{i_1,\ldots,i_S}$ in the variance decomposition of eq.

(6) strictly following their definition equals $N^2(2^k - 1)$, with k representing the number of model inputs. This cost makes the calculation rapidly infeasible as N or k increase or when the computational time of the model increases. This cost has been drastically reduced over the last years in a series of works (Homma and Saltelli 1996; Lewandowski et al. 2007; Saltelli 2002; Saltelli et al. 2010). As for estimation, in this work, we use the algorithm in (Saltelli et al. 2010), which enables the estimation of all first and total order indices at a computational cost of $N\left(k+2\right)$ model runs.

However, the fact that all global sensitivity measures rest on a common rational has two implications. The first, conceptual, is that all their properties depend on the inner statistic. The second is practical. They can all be estimated from the same design, because what we need to estimate them are the conditional and unconditional model output distributions. Using the *given data* logic (Lewandowski et al. 2007; Plischke et al. 2013) one obtains all sensitivity measures for individual model inputs at a cost of N model runs, which is the minimal cost within a MC framework. The given data estimation is based on a sequence of partitions of the same dataset and is not related to a specific design. For instance, in our case, we can use the dataset generated for estimating all first and total order indices according to the scheme of (Saltelli et al. 2010) to obtain also distribution-based sensitivity measures.

Finally, we need to conclude this review of global SA with an important methodological concept for sensitivity analysis introduced in (Saltelli and Tarantola 2002; Andrea Saltelli 2002). For a correct result interpretation and communication of sensitivity analysis results, it is recommended to clearly frame up front the sensitivity analysis exercise. In global SA, this is accomplished using the concept of SA-setting (Saltelli and Tarantola 2002; Andrea Saltelli 2002). A setting is a formulation of the SA goal that allows the analyst to frame the sensitivity exercise in order to identify the most suitable techniques to obtain the desired quantitative insights (Anderson et al. 2014; Borgonovo 2010; Saltelli et al. 2008). In the literature, several SA settings have been defined: factor prioritization, factor fixing, model structure and sign of change (Borgonovo 2007; Saltelli et al. 2008). In this work, we discuss the meaningful settings in the context of LCA.

2.4
Uncertainty quantification in LCA: State of the Art

The distinction that the SA community adopts between local and global approaches has not yet become a standard in the LCA community. Nevertheless, a series of methodological papers have formalised the use of uncertainty evaluation and propagation techniques in LCA. These techniques serve in some cases the same goal of local SA and global SA without, however, directly contemplating the use of similar tools or jargon.

Among these quantitative tools, we may distinguish three main complementary numerical approaches that have been proposed in LCA (Heijungs 2010):

- uncertainty or error propagation (Heijungs 1994; Lloyd and Ries 2007) or uncertainty analysis (Heijungs and Kleijn 2001), defined as the systematic study of the propagation of uncertainty from input uncertainties to output uncertainties;

- perturbation analysis (Heijungs and Kleijn 2001; Sakai and Yokoyama 2002), or marginal analysis (Heijungs 1994; Heijungs et al. 1992), oriented at analysing how much small marginal perturbation of the model inputs propagate as smaller or larger deviations of the resulting output;

- key-issues analysis (Heijungs 1996) or uncertainty importance (Heijungs 2010; Mutel, de Baan, and Hellweg 2013), defined as the identification of the most influential input that determine the output uncertainty, on which one should focus research efforts to obtain more accurate results.

Looking at the definition of local SA and global SA (Section 2.2), perturbation analysis corresponds conceptually to a local OFAT approach, while uncertainty importance may be considered as a possible class of global SA. According to data availability and according to the focus that a study has, a combination of these techniques may be used. In combination with these techniques, a MC simulation (Robert and Casella 2010) is usually carried out, either using subjective uncertainty estimates, or using uncertainty estimates gathered from the analysis of data.

In the LCA practice, in the few cases where an explicit reference to SA is done, this refers to the comparison of alternative scenarios built varying a set of model inputs around their mean, or built by comparing results obtained using different input values obtained from the literature for selected model inputs, thus to what has been defined as perturbation or marginal analysis, both of which are formally OFAT approaches (Björklund 2002; Huijbregts et al. 2001). Following the OFAT approach, it is up to the practitioner to decide which model input to change and by which amount (Mutel et al. 2013), which may, in turn, lead to misleading results if the scope of the analysis is assign a measure of importance to the model inputs.

Imbeault-Tétreault and colleagues (Imbeault-Tétreault et al. 2013) analyse the output of the life cycle impact assessment (LCIA) phases, considering log-normally distributed model inputs from the ecoinvent database (Frischknecht et al. 2004). For each considered impact category, the analysis aims at defining the model inputs that are likely to be the most influential on the output. The analysis is defined as *sensitivity*, and corresponds to the definition of alternative scenarios and the calculation of sensitivity coefficients, using an OFAT approach.

Geldermann et al. (Geldermann, Spengler, and Rentz 2000) use a set of sensitivity intervals and weights stemming from the use of multi-criteria decision analysis and the fuzzy outranking technique to conduct SA. In (Lewandowska, Foltynowicz, and Podlesny 2004), changes in input data of ±1% and ±10% are applied and the impact of inputs on the output are calculated based on subjectively-defined qualitative sensitivity indicators (e.g., low sensitivity, very high sensitivity). Ardente and colleagues (Ardente et al. 2008), which state that SA can be applied with arbitrarily selected ranges of variation, perform the analysis on the input data of a study on a solar thermal collector. Based on an investigation of the literature, they define alternative scenarios for the key processes of the life cycle (e.g., alternative electricity consumption scenarios, or transportation scenarios with minimum, average and maximum values).

Zhou and Schoenung (Zhou and Schoenung 2007) define a framework with the application of quality management tools (e.g., process mapping, prioritization matrix) and statistical methods (e.g., multi-attribute analysis, cluster analysis) to study the technology of a computer display. Alternative weighting schemes are used as a basis of a SA, which consist, for each impact category considered in the study, in the tabular comparison of the contribution of each impact category to the total impact. Alternative scenarios are defined as SA also in (Martínez et al. 2010), which present as SA the change in impact scores from the variation of single model inputs in four main phases of the lifecycle of a wind turbine, namely maintenance, manufacturing, dismantling, and recycling. Ranges are selected in the contour of the mean of each model input considered.

In the LCA-model development field, the work of Verones et al. (Verones, Pfister, and Hellweg 2013) use SA for the statistical analysis of regionalized fate factors developed for the evaluation of consumptive water use. Once again the SA corresponds to the identification of alternative scenarios, built varying local characteristics in a defined range (e.g. underlying area, hydraulic properties), and to the comparison of the newly obtained fate factor to those obtained in a base average-case.

In Padey et al. (Padey et al. 2013), we find the first available study which uses global SA, as defined in section 2.2, to identify key model inputs explaining the impact variability of wind power systems over their entire life cycle. This work represents the only documented case of the explicit use of a global SA technique in the field of LCA.

3
Global SA and impact assessment models: a protocol and an application to an LCA noise impact assessment model

3.1
LCA as a complex model: interpretation of techniques currently in use

The LCA framework as defined by the ISO standard (ISO. 2006) may be considered in itself as a complex model, which may be analysed by means of SA. In a specific phase of LCA, the interpretation phase, the models and their results are analysed and interpreted. At this stage, significant issues are identified, also regarding the completeness and the variability of data. The ISO standard on LCA recommends performing a sensitivity check on the data and methods as part of the evaluation of the information that is used in a study (ISO. 2006). The standard does not refer to a particular numerical technique, nor addresses the user to a particular approach or way the data should be perturbed, thus leaving it open to the LCA-study performer to select the appropriate technique and interpret the results.

At different stages of an LCA study, uncertainty may be analysed and propagated. Focusing on the LCI and LCIA phases, one may be interested in understanding the uncertainty that propagates from the inventory to the impact scores, and to understand which of the model inputs are important in determining the uncertainty of the output.

Considering a full set of processes and economic flows which are used in LCA, the output variance could well be the result of the variance of thousands of terms. Uncertainty importance or key issues analysis, as defined in (Heijungs 2010), respond to the impossibility of defining a distribution function for the thousands uncertain model inputs of the equation that should be considered, due simply to a lack of sufficient data. In such case, a global SA as formally defined may not be performed, without running the risk of obtaining unrepresentative results. However, this condition does not hold true for the LCIA phase of LCA, in which the LCIA model-developer typically has a full visibility over the model inputs and the input-output mapping. In such a case, it is possible, by analysing the data at hand (e.g. a deposition map, an elevation map), to identify the distribution for the model inputs and apply a global SA approach. Therefore, for the case of characterisation models it is recommendable to use global SA techniques, which allow to fully evaluating the complex non-linear, non-monotonic models that are used in LCA.

The characterization models and resulting characterisation factors are often a major source of uncertainty for LCA studies (Heijungs et al. 2007). Yet this is a topic that has not attracted sufficient attention from the field of LCA, and especially among model-developers. Together with the evaluation of how to propagate uncertainty in characterisation models, an accurate SA should be conducted and documented. In this study, we focus on the development phase of an impact assessment model and we limit the focus to uncertainty about the way the interaction between technosphere and biosphere has been modelled (Koning et al. 2002). We focus here on how to identify the sources of such uncertainties in the input model inputs, on how to classify them in terms of statistical importance, and on how to apportion the total uncertainty of the output to each of the inputs that are used in characterization models to calculate characterization factors.

3.2 A protocol for the LCIA-global SA of a characterization model

3.3 Global sensitivity analysis settings for characterization models

In this section, we demonstrate the use of global SA to develop and study a characterisation model in LCIA. The protocol here proposed is applicable to all other parts of the LCA framework that require the use of complex non-linear IAMs, as well as to other IAMs used in the environmental sciences. We propose a combination of global SA techniques to be applied in the study of impact assessment models developed for LCIA, with particular attention to the case of newly-developed impact categories.

6

As a starting point for the protocol, let us consider the characterisation model ϑ represented in Figure 1, as part of the impact assessment phase of LCA (ISO. 2006).

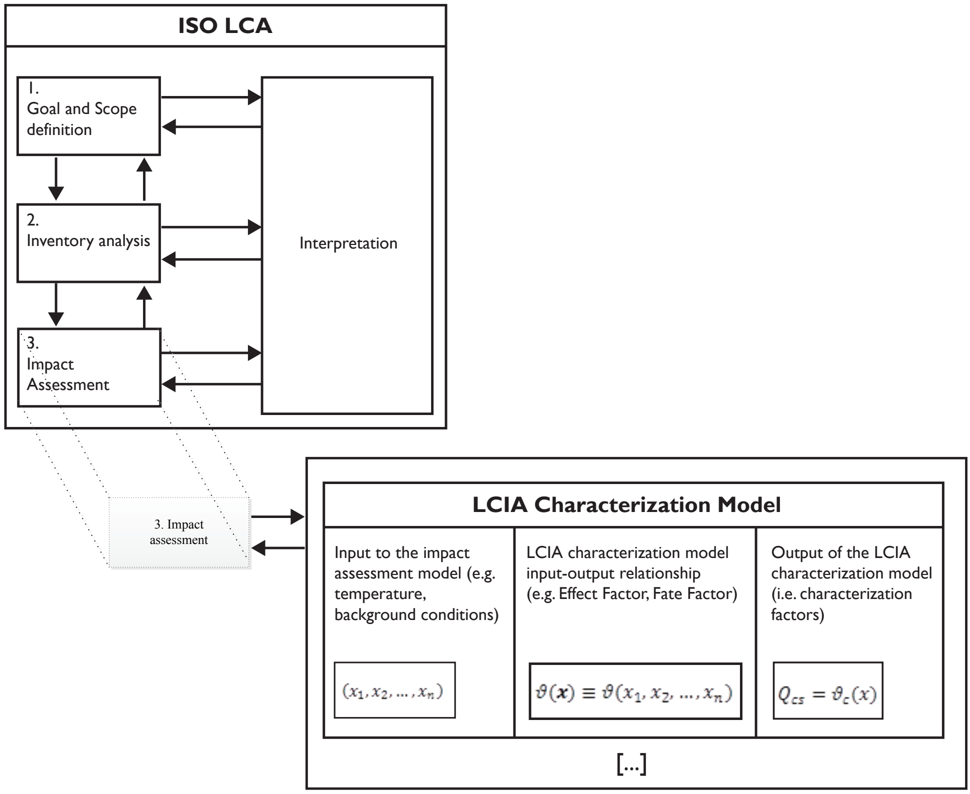

Figure 1. Characterization model in relationship to the LCA framework

The characterisation model is a function of a series of model inputs [e.g. effect factor, fate factor, damage factor; see (Rosenbaum, Margni, and Jolliet 2007)], which are, in turn, dependent on the stressor-specific components that characterise a certain impact category (e.g. temperature, deposition, concentration).

We may define a generic characterisation model for a generic impact category c:

$$Q_{cs} = \vartheta_c(\boldsymbol{x}) \tag{17}$$

where ϑc represents the non-linear function representing the characterization model for impact category c, per stressor s and Q_{cs} is the characterisation factor, which is a function of a variety of model inputs x.

At this stage the LCA analyst may consider a generic ϑ that represents a generic characterisation model, of which one wants to understand the behaviour and study the structure, without any *a priori* physical assumption (Rabitz and Aliş 1999) on the nature of the model input–output relationships. We consider all model inputs that influence the characterization model and are part of its structure. The following steps may be considered as a paradigm of action for any characterisation model in LCIA (see Figure 1).

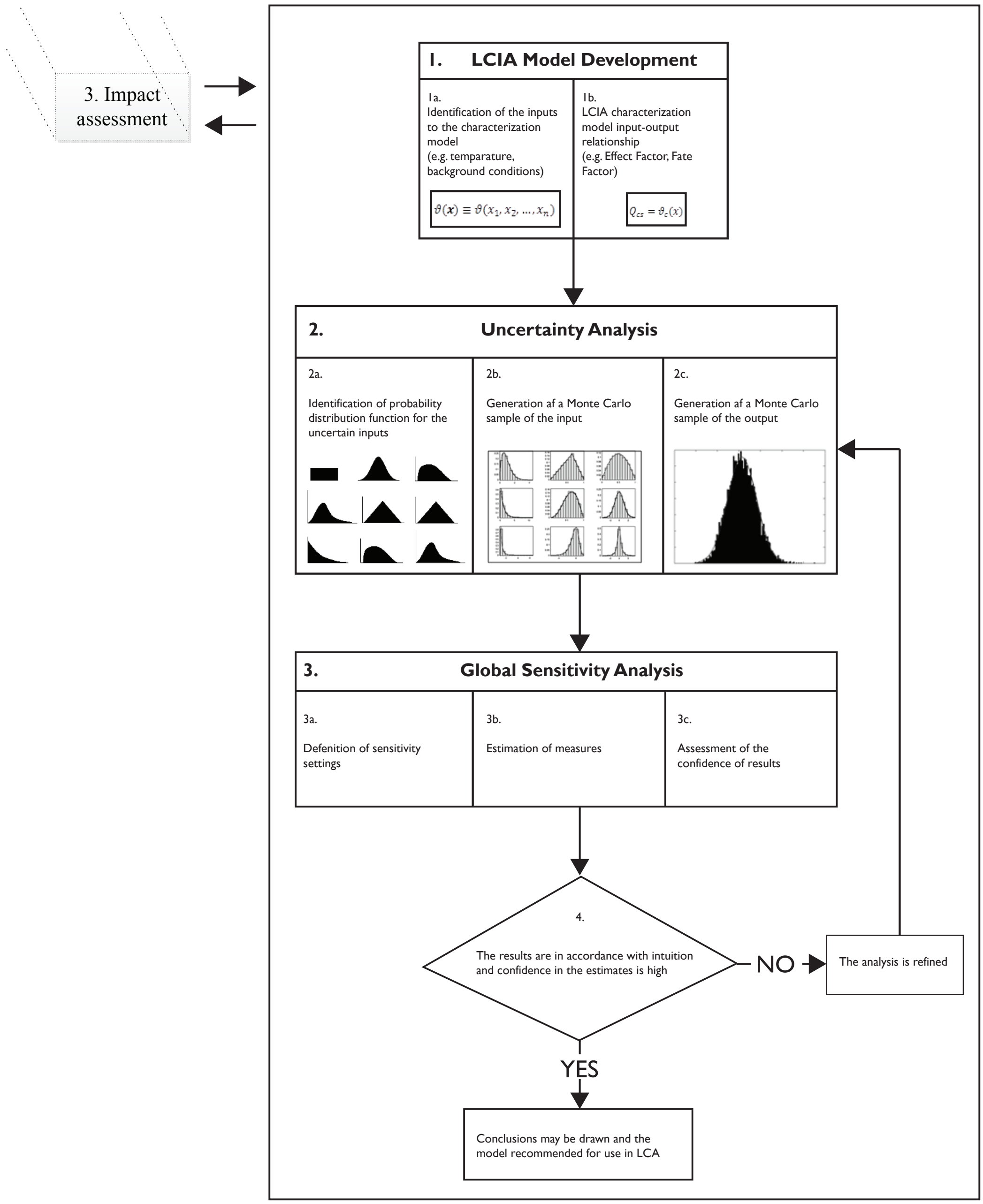

Figure 2. Protocol for the analysis of an LCIA characterization model

6

The protocol in Figure 2 nests model development with uncertainty analysis and global SA. In the model development phase, the LCA analysis identifies the uncertain model inputs (step 1a in Figure 2), and identifies the input-output programming of the LCIA characterization model (1b; i.e. the LCIA model input-output relationships).

Step 2 deals with what is commonly identified as uncertainty analysis (or uncertainty propagation). The analyst identifies the probability distribution functions for the uncertain model inputs (2a). The distributions can be obtained from expert opinions or from available data (which can be collected either in the literature, or from the analysis of spatially-explicit data in GIS collected during the model development exercise). A MC sample of the model inputs is generated (2b). This generation can be obtained using a crude MC generator. However, for a more efficient exploration of the model input space a Latin Hypercube or a quasi-random design is preferred [the reviewer is referred to (Helton and Davis 2002; Owen 1998, 2006; Sobol' et al. 1992) for additional details]. The following step (2c) consists in the evaluation of the model in correspondence of the generated sample to obtain the model output distribution.

In step 3, the analyst establishes the sensitivity analysis settings, that is, she formulates the sensitivity questions and identifies the sensitivity measures for obtaining the consistent answers. If computational time allows, the model can be run according to specific designs to obtain the appropriate sensitivity measures. Otherwise, the dataset generated by MC simulation is post-processed to obtain the required sensitivity measures. Before coming to conclusions and recommendations, it is suggested to assess the confidence in the estimates of the sensitivity measures. This can be done, for instance, using bootstrapping (Archer, Saltelli, and Sobol 1997).

If the results are in accordance with intuition and confidence in the estimates allows, conclusions can be drawn and the model can be given to decision makers and used in LCA (step 4). If not, one needs to repeat the analysis. In the case repetition is due to results not in accordance with intuition, then the analyst needs to establish whether the sensitivity results reveal some hidden phenomenon that was not taken into account or a numerical error is present in the code or in the distribution assignment (in this case, we are in a debugging mode). The remedy is to intervene on the code or on the model input distributions. If the repetition is due to low confidence in the estimates, then the remedy is an analysis at a larger sample size, if computing time permits.

3.4
Application of LCIA-global SA protocol to the noise characterization model

The protocol is here applied to a characterisation model developed for the quantification of the impacts on humans of sound emissions from various classes of sources in a life cycle [noise-model, from now on; (Cucurachi et al. 2012; Cucurachi and Heijungs 2014)]. Cucurachi et al. (Cucurachi et al. 2012) define a theoretical framework for the inclusion of the impacts of noise on humans in LCA studies. In Cucurachi and Heijungs (Cucurachi and Heijungs 2014), the methodology has been operationalized and characterisation factors are provided to be used in LCA studies. In the following, the protocol is applied to the two acceptations of this IAM.

Step 1: Noise-model definition

The noise-model is based on the quantification of the noise impacts of sound emitted by any source operating in a life cycle (Cucurachi et al. 2012). The sound power emitted by a source, or combination thereof, at the emission compartment determines a change in sound pressure at the exposure compartment. A series of conditions intervene to attenuate or propagate the trajectory of sound waves, thus influencing the way the sound emissions are perceived eventually as noise by human targets that are exposed to them. Generic characterisation factors are calculated according to the formula:

$$Q_{cs} = \frac{20}{\sqrt{W_{amb}}} \times Nf \times 10^{\frac{(D-A_{att})}{20}} \times 10^{\frac{(\alpha+\beta)}{20}} \quad (18)$$

6

where W_{amb} represents the environmental sound power at the emission compartment, thus assuming that some sound emissions are already present in the environment, Nf represents the number of targets that are exposed to the sound power, D is a directivity factor that determines the direction of propagation, A_{att} defines a series of attenuations factors that intervene and limit the propagation of sound waves between emitting source and receiver, α is a specific factor related to the frequency of emission, β refers to a penalty added according to the time of the day the emission takes place. Furthermore, A_{att} may be expanded into:

$$A_{att} = A_{div} + A_{atm} + A_{ground} + \ldots A_{other} \quad (19)$$

thus it represents a series of context-specific attenuation factors that are a function of the distance between source and receiver (A_{div}), the atmospheric conditions (A_{atm}), the ground composition (A_{ground}), and any other attenuation that may be relevant to the system under study (A_{other}). For the sake of simplicity, we omit in the characterisation factors formulas the indexes used in LCA to define the compartments of emission and exposure and refer to (Cucurachi et al. 2012; Cucurachi and Heijungs 2014) for more details on the model.

We may consider the complete formula for the calculation of the characterisation factors as the input-output-noise-model to which we want to apply the LCIA-global SA settings, and the model inputs reported below in eqs. (18) and (19) as the uncertain variables that will be analysed (step 1a in Figure 2). We considered two alternative configurations of the noise-model:

- **Simple model**, based on eq. (18), and considering A_{att} as an uncertain model input with a given distribution (see table 1):

$$y_{SM} = \vartheta_{SM}\left(\boldsymbol{x}\right) = f(W_{amb},\ D, A_{att}, Nf,\ \alpha,\ \beta) \tag{20}$$

- **Extended model**, including the expansion of A_{att} to be, in turn, a function of the specific local conditions of e.g. temperature, humidity (see Table IV),

$$y_{EM} = \vartheta_{EM}\left(\boldsymbol{x}\right) = f(W_{amb}, D,\ A_{att}[T, Prs, \mathrm{Rel}Hum, fm, d, G], Nf, \beta) \tag{21}$$

In the extended model, A_{att} is calculated by an iterative process involving a combination of intermediate calculation model inputs and uncertain variables, on which A_{att} depends ($[T, Prs, \mathrm{Rel}Hum, fm, d, G]$; see Table IV). In the simple model the analysis is limited to assigning a probability distribution to A_{att}, based on the a priori knowledge of the model. A series of additional model inputs is introduced, and compared in the analysis with the simple model composition. Model input α (i.e., frequency component) is excluded from the extended model, because it becomes dependent on fm. The two alternative configurations refer to two different times of the process of development of an LCIA model. Respectively, the simple configuration refers to the phase of theoretical definition of the model, the extended configuration to a later phase in which the modeler has already a deeper knowledge of the functioning of the model and more data is available on the variables that are used.

We then proceeded according to the protocol and a computer model was created to encode the input-output mapping for the simple and extended model configurations (step 1b of the protocol in Figure 2).

Step 2: Uncertainty analysis

In order to identify the most-representative distributions for the model inputs (step 2a of the protocol; see Figure 2), the data provided in Cucurachi and Heijungs (Cucurachi and Heijungs 2014) were confronted with data from the noise literature. In Table IV below, the distributions are defined for the input variables for both the simple and the extended configurations. Similar distributions were chosen for variables that appear in both the simple and extended noise-model.

Table IV. Uncertain inputs in the noise-model in the two alternative configurations

Simple model		
Variable		**Probability distribution function**
W_{amb}	Background sound power level [dB]	Lognormal (meanlog=2.3, sdlog=1.09)
D	Directivity component [dB]	Normal (mean=3, standard deviation=1)
A_{att}	Attenuation factors [dB]	Normal (mean=5, standard deviation=1)
Nf	Population level	Lognormal (meanlog=2.3, sdlog=1.09)
α	Perceived frequency model input [dB]	Uniform (min=-26.2,max=2)
β	Penalty for time of the day [dB]	Triangular (0;10;5)
Extended model		
Variable		**Probability distribution function**
W_{amb}	Background sound power level [dB]	Lognormal (meanlog=2.3, sdlog=1.09)
D	Directivity component [dB]	Normal (mean=3, standard deviation=1)
Nf	Population level	Lognormal (meanlog=2.3, sdlog=1.09)
β	Time of the day penalty [dB]	Triangular (0;10;5)
T	Temperature [°C]	Normal (mean=15, standard deviation=5)
Prs	Ambient pressure [Pa]	Uniform (min=2000,max=101325)
$RelHum$	Relative humidity [%]	Uniform (min=10,max=100)
fm	Frequency of the emission [Hz]	Triangular (63;8000;4000)
d	Distance from source to receiver [m]	Lognormal (meanlog=3.9, sdlog=1.09)
G	Ground composition factor	Triangular (0;1;0.5)

Given the low calculation time required by the running of the two configurations of the model a MC sample of N=120000 was selected. Sobol' quasi-random sequences (Bratley and Fox 1988; Sobol 1998, 2001) were used to generate the sample for the uncertain inputs (step 2b). Data was stored and used for the calculation of the two outputs y_{SM} and y_{EM}, according to the defined computational model (step 2c).

Step 3: Global Sensitivity Analysis

The analysis proceeded with definition of the global SA settings (step 3a). The following settings were defined as a basis of the global SA of the noise-model:

1. **LCIA Model Structure:** to determine whether the behaviour of the quantity of interest (model output) is the result of individual effects or of interactions among the model outputs. This goal is reached by estimating first order sensitivity indices and comparing their value to unity (see section 2.2). Possibly, if computing time allows, one can estimate also the total order sensitivity indices or higher order indices.

2. **Factor prioritization:** to determine key uncertainty drivers in the impact assessment model, namely the model outputs on which to put resources to reduce uncertainty. The process can possibly identify those model inputs that can be fixed to a nominal value without the risk of adding extra uncertainty to the model. For the LCIA-global SA of a characterization model, the estimation of the important measures defined in section 2.2 offers a valuable piece of information on the importance of a certain model input in a characterization model.

Based on the settings, we proceeded with estimating the global SA measures presented in section 2.2. As mentioned in section 2.3, first order variance based sensitivity indices and the sensitivity measures δ^{B}, δ^{KS} and δ^{KU} can be estimated from the same MC sample with no additional model evaluations, while a specific design is necessary to estimate total indices. We used the sobol2007 function of the package sensitivity of the software [R] (Cran-R n.d.). The function allows implementing MC estimations of both first- and total-order sensitivity indices simultaneously, at a computational cost of $N(k+2)$ (Saltelli et al. 2010). The same MC sample was used both to estimate the total indices in the required specific design and for the estimation of the sensitivity measures in eqs. (8), (14),(15), and (16).

Setting 1: LCIA Model Structure. In order to study the structure of the model, first and total order indices were calculated for the simple and the extended noise-model. In Table V, the results are reported for both configurations (step 6 of the protocol).

Table V. First order and Total order sensitivity indices [a]

Simple model			
		Analysis of model structure	
Variable		**First Order**	**Total order**
W_{amb}	Background sound power level [dB]	0.021	0.296
D	Directivity component [dB]	0.002	0.047
A_{att}	Attenuation factors [dB]	0.002	0.052
Nf	Population level	0.175	0.858
α	Perceived frequency model input [dB]	0.026	0.183
β	Penalty for time of the day [dB]	0.003	0.062
Extended model			
Variable		**First Order**	**Total order**
W_{amb}	Background sound power level [dB]	0.003	0.422
D	Directivity component [dB]	0.009	0.009
Nf	Population level	0.003	0.932
β	Time of the day penalty [dB]	0.006	0.978
T	Temperature [°C]	0.003	0.003
Prs	Ambient pressure [Pa]	0.003	0.517
$RelHum$	Relative humidity [%]	0.003	0.003
fm	Frequency of the emission [Hz]	0.003	0.261
d	Distance from source to receiver [m]	0.004	0.946
G	Ground composition factor	0.003	0.068

[a] Top contributors in bold

Table V shows that, in the simple model configuration, the highest contributor to the output variance is Nf the population level, which contributes for about 18% of the output variance. The total sum of the first order indices adds up to around 20%, suggesting the presence of strong interactions between model inputs even in the simple model configuration. The results of the total order indices show that Nf explains 85% of the output variance when all interactions with other inputs are considered.

In the extended model configuration, Table V shows that the highest contributors are, respectively, D, β, and d. However, the total sum of the first order indices adds to less than 1%, thus suggesting that interactions strongly influence the model behaviour. Thus, as far as this setting is concerned, we can conclude that the model is non-additive, and interaction effects dominate over individual effects.

We then come to the analysis of the *Key-Uncertainty Drivers*.

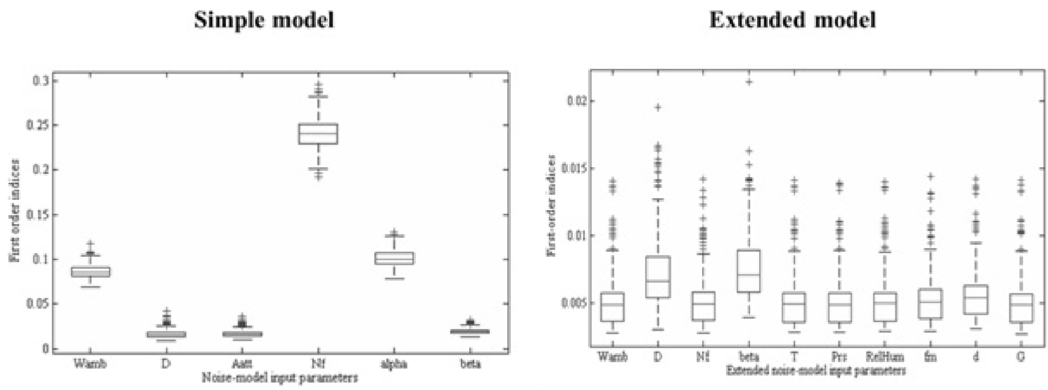

Figure 8. Result of 500 bootstrap runs of the calculation of first order indices for the simple and the extended model

For the model at hand interaction effects strongly influence the model behaviour, limiting the possibility of extracting conclusive information from first order variance-based indices. The total order indices suggest that, for a number of model inputs (in bold in Table V), the contribution to the output variance is almost totally due to interactions. At the same time the extremely low values for model inputs D, T, and $RelHum$ may again suggest a methodological issue in the estimation of variance-based measure in the presence of a multiplicative function. The estimation of first order indices becomes particularly challenging *in the presence of nonlinearities and interaction, e.g., multiplications, between model outputs* [(Borgonovo et al. 2013); p. 3; see also the multiplicative model in (Borgonovo et al. 2013), for which estimation of variance based sensitivity measures results inaccurate].

We then used bootstrapping (Archer et al. 1997) to assess our confidence in the estimates. For the case of the total order indices, such analysis could not be conducted due to the specific design that was used. On the other hand, it was possible to use the generated MC sample to obtain confidence intervals for the first order indices. Figure 3 displays the confidence intervals obtained using 500 bootstrap replicates.

Figure 3 shows that for the simple model we have limited variability in the estimates, and, therefore, we are confident about the ranking obtained with S_i^{FIRST}. Conversely, a great variability is obtained for the calculation of the first order variance-based sensitivity indices for the extended model. This variability should lead an analyst to a diminished confidence in the obtained ranking.

Based on the results of the confidence test and on the considerations above, we used an ensemble of sensitivity measures to reinforce the analysis. As described in section 2.3, from the same dataset used to compute the first and total order indices, it is possible to estimate also the importance measures δ^{B}, δ^{KS} and δ^{KU}. The values are reported in Table VI (step 7 of the LCIA-global SA).

The confidence of the results was tested, once again, by means of bootstrapping. We show the results of 500 bootstrap runs for the δ^{B} importance measure (see Figure 9). For both configurations of the noise-model we have limited variability of the estimates, thus suggesting that the distance-based importance measures are better able to deal with the noise-model interactions.

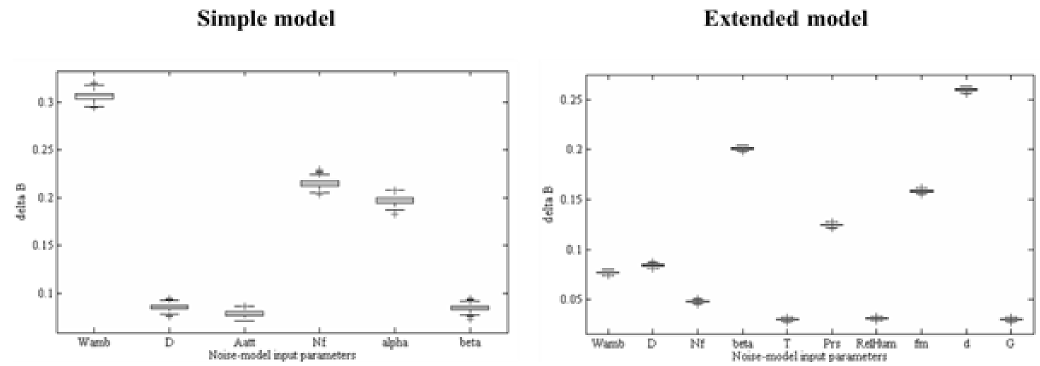

Figure 9. Result of 500 bootstrap runs of the calculation of δ^{B} for the simple and the extended model

In the simple configuration, the most influential factors are Nf (population level) and W_{amb} (background sound power level) according to all of the three distance-based measures used. The importance of W_{amb} had not been spotted by the variance-based indices estimated in section 0. Other model outputs have an intermediate influence on the output. According to distance-based sensitivity measures, the background context of emission is the model input to focus the attention for model development if the attenuations were not considered in the full specification, together with the number of targets that are exposed to a level of sound emissions that may be perceived as noise (Cucurachi et al. 2012).

Table VI. Importance measures for the simple and extended noise-model configurations

Simple model				
Variable		**Importance measure**		
		δ^{B}	δ^{KS}	δ^{KU}
W_{amb}	Background sound power level [dB]	0.29	0.27	0.29
D	Directivity component [dB]	0.13	0.05	0.08
A_{att}	Attenuation factors [dB]	0.12	0.05	0.07
Nf	Population level	0.31	0.29	0.32
α	Perceived frequency model input [dB]	0.17	0.16	0.18
β	Penalty for time of the day [dB]	0.01	0.06	0.08
Extended model				
Variable		**Importance measure**		
		δ^{B}	δ^{KS}	δ^{KU}
W_{amb}	Background sound power level [dB]	0.13	0.04	0.06
D	Directivity component [dB]	0.15	0.11	0.13
Nf	Population level	0.12	0.08	0.09
β	Time of the day penalty [dB]	0.30	0.27	0.29
T	Temperature [°C]	0.15	0.03	0.05
Prs	Ambient pressure [Pa]	0.14	0.12	0.13
$RelHum$	Relative humidity [%]	0.15	0.03	0.05
fm	Frequency of the emission [Hz]	0.20	0.19	0.20
d	Distance from source to receiver [m]	0.22	0.20	0.21
G	Ground composition factor	0.15	0.03	0.05

In the extended configuration, β (time of the day penalty) and d (distance of propagation) become the most influential factors. The importance of β had not been spotted by the first order variance-based indices, but is revealed by the total indices.

The results in Table VI suggest that, if more resources were to be available, a modeller would have to investigate the exact time of the day an emission is taking place, and the exact distance between the source of the sound emission and the receiver/receivers. Such information also provides a way of prioritizing the recording of information at the LCI phase of an LCA study, expanding on the information gathered using the variance-based techniques.

Step 4: Results Evaluation

With these results in mind, following the final decision step 4 of the protocol presented in Figure 2, we decided that the results provide sufficient information to judge the noise-model. It was resolved that no further analyses were needed and that the N selected was suitable to obtain accurate estimates. We turned, then, to the investigation of the extent to which measures agree/disagree in the identification of key uncertainty drivers (Kleijnen and Helton 1999). The inputs for both configurations of the model did not have the same influence with respect to the global sensitivity measures used. The calculation of the correlation coefficient among Savage scores allows us to study the accordance among different rankings [see (Borgonovo, Gatti, and Peccati 2010)]. Such a technique emphasizes the agreement/disagreement for the most important variables and places reduced weight on agreement/disagreement for the variables of low importance [(Kleijnen and Helton 1999); p. 166]. Table VII displays the resulting correlations mong Savage scores are presented.

Table VII. Correlation among Savage scores across global sensitivity measures

Simple model					
	First Order	Total order	δ^{B}	δ^{KS}	δ^{KU}
First Order	1	0.93	0.46	0.51	0.51
Total order	0.93	1	0.68	0.72	0.72
δ^{B}	0.46	0.68	1	0.96	0.96
δ^{KS}	0.51	0.72	0.96	1	1
δ^{KU}	0.51	0.72	0.96	1	1
Extended model					
	First Order	Total order	δ^{B}	δ^{KS}	δ^{KU}
First Order	1	0.68	0.59	0.60	0.62
Total order	0.68	1	0.66	0.73	0.72
δ^{B}	0.59	0.66	1	0.98	0.99
δ^{KS}	0.60	0.73	0.98	1	0.99
δ^{KU}	0.62	0.72	0.99	0.99	1

In the simple configuration of the model, the correlation coefficients suggest that most measures agree with the ranking of inputs. The Savage scores for the measures δ^B, δ^{KS} and δ^{KU} strongly correlate to one another (~1). A lower positive correlation of Savage scores is obtained comparing the measure δ^B with both first and total order indices. For the extended model, the rankings between variance-based and the other importance measures put forward a similar picture. Greater differences are highlighted between the invariant importance measures and the first and total order indices, with δ^B once again presenting the lowest correlation value.

In summary, the calculation of the correlation of Savage scores and the use of bootstrap sampling further helps the LCA modeler to study and understand the developed model, and it is advised as a supporting analysis for the protocol presented in the previous sections. In our case, the analysis shows that the factors W_{amb} and Nf can confidently be considered as the key uncertainty drivers for the simple model, while factors d and β are the key drivers in the extended configuration.

4
Discussion: striving towards improved life cycle assessment models

The LCA community is recognizing the need of improving its methods for the sensitivity and uncertainty analyses of LCA codes. Our work has investigated this issue, unveiling several aspects. First, we have seen that the complexity of LCA models might make it impossible to perform a fully blown global SA at the whole LCA scale, due to its complexity. However, we have seen that global SA is applicable in portions of the evaluation and, in particular, in the crucial LCIA phase, where performing a full-fledged global SA not only becomes possible, but is capable of producing insights for the analyst that would otherwise go lost. The SA measures are responsive to non-linearities in LCIA models, also in the presence of correlated inputs. The ability to capture dependencies among factors and the importance of factors to the output of the model makes the protocol extendable to other phases of LCA, in which input are used to calculate an output. For instance, at the inventory phase the influence of inventory items on the output of a study may be also evaluated taking into account model-structure measures and importance measures.

The protocol proposed here allows extracting information on a model (LCIA or otherwise) directly from the results of a MC simulation, without the need to obtain a specific design. This is advantageous, because most of the software packages that are used to conduct LCA studies already contain MC subroutines* . MC simulation alone, however, does not allow the analyst to identify key drivers of uncertainty, and to understand the structure of the input-output model (Anderson et al. 2014). In this respect, an issue is represented by the need to define a joint distribution function that truly represents the decision-maker's degree of belief about the model inputs. In the context of LCIA model development, modellers typically have sufficient data to define how the model inputs are distributed.

In the preliminary phases of the analysis, global SA can help gathering focus on important factors based on estimates and expert judgement. Later, a complete global SA can be performed when a better coverage of data is available. In our application, we considered two different configurations of the same model that correspond to two model development stages. As noted, even though some inputs had the same distribution function in both configurations, their importance changed.

Finally, a combination of measures is recommended for the identification of key uncertainty drivers. Using an ensemble of sensitivity measures allows an analyst to overcome the limitations of each single method and to obtain a robust ranking of model outputs. Then, an analyst has information about which values is possible to fix in the remainder of the analysis. This is particularly relevant in the context of LCIA modelling, where it is common to use characterisation factors that are often representative of certain average conditions (e.g. a certain geographical location is taken as representative of a wide area). Here, the protocol can guide the modeller in deciding which model inputs could be averaged without affecting the uncertainty of the model. Once the modeller has a clear idea of the structure of the model and of the key input drivers, it is also possible to further evaluate the need to produce geographically-explicit characterisation factors with high level of spatial resolution. For all LCIA models for which only few inputs would be determinant in varying the output, it would be a questionable use of resources to define characterisation factors that are specific to highly-localised conditions. Those model inputs with the largest values of all measures should be prioritized and further analysed and localised.

* *Also, fully-documented computer subroutines are freely available for the most used global sensitivity tools, allowing for a straightforward application of the measures to any context, including that of LCA, without any additional modelling time. For the calculation of sensitivity measures in this article both [R] and Matlab® (MathWorks 2013) subroutines were used.*

5
Conclusions

This article has discussed the use of global SA techniques to increase the trust in LCIA models, thus of LCA as a tool of sustainability assessment. The application of the proposed global SA techniques would increase the confidence of decision makers and users of existing LCIA models, and also of any future developments of novel impact assessment models and characterisation factors. Relying on an ensemble of sensitivity measures, the protocol provides the LCA modeller with a series of powerful tools that increase the validity of the LCA framework, and particularly the transparency of the modelling phase of LCIA characterisation models.

The insights of this work can be extended to all other tools of the environmental, climate change and risk sciences in which complex models are used and where global SA is a key-ingredient to increase model validity and reliability.

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No matter – how? Dealing with matter-less stressors in LCA: the case of noise in wind energy systems

No matter – how?
Dealing with matter-less stressors in LCA: the case of noise in wind energy systems

Based on:
Stefano Cucurachi, Coen C. van der Giesen, Reinout Heijungs, Geert R. de Snoo, *Journal of Industrial Ecology.* Submitted.

Summary
The portfolio of impacts that are quantified in Life Cycle Assessment (LCA) has grown to include rather different stressors that require complex models. Some of these are still in a seminal phase of development, and have not yet been included in any LCA study. This the case for sound emissions and noise impacts, which have been the result of recent modelling that expands the scope of the existing noise impact assessment models in LCA. Sound emissions are a rather specific type of emissions that are matter-less, time-dependent and bound to the physical properties of waves. The way sound emissions and the relative noise impacts are modelled in LCA are paradigmatic for the way new or existing matter-less impacts can be dealt with. In this study, we analyse, through sound emissions, the specific features of other matter-less impacts that do not stem from the use of a kg of matter, nor are related to the emission of a kg of matter. We take as a case study the production of energy by means of wind turbines, contradicting the credo that windmills have no emissions during use. We show how to account for sound emissions in the Life Cycle Inventory (LCI) phase of the life cycle of a wind turbine, and then calculate the relative impacts using a noise Life Cycle Impact Assessment (LCIA) model.

Keywords
LCA; LCIA; LCI; wind turbine; matter-less stressors

1
Introduction

The list of impacts recommended back in 1992 by the report of Heijungs et al. (1992a, 1992b) has remained fairly constant over the years. However, discussions have always taken place on the best set of possible impacts to be considered in the Life Cycle Impact Assessment (LCIA) phase, with impact assessment methods under different methodological and conceptual assumptions being developed by several research groups around the globe (Bare 2010). The landmark ISO14040 series (ISO 2006) proposed standard principles, procedures and requirements for the LCA framework. The availability of such standard increased the methodological robustness of LCA, defining the criteria, according to which most of the later contributions and studies tried to adhere. Nevertheless, the standard did not provide a shortlist of impacts to use, but recommended impact categories and characterization models to be based on an international agreement or approved by an international institution (ISO, 2006). The LCA community has been trying in the last years to reach a consensus of best practices and best impact assessment models. According to Huijbregts (2013), the quest for a consensus entered a new phase with the ILCD report on recommended practice for life cycle impact assessment methods in a European context (Joint Research Centre 2011; Hauschild et al. 2013).

The European Commission tried, in fact, to define the best practice in the LCA scientific domain from a conceptual and methodological point of view (EC-JRC 2010a, 2010b, 2011). A total of 91 characterization models were short-listed and recommended as best practice within their impact categories, according to criteria such as scientific quality and applicability (Hauschild et al. 2013). Furthermore, the absence of other classes of impacts was indicated as one of the shortcomings of the current LCA framework (EC-JRC, 2011), since it may restrict the efficacy of LCA to act as a comprehensive environmental decision support tool. However, it has been claimed that not all impacts should be included in LCA (see e.g. Udo de Haes 2006), though as claimed by the ILDC handbook "an open mind" should be kept towards emerging impacts. Some impacts have high priority on the list, because they are related to emerging technologies (such as nano-materials), which will eventually penetrate the market, thus increasing the size of the related impacts and the number of humans and ecosystems exposed to them. The absence of certain impact categories may be due to the necessity of dealing with unusual LCI and LCIA methodologies.

Some of the impacts that should be developed in LCA or for which the modelling effort of developers should be increased regard matter-less impacts, thus impacts that are not related to the release of a quantity of matter. The case of noise (see Cucurachi et al. 2012 and Cucurachi and Heijungs 2014) is used in this study as a model-type to illustrate how to deal with matter-less emissions and impacts. We discuss, through the example of sound emissions and noise impacts, the specificities of emerging matter-less impacts that are relevant also for emerging technologies and their assessment.

We analyze the case of wind turbines to test the applicability of the noise-impact method and to further understand the importance of the analysis of emerging impacts in the field of LCA. While existing LCA studies show that only upstream processes in their life cycle contribute the most to emissions and impacts (see e.g. Dolan and Heath 2012), we show that it is now possible to quantify the noise impacts of wind turbines during their operation and during other phases of their life cycle phases that emit sound. The operation of this type of systems produces emissions that are not related to a release of matter, but do have, just like e.g. toxic emissions, an impact on the population living in the area surrounding a turbine.

2
The input, the output and the necessity for a shift of paradigm
2.1
Matter-less impacts

At the basis of LCA the assumption holds that only activities that are related to and affected by a functional unit should be included in the LCI, and then in the LCIA (Rugani et al. 2012). Originally, only impacts (and activities) related to physical extractions and emissions, thus to material inputs and outputs from a product system were modelled in LCA (Udo de Haes et al. 2004). During the last decade, however, researchers expanded the boundaries of LCA, allowing also other impacts to be included also in the cases in which the relationship to a functional unit is not mediated by the extraction/emission pattern.

A number of stressors (i.e. pressure on the environment) that are included or recommended for inclusion in the LCA framework are not substance-induced, nor directly related to emissions and physical exchanges of matter with the environment. Stressors such as noise or light pollution correspond to a matter-less emission, which cannot be directly taken in by e.g. respiration or food consumption. In particular, we define here as matter-less stressors those that are not related to a release of a certain quantity of matter (e.g. kg of carbon dioxide). Moreover, the damage such stressors determine involves a mix of physiological and psychological conditions of exposure that make their analysis rather specific. The process of modelling of such matter-less impacts has not developed as fast as that of the traditional substance-induced impact categories.

The reasons behind this slower pace of development reside in the difficulty of modelling the stressors in a way that accommodates the computational structure of LCA (see Heijungs and Suh, 2002), or in the level of knowledge of the mechanisms that determine their impacts (see Cucurachi et al. 2014).

Examples of matter-less stressors, for which methodological attempts have already been made, include land-use (Milá i Canals et al. 2012; de Baan et al. 2013; Brandão and Milá i Canals 2013), noise (Althaus 2009a,b; Cucurachi et al. 2012; Cucurachi and Heijungs 2014) and thermal pollution (Verones et al. 2010). In other cases, matter-less impacts have been related to the exchange of a certain quantity of matter between the ecosphere and the biosphere. This is the case of the introduction of exotic species by means of freight transport of goods in Hanafiah et al.(2013), and the impacts of ionizing radiation due to the release of radioactive substances in Frischknecht et al. (2000).

Though the modelling assumptions behind each model are different, general considerations can guide future developments of new models for those categories that are still outside LCA, and for the improvement and adaptation to the specific structure of LCA of models that have already been tackled by modelers. Such considerations will be further clarified in the case study of a wind turbine.

2.2
The inventory analysis and the relationship to a functional unit

In LCA, the study of a life cycle of a product system scales all inputs to the functional unit that best represent the goal and scope of the system under analysis. The usual way to proceed in the Life Cycle Inventory analysis (LCI) phase is to detail the conversion of inputs (e.g. products, waste, and resources) into outputs (e.g. products, waste, residuals to the environment; Curran 2012). Practitioners have matured a great deal of experience in treating emissions that are related to the release of a quantity of matter, or, alternatively, to the depletion of a certain quantity of a natural resource. However, for some unit processes and/or stressors, the relationship between inputs and outputs is not immediately paramount. We show that, in some cases, before an emission can be recorded in the inventory table it is necessary to define a further emission-specific conversion factor that allows for similar emissions across the life cycle to be compared. The necessity of adding extra steps to the already complicated and time-consuming LCI phase is particularly relevant for the case of matter-less impact categories.

In general, the LCI phase deals with the representation of the relationship between flows of inputs and outputs and unit processes. Using a simple representation one could describe a unit process as in Figure 1:

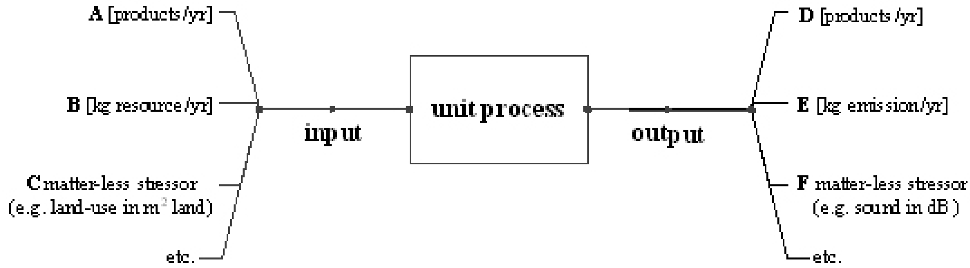

Figure 1. Inputs and outputs of a unit process in the LCI phase. The flows are here including a "per year" property, in contrast to the usual LCA practice where the flows are written as amounts ("kg", "product", etc.).

If we follow the notation introduced in Figure 1, to express all resource inputs and emissions per unit of product the process must be multiplied by a scaling factor $1/D$. Mind that this scaling factor has the dimension of time. It can be interpreted as the time it takes for the unit process operating at full production volume to produce 1 unit of product (Heijungs and Suh 2002). The resource input then becomes $B\times 1/D$ and the emission $E\times 1/D$. These results are in kg. For the case of C, and considering as in the example a land-use input, we would proceed by calculating $C\times 1/D$, thus with the dimension m² $\times$ yr (Brandão and Milá i Canals 2013). So far, this works fine, because products, mass and area are aggregatable quantities. Let us consider a matter-less output, see e.g. F in Figure 1. If we consider the example of sound, the output is typically expressed in dB, which, in contrast, may not be aggregated by simple addition. Thus, the non-linear dB is inconvenient for the purely linear aggregations and additions that are common in LCA. It should be first converted into an energy unit (the Joule) to be aggregatable. The amount of sound, thus, becomesg$(F)\times 1/D$, where $g(F)$ is a transformation function (Cucurachi et al. 2012; Cucurachi and Heijungs 2014). This result is in $W \times yr$, which corresponds to J.

The crucial element of this whole discussion is in the function g, which transforms a non-material elementary flow that is non-aggregatable into an aggregatable one. The transformation function g is defined according to the local conditions of the system under study and to the specific properties (i.e. physical or otherwise) of the matter-less emission under consideration. Several local parameters (e.g. production rate of a system, speed of a vehicle) may be needed according to the type of matter-less emission under consideration. This counts also for emissions related to electromagnetic or light emissions, which are associated through the physics of waves with the transportation of energy, but not with that of matter (see Georgi and French 2007 for a detailed analysis of the physics of waves).

2.3
Life Cycle Impact Assessment

Once the LCI phase is concluded, if enough information has been stored in the LCI, a modeler dealing with the definition of a suitable impact assessment model for a matter-less stressor would have to take into account in the modelling process a series of emission-specific properties, and solve all potential non-linearities. The impact score for that specific impact category under consideration would be obtained simply by multiplying it by the relative inventory item. For some matter-less impacts that are highly localized (e.g., that depend on population density or the ambient pH), time-specific (e.g., that depend on the time of the day or the year), property-specific (e.g. that depend on the frequency or polarization) a system of characterization factors may be needed to represent all possible conditions of fate, effect, exposure, and damage. 3

The life cycle of a wind turbine

In the previous sections we have dealt with the specific considerations needed to include matter-less stressors in LCA. In the following, the example of the life cycle of wind turbines is considered to show a practical example of how the matter-less sound emissions may be accounted for in LCA.

3.1
Wind energy, wind turbines and their impacts in LCA

Wind turbines are classified as promising "sustainable" energy sources for our energy supply portfolio, and have become one of the most often cited source of electricity generation to address e.g. climate change issues (Doblinger and Soppe 2013; GWEC 2013). With the exception of direct solar heat and light, wind energy is believed to have the least adverse environmental impacts of all renewable energy technologies (Tabassum-Abbasi et al. 2014). Though these features of wind power are promising, the use of kinetic energy for the production of power does not come free of impacts.

Within the field of LCA, Dolan and Heath (2012) identified 240 LCA studies that have investigated the environmental impacts of electricity from onshore and offshore wind farms. To our knowledge, none of these studies accounted for the impacts of wind turbines in the use-phase of their life cycle, apart from the impacts related to the maintenance and lubrication of components, which assumes that wind turbines do not have any direct measurable environmental impact related to their operation. However, a variety of potential environmental effects have been related to wind turbines. These include noise, electromagnetic interference, visual impacts, impacts on wildlife, and, the more recently investigated, impacts on local weather and surface temperature (Boyle 2004; Walsh-Thomas et al. 2012; Zhou et al. 2012; Tabassum-Abbasi 2014; Vautard et al. 2014).

The current list of stressors covered by existing impact assessment methods keeps the aforementioned impacts, related to the use-phase of wind turbines, outside the study of their life cycle. However, for the case of the noise impacts, recent developments in LCIA allow to deal with sound emissions related to any sound emitting source, including static sources (e.g. a wind turbine), and mobile sources (e.g. transportation means) in all life cycle stages (Cucurachi et al. 2012; Cucurachi and Heijungs 2014). Noise has not been considered in any LCA study on wind turbine, though it is admittedly the most claimed issue related to the setting up of a wind farm (Tabassum-Abbasi 2014). The life cycle of a wind turbine provides a perfect opportunity to hold the model of Cucurachi and Heijungs (2014) to the test.

3.2
Goal and scope of the study

The goal of the current study is to evaluate the impacts of sound emissions from resource extraction to operation next to commonly measured impacts. We complement the inventory of the recent study by Caduff et al. (2013) with inventory data regarding the emission of sound and with the background data provided by the ecoinvent database version 2.2 (Frischknecht et al. 2005). A variety of wind turbine configurations are compared to show how prone to variability sound emissions and impacts are, depending on the local conditions under study. The LCA software CMLCA version 5.2 (Heijungs 2013) was used to model the different configurations and perform the analysis and calculations.

3.3
System definition and relationship to the functional unit

The model defined by Caduff and co-authors (2013) uses scaling and size equations to identify the relationship between a certain configuration of wind turbine and the elementary flows (e.g. used materials and assembly of a component of the generator). Basic wind power equations are used to calculate the produced electricity per year (i.e. in kWh/year) at different nominal powers and similar hub heights and diameters. A functional unit of 1 kWh was selected.

In the current study, we adopt a similar system definition as in Caduff et al. (2013) and include in the analysis the following phases of the life cycle: resource extraction, material manufacturing and processing, production of the components, transport to the erection site, turbine maintenance and disposal, and turbine operation (see Figure 2 below).

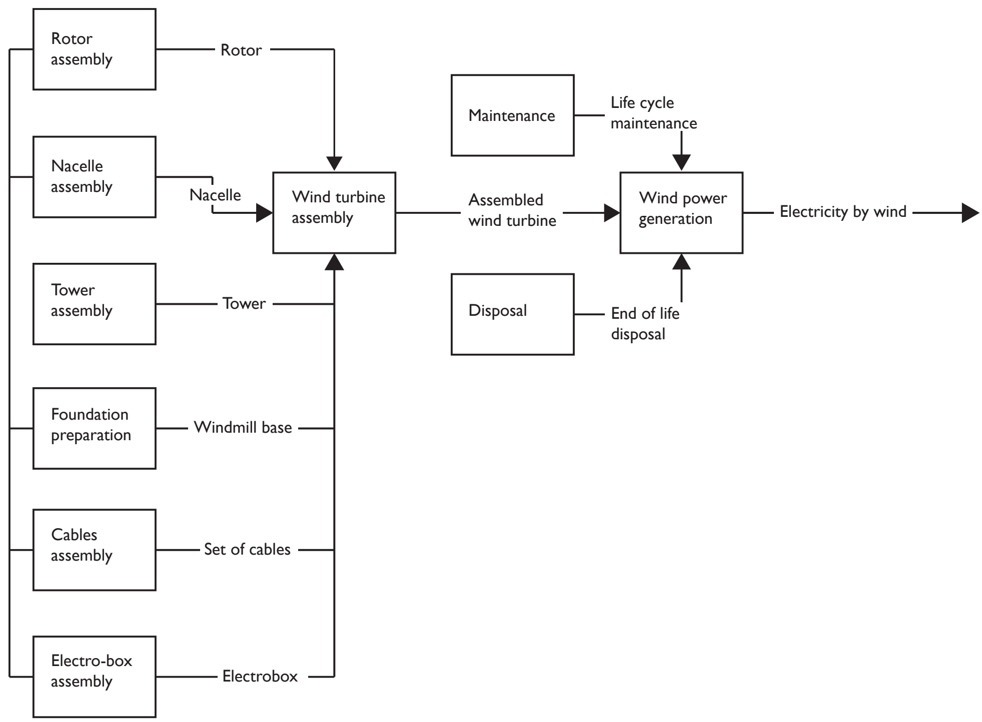

Figure 2. System flowchart: definition of elementary flows and input/output relationships. Boxes represent processes, arrows represent products.

Due to lack of specific data, we excluded from the analysis the energy for the assembly of components and for the decommissioning of the wind turbine (see Caduff et al. 2013). Inventory data for resource extraction, transportation of components, material manufacturing, disposal and land use was associated to each of the components of the wind turbine (i.e. rotor, nacelle, tower, foundation, cables, electro-box) according to the indication of Caduff et al. (2013).

In this study, we selected a number of representative configurations based on the availability of sound emissions data for models of wind turbines analyzed in Caduff et al. (2013). Different local conditions were defined in order to stress the influence on sound emissions of different local conditions of wind speeds and revolutions per minute (RpM), also for systems with the same nominal power, but different hub heights and diameters. The defined configurations are reported in Table 1 and were used to calculate the total potentially produced electricity following the engineering approach detailed in Caduff et al. (2013).

The sound power is the amount of sound energy a source emits, by converting a different kind of energy (e.g. mechanical) into sound energy, with the loudness of the sound depending on how rapidly such a conversion takes places (see Blackstock 2000 for a thorough study). Therefore, sound power is a measure of the sound energy produced versus time, thus it has units of Joules per second, i.e. Watt. The sound power level of a source is expressed in decibels (dB) relative to a reference sound power of 1 picowatt (i.e. 10-12 Watt). We obtained sound power levels from the study of Zanetta (2008), in which sound power levels are provided for a variety of configurations of wind turbine.

Table 1. Configurations of wind turbine considered in this study. Local and technical specifications determine the effective electricity produced by each system.

Configuration	Nominal Power [a] [kW]	Wind speed [m/s]	Diameter [m]	Revolutions per minute [1/min]	Hub height [m]	Produced electricity per year [kWh/yr][b]
[A1]	500	8	37	30	56	6.25E+06
[A2]	500	8	40.3	38	65	1.02E+07
[A3]	500	10	40.3	38	65	8.16E+06
[A4]	600	8	44	34.5	78	1.74E+07
[A5]	600	9.5	44	34.5	65	1.22E+07
[A6]	600	8	44	34.5	65	1.45E+07
[A7]	600	8	46	25	56	1.49E+07
[A8]	600	9.5	46	25	56	1.26E+07
[A9]	600	8	42	28.2	56	1.04E+07
[A10]	600	8	48	23	56	1.77E+07
[A11]	800	5	48	29.5	56	2.83E+07
[A12]	800	6	48	29.5	56	2.36E+07
[A13]	800	7	48	29.5	56	2.02E+07
[A14]	800	8	48	29.5	56	1.77E+07
[A15]	800	9	48	29.5	56	1.57E+07
[A16]	800	10	48	29.5	56	1.42E+07
[A17]	1500	10	70	19	65	7.43E+07
[A18]	1500	8	66	22	67	7.57E+07
[A19]	1500	10	70.5	20	65	7.64E+07
[A20]	1500	8	70.5	20	65	9.56E+07
[A21]	1500	8	77	18	100	2.09E+08
[A22]	1500	10	70	19	65	7.43E+07

[A23]	1500	9	70.5	20	56	7.32E+07
[A24]	1500	8	70.5	20	65	9.56E+07
[A25]	1500	8	77	18	56	1.17E+08
[A26]	1500	8.4	77	18	56	1.12E+08
[A27]	1500	10	70	19	65	7.43E+07
[A28]	1500	8	64	17.3	80	7.99E+07
[A29]	1500	8	72	17.3	64	1.02E+08
[A30]	1500	7.7	82	14.4	93.6	2.62E+08
[A31]	1500	8.3	70	19	114	1.57E+08
[A32]	1500	10	70	19	56	6.40E+07
[A33]	1650	8	82	14.4	93.6	2.52E+08
[A34]	2000	6	71	20	64	1.29E+08
[A35]	2000	8	71	20	64	9.68E+07
[A36]	2000	9	71	20	64	8.60E+07
[A37]	2000	10	71	20	64	7.74E+07
[A38]	2000	6	82	19	85	3.05E+08
[A39]	2000	7	82	19	85	2.61E+08
[A40]	2000	8	82	19	85	2.29E+08
[A41]	2000	7	82	17.1	80	2.46E+08
[A42]	2000	7.6	92.5	15	80	3.67E+08
[A43]	3000	8	104	15.3	56	3.90E+08

[a] The nominal power indicates maximum power that can be safely dissipated by the wind turbine.

[b] The output electricity produced by the wind turbine is calculated based on the engineering equations reported in Caduff et al. (2013).

3.4 Process data and assumptions

Given the emphasis of the current study on introducing sound emissions and noise impacts in a LCA study, we focus on adding inventory data relating to sound to the existing life cycle inventory from Caduff and co-authors (2013) rather than refining its existing LCI data. We use the modelling principles reported in the main body and supplementary information to that study to define the configurations of interest reported in Table 1. The analysis of the use-phase of all the 43 configurations of wind turbine was complemented in the current study with their relative sound emissions.

Based on the investigation of the specialist literature we consider that each system has a sufficient amount of wind to operate for 30% of the time (see e.g. Boccard 2009, 2010), thus only for a fraction of the 8760 hours considered in Caduff et al. (2013). The matter of the influence of the capacity factor on the results of LCA studies of wind turbines is discussed with detail in Arvesen and Hertwich (2012). The assumption relates to an onshore site with good wind availability, considering that the average capacity factor (i.e. long-term wind intensity) for Europe is currently of ~22% (Boccard 2010). Further assumptions related to the physical relationships (e.g. efficiency factors and losses) between engineering parameters and the inventories were maintained.

3.4.1
Inventory of sound emissions

Across several phases of any life cycle it is possible to attribute sound emissions to processes, based on the time each unit process is working to obtain the desired output. In the life cycle of each wind turbine, data availability allowed to associate sound emissions to the following processes in the life cycle: transportation of components by freight train and by lorry, transportation by passenger car of a technician to maintain the turbine, excavation of the foundations of the wind turbine, and actual operation of the system.

As recommended in Cucurachi and Heijungs (2014), we collected for each of the relevant sound-emitting phases of the wind turbine life cycle the respective sound power levels. Sound power levels were differentiated where possible in octave bands and expressed in the logarithmic decibel scale. In order to obtain a sound energy in joule, the following transformation function was applied (Cucurachi et al. 2012):

$$m = \left(10^{-12} \times 10^{\frac{Lw}{10}} \right) \times t \quad (1)$$

where m represents the sound energy in Joule to be inventoried at the LCI stage, Lw represents the sound power level in decibel, and t represents the time in second in which a certain process is working for the output under study (thus implicitly for the functional unit) at a certain time of the day and location. Emissions are recorded at a specific center-frequency band, time of the day, and location. The sound power level Lw depends only on the center-frequency band and does not change according to the time of the day and location. The time t is calculated based on the input/output rate of production of the process under study and varies per time of the day and location. The factor 10^{12} has a unit of Watt.

Transportation

At different phases during the life cycle of a wind turbine a variety of basic components need to be transported e.g. from the production site to the assembly site. This study included transportation by freight train, lorry and passenger vehicle. Sound power levels for each transportation mode were calculated using the indication of the reference report on Common Noise Assessment Methods in Europe and attributed to the transportation modes used in the study (CNOSSOS-EU; Kephalopoulos et al. 2012).

Transport demands from Caduff et al. and ecoinvent were used. The process of transportation of goods has in the ecoinvent database the unit of tonne-kilometer (tkm) or person-km (pkm), which represents the transport of one tonne of goods/person by a given transport mode over a distance of one kilometer. For each of the different transport modes different assumptions and calculations were necessary to associate to a tkm/pkm the relative time t necessary to transport a certain good/person for the functional unit under analysis (i.e. 1 kWh). Details of the calculations are reported in the Supporting Information. All the calculated values of sound energy in joule were associated as environmental extensions to the operation of each transportation mode in CMLCA.

Excavation of foundations

In the process of excavation of the foundation work for the wind turbine, the time to calculate corresponds to the time necessary for a hydraulic digger to excavate the material for the foundation. The process of excavation by hydraulic digger was selected from the ecoinvent database. The sound power level for the hydraulic excavator was defined according to the council directive 2005/88/EC of the European Commission (EU 2005) and represents the permitted maximum allowed sound power level for excavator loaders. A combined sound energy of 9.064×10^{-01} J/m^3 was calculated and associated in CMLCA to the environmental extensions related to the excavation process.

Use-phase of the wind turbine

During the use-phase in the life cycle of a wind turbine, sound is emitted by the functioning of the mechanical components (e.g. yaw motors), and by the aerodynamic flow of air around the blades and tower (Pedersen and Waye, 2004). The dominant component is usually in the range of 500 to 1000 Hz, and, while the mechanical sound emissions have been over the years curbed by manufacturers, aerodynamic sound emissions determining a "whooshing" sound are highly variable and dependent upon the technical features of the wind turbine and upon the local atmospheric conditions (e.g. wind speed, RpM). Both the mechanical and aerodynamic specifications contribute to the sound power levels reached by the wind turbine (Pedersen and Waye 2004).

We selected the 43 configurations reported in Table 1. For the configuration of 3000 MW (i.e. identified with number 43 in Table 1) we assumed similar sound power levels as for the 3600 MW configuration reported in Zanetta (2008). In order to measure the time necessary for the wind turbine to produce 1 kWh, the total produced electricity over the 20 years lifetime of the wind turbine was calculated for each configuration. Time in seconds per 1 kWh was then obtained, and the respective sound energy per octave-band center frequency were recorded as environmental extensions of each wind turbine during the use-phase (see Supporting Information). Sound energy values were recorded at an unspecified time of the day and unspecified location.

Inventory of other elementary flows

Other processes in the life cycle were selected from ecoinvent based on the indications in Caduff et al. Calculations are reported in the Supporting Information. A lifetime of 20 years was assumed for all components of the wind turbine: nacelle, rotor, tower, foundation, cables and electronic box. The total electricity produced per year, and per lifetime of the generator was calculated using standard equations of wind power systems (see Caduff et al. 2013; Table 1, page 4727).3.5

Characterization of the inventory

The latest update of CML-IA database of midpoint characterization methods was considered (Van Oers 2013). Inventory data was characterized (ISO, 2006) using the CML-IA characterization factors. We complemented the CML-IA method with the noise impact assessment method for the quantification of the impacts of noise on humans and characterization factors as provided by Cucurachi and Heijungs (2014), which means a list of characterization factors to characterize sound emitted at specific frequency bands, time of the day and locations. In this study, we used the characterization factors needed to characterize the sound inventoried according to the definition earlier reported. It was not possible to define at the time of the analysis a specific country of installation of the wind turbine, therefore only archetypical locations of emissions (and exposure) were considered. Other inventory items were characterized according to the CML-IA list. 4

Results

4.1

Analysis of noise impacts on humans

The noise results after characterization are expressed in units of *person × pascal × second,* and indicate at the midpoint level the amount of sound pressure each person exposed to a certain sound power would receive per second, integrated over the full life cycle. The results links, according to the traditional ISO 14044 characterization scheme (ISO, 2006), the inventory item $m_{i,c,f}$ specified at the inventory stage with the specific characterization factors $CF_{i,c,f.}$ The subscripts i, c, and f represent, respectively, the center-frequency band, time of the day, and location of emission.

Thus, the human-noise impact (HN) was obtained by:

$$HN = \sum_i \sum_c \sum_f m_{i,c,f} \times CF_{i,c,f} \quad (2)$$

where HN is the impact of noise on humans, per frequency band i, per time of the day c, and location *f*. The resulting human-noise impacts ranged between 18600 and 55500 *person* × *Pascal* × *second*, respectively the total noise impact values for configuration [A37] and [A10] (see Figure 3 below). The lowest score was obtained for the configuration at a nominal power of 2000 kW, with a wind speed of 10 m/s, a diameter of blades of 71 m, a height of the hub of 64 m and a total speed of 20 RpM. Conversely, the highest score was obtained for the wind turbine with a nominal power of 600 kW, a wind speed of 8 m/s, speed of 25 RpM, a height of the hub of 56 m, and a diameter of the wind turbine of 48 m.

The results do not suggest a clear pattern that links the noise impacts to specific values of nominal power, hub heights RpM or size of the blades. The calculation of the Pearson correlation coefficient between noise impacts and the remaining set of parameters did not highlight any strong correlation for the data representing the 43 configurations.. The correlation between the noise impacts and the time necessary for a certain configuration to obtain 1 kWh of wind electricity resulted in a value of 0.53, thus a lower total time determined in general lower noise impacts. The measure of time typically provides a combined measure of the efficiency of the combination of configuration-parameters in producing a functional unit.

The analysis of the structure of the wind turbine life cycle and the relative contributions in CMLCA allowed identifying the most relevant processes in contributing to the noise impacts for each configuration. In all cases, the results indicate that the operation phase contributes the most to the impacts of noise to produce a functional unit of 1 kWh of energy (see Figure 3 below). The transportation of components by freight train and by lorry contributed for the remaining of the impacts for all configurations. The combined contribution of transportation determined 50% of the overall impact for configuration [A11]. Frequencies in the lower range of the spectrum contributed to the total noise impact, particularly those between 250 and 1000 Hz, with the highest contributions (in the range 6-38%) determined by sound emitted at 500 Hz. This finding is in line with the typical spectrum of sound emitted by wind turbines.

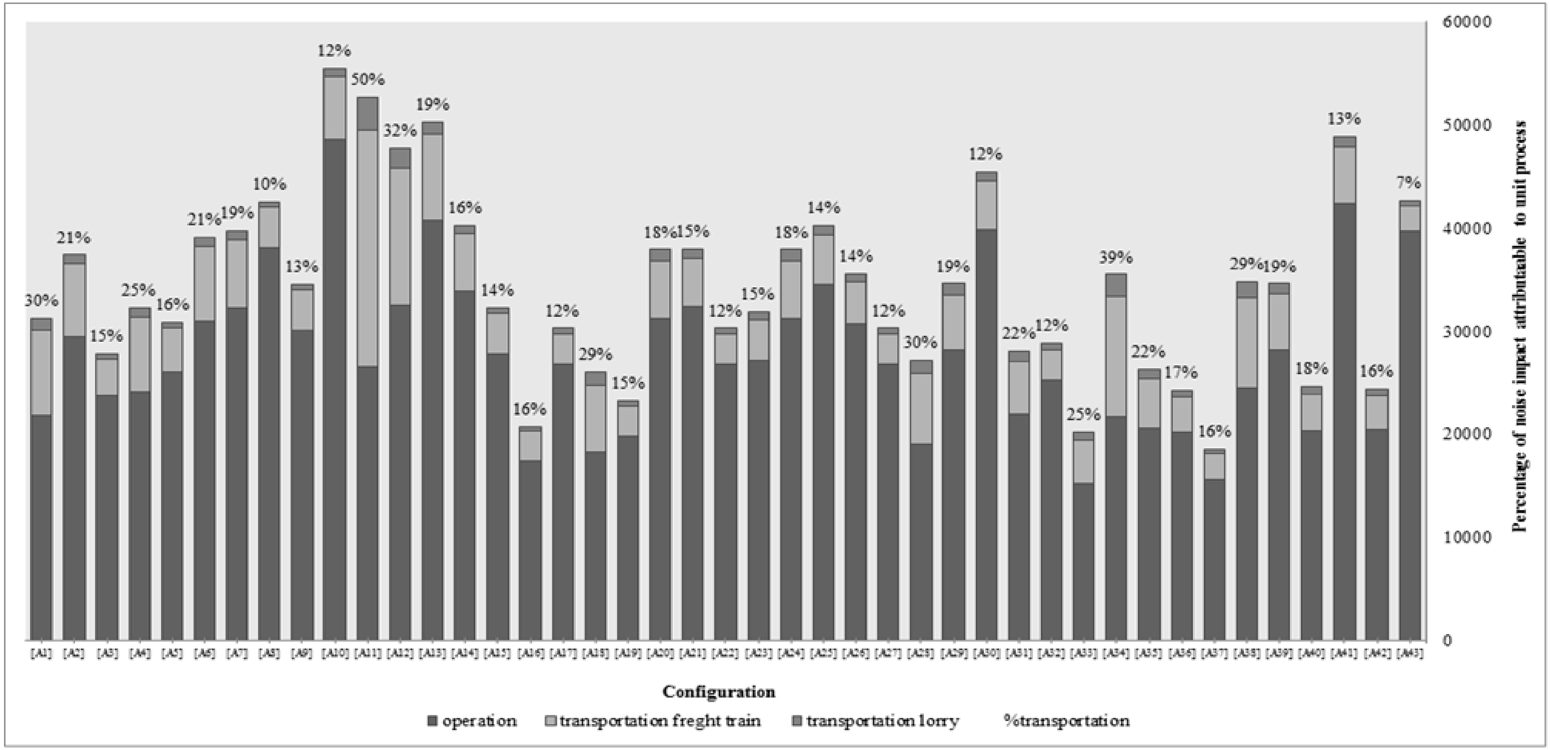

Figure 3. Noise impacts on humans under all configurations considered. Share of the impacts determined by the cumulative sum of transportation by means of freight train, and transportation by means of lorry is reported in the graph. Other sources of noise accounted for less than 1% of the total and are not reported in the figure.

4.2
Analysis of other impacts

The results obtained applying the CML-IA impact categories to the configurations are reported in detail in the Supporting Information. We focus here on the performance of a selection of configurations, representing one configuration per each class of nominal power. The worst and best performers in terms of noise impacts (i.e. [A38] and [A8]) are also included. Table 2 reports the results for this selection of configurations.

Table 2. Selection of CML-IA impacts for a number of configurations.

Power [kW]	**500**	**600**	**800**	**1500**	**1650**	**2000**	**3000**	
Configuration	**[A1]**	**[A8]**	**[A11]**	**[A17]**	**[A33]**	**[A38]**	**[A43]**	**Unit [per KWh]**
FSET[c]	1.92E-01	8.10E-02	**4.63E-01**[a]	6.18E-02[b]	8.78E-02	1.57E-01	7.38E-02	kg
GW20a	5.27E-02	2.64E-02	**1.57E-01**	1.81E-02	2.58E-02	5.96E-02	1.71E-02	kg
GW100a	4.71E-02	2.37E-02	**1.41E-01**	1.62E-02	2.31E-02	5.34E-02	1.54E-02	kg
TAE	1.16E-05	8.73E-06	**4.64E-05**	5.38E-06	7.65E-06	1.82E-05	3.17E-06	kg
MAE	4.19E-02	1.94E-02	**1.09E-01**	1.49E-02	2.12E-02	3.77E-02	1.60E-02	kBq
FAE	8.28E-02	3.61E-02	**2.05E-01**	2.79E-02	3.97E-02	7.00E-02	3.17E-02	kg
OD	2.39E-09	1.95E-09	**1.02E-08**	1.06E-09	1.52E-09	3.24E-09	8.47E-10	kg
HT	2.44E-01	9.40E-02	**5.11E-01**	6.63E-02	9.43E-02	1.74E-01	1.08E-01	kg
Low NOx PO (Europe)	1.48E-05	5.81E-06	**3.59E-05**	4.80E-06	6.82E-06	1.51E-05	4.35E-06	kg
High NOx PO (Europe)	1.66E-05	8.41E-06	**4.85E-05**	6.33E-06	9.01E-06	1.87E-05	5.13E-06	kg
Malodours air (Global)	8.05E+02	3.45E+02	**2.06E+03**	2.73E+02	3.87E+02	8.66E+02	2.40E+02	kg
Ionising radiation (Global)	1.65E-10	8.95E-11	**5.02E-10**	5.68E-11	8.08E-11	1.80E-10	5.82E-11	kg
Depletion of abiotic resources (Global)	-3.42E-04	-1.72E-04	-1.01E-03	-1.18E-04	-1.68E-04	-3.77E-04	**-1.08E-04**	kg

[a] In bold highest values in the selection

[b] In italic lowest values in the selection

[c] Correlation of results per configuration to the relative noise impacts. d List of acronyms used in the table: FSET: Freshwater sedimental ecotoxicity (measured with the global freshwater sedimental ecotoxicity potential with a time horizon of 20 years); GW: Global warming (measured with the global warming potential with a time horizon of 20 years); TAE: Terrestrial ecotoxicity(measured with the global terrestrial ecotoxicity potential with a time horizon of 20 years); FAE: Freshwater aquatic ecotoxicity (measured with the global freshwater aquatic ecotoxicity potential with a time horizon of 20 years); OD: ozone layer depletion (measured with the global ozone depletion potential with a time horizon of 20 years); HT: Human toxicity (measured with the global human toxicity potential with a time horizon of 20 years); low NOx PO: Photochemical oxidation low NOx.

In the selection of CML-IA impact categories reported in Table 2, we see that the configuration with the highest nominal power, [A43], results as the best performer for the majority of impact categories (see the Supporting Information for further details on the other configurations). The worst performer per functional unit is the configuration with a nominal power of 800 kilowatt. The results suggest the difference in local conditions (i.e. different wind speed, hub height, RpM, and diameter) may alter the trend suggesting that smaller wind turbines carry higher impacts. The score of the contributions to the global warming impact are in line with those found in the review by Arvesen and Hertwich (2012). No strong correlations were found between noise impacts and the other impacts reported in Table 2.

5
Concluding remarks

LCA deals with a number of emissions and impacts that are matter-less. Impact assessment models for some of these impact categories have been developed and proposed by developers, but are seldom considered by practitioners in LCA studies. A reason for this is due to the absence of suitable inventory data to deal with these matter-less impacts, to their absence in the LCA software in use, or to an insufficient knowledge of the mechanisms and procedures that would allow to clearly define the inputs and outputs of the system under study, also from the point of view of the interpretation of the relative impact scores. The decision to include or exclude an impact category from an LCA study is, in fact, left to the one conducting the study. Most guidebooks, in fact, tell that a practitioner should include a complete set of impacts, while most case studies take a selection that is dictated by the available databases and software. The a priori exclusion of a certain impact category may influence the usability of results, since important aspects of the study of a life cycle may be inadvertently neglected.

We have presented a detailed analysis of the case study of wind turbines, which includes for the first time the evaluation of the impacts of sound emissions across all phases of the life cycle of a wind turbine. Through the test-case of the wind turbine we have showed in detail how sound emissions may be attached to a variety of processes in a life cycle, from extraction of resources to operation, and how these can be modelled. The results show that it is now possible to compare the human-related noise performance of systems with a similar functional unit and similar definitions. The study of the single configurations of wind turbine indicated that in the case of sound emissions also the local conditions considered for the modelled configurations, i.e. wind speeds, are relevant to obtain a significant result. In all cases it was the operation phase of the life cycle that contributed the most to noise impacts. For other impacts, the local conditions do not seem to have a strong influence on the entity of the impacts and the conclusion of Caduff et al. (2013) holds, thus bigger wind turbines have lower impacts per functional unit (see the review of Arvesen and Hertwich 2012).

Previous studies of noise in the context of LCA focused on the transportation sector (see e.g. Althaus et al. 2009a, b). In the current study, we showed that also the sound emissions (and the relative noise impacts) of other phases in a life cycle of a product system may be accounted for. Such approach allows bringing the study of noise impacts in LCA in line with other impact categories. Characterisation factors for noise impacts quantified in a variety of archetypal contexts could now be potentially included in LCA databases (e.g. Ecoinvent) and regularly used in case studies.

The selection of the life cycle of a wind turbine allowed dealing with the impacts of an emerging technology, on which a great deal of hope is put in future energy scenarios (see e.g. Krewitt et al. 2009 and SSREN 2011). We show that it is important to also include in the analysis those impacts that are related to the operation phase of the life cycle. Similar conclusions may be drawn for other emerging technologies (e.g. electric cars), which are claimed to have negligible impacts during their use. Some of these impacts will prove to be non-negligible when a suitable method becomes available to quantify them.

The limits of the currently available LCA studies of wind turbines are amply discussed by Arvesen and Hertwich (2012) and are outside the scope of the current study. We only note that particular attention should be given to the modelling of an accurate capacity factor that best represents the location when the system operates. Selecting too high capacity factors does influence the meaning of results. The inventory of the wind turbine configurations was composed using data already available in the study of Caduff et al. (2013), and, therefore, similar uncertainties and limitations may be assumed for the current study. For the case of sound emissions, the quality of data varied. The availability of a report specifically oriented at the operation phase of wind turbines allowed for an accurate modelling of sound power levels at specific local conditions, but limited the number of considered configurations to just a set of 43. For other configurations, a case-by-case analysis would be needed. For the phase of sound emissions from different transport modes, it was possible to use the CNOSSOS reference report (Kephalopoulos 2012), which also allowed for an accurate modelling of sound power levels. For the phase of excavation of the foundations the data found was not detailed in terms of frequency bands, thus it was not possible to give this extra nuance in the specification of the characterization of the emission data. The selection of the sound power level as a measure of sound emissions proved to be a reasonable modelling expedient, which simplifies the collection of sound emission data.

The results after characterization are presented at a midpoint level. A transition to the human health area of protection in units of years, or disability-adjusted-life-years (DALY) is proposed in Cucurachi and Heijungs (2014). In that study, we assumed a linear transition from midpoint to endpoint by means of a conversion factor linearly translating the midpoint unit person × Pascal × second to DALY. The multiplication of the score obtained in the current study with that in Cucurachi and Heijungs (2014) yields a damage score per functional unit ~0.002 DALY/KWh. Further investigations and modelling efforts are needed to evaluate the linearity of the midpoint-endpoint transition and the additional uncertainty that one may encounter when moving from the midpoint to the endpoint level of the impact pathway.

From a methodological standpoint, the criteria used for the inventory of sound emissions may reveal to be exemplary for the handling of other types of matter-less physical impacts in LCA that do not stem, just like sound and noise, from the extraction or release of a kg of matter. The process of linearization and inventory of sound emissions by means of a time-based factor provides indications on how other physical impacts may be analogously modelled. In order to open-up the LCA framework to new impacts that do not have the traditional extraction/emission features, these indications may come handy to approach the modelling phase, especially in the case of matter-less emissions and impacts. LCA, however, should not aim to measure all possible impacts and guidelines should be followed on which impacts to include and to which to give priority (see Cucurachi et al. 2014). For an assessment, especially at a very local level of detail, other decision-support tool in the environmental sciences would be more suitable and would provide less uncertain results.

The on-going modelling effort to provide LCA with a growing level of spatial detail (see e.g. Mutel et al. 2011) and temporal detail (Tessum et al. 2012) will certainly help giving the LCA framework the possibility to portray a wide variety of local conditions of emission and exposure. However, this current study shows how difficult it is to model geographical differences when no specific information is available on the location in which certain emissions took place. In principle, the model by Cucurachi and Heijungs (2014) provides spatially-explicit characterization factors for the EU. The use of such factors in the current study was of limited interest since it was not possible to specifically relate emissions to a certain location. In future studies, if extra information on the specific location of a wind turbine is available to the practitioner, those location-specific characterization factors may be used. However, even then we should check the balance between the added value of a regionalized approach and the added efforts to do the analysis (cf. Heijungs, 2012).

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7

8

Answers to the research questions and concluding remarks

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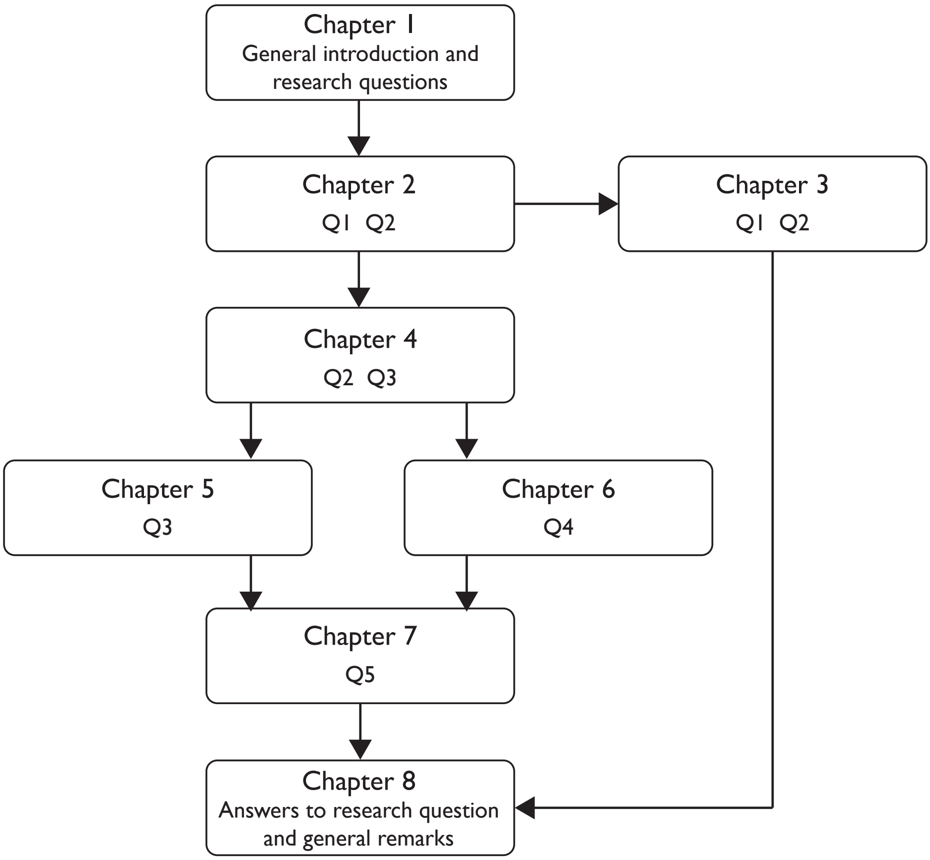
1
Introduction

This thesis examined in depth the process of development of a characterization model for matter-less stressors in LCA. Each chapter of the thesis functions as a milestone of this development process and provides a logical and rigorous process, which facilitates the model development.

By analysing this sub-set of underdeveloped stressors in LCA, this work touched upon the practical and methodological issues that are broadly relevant for any new characterization model. The relevant aspects of the modelling activity of the LCI and LCIA phases of LCA may be immediately translated also to other missing impact categories in the framework (e.g. odour, introduction of genetically-mofidied organisms). The development of a complete characterization method to determine the impact of sound emissions showed that matter-less stressors can be modelled in LCA and applied in LCA studies, making LCA a scientifically sounder decision-support tool in the environmental sciences. This thesis proves that LCA models may be more rigorous if appropriate statistical measures, such as global sensitivity analysis, are used. The thesis also brings back into the agenda of the LCA community the importance of the computational structure as a pillar of the framework, rather than a limiting factor.

This chapter provides the answers to the research questions that inspired this thesis, in relationship with the rest of the chapters presented in the previous pages of the thesis (see Figure below). An outlook on the future of LCA with respect to new developments closes the thesis and provides a number of cases for reflection for the vast community of modellers and users of LCA.

Figure 1. Relationship between research questions and chapters in the thesis.



2
Answers to the 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?

The framework of LCA has evolved into a more systematic tool for identifying and quantifying the potential environmental burdens and impacts of a product, process or an activity (Jeswani et al., 2010). Now that LCA is able to treat a wide variety of stressors and that the science behind existing and established impact assessment models is more solid, LCA modellers may work on deepening and broadening LCA. The increased attention of policy makers to stressors such as sound, electromagnetic waves and light (see e.g. Holzman, 2014) has had the direct effect of influencing the LCA community. The recommendation from the The International Reference Life Cycle Data System (ILCD;

EC-JRC, 2011) to broaden the spectrum of impact categories and to perfection methods directly springs from this increased awareness of harmful impacts of stressors that were before left at the margins of the LCA framework.

Chapter 2 showed that among the potential stressors that may be modelled in LCA, not all have the same level of priority. The selection criteria proposed in the form of a stepwise approach aim to guide the modeller and to make sure that the complexity of the fundamental knowledge at the basis of a certain impact is fully comprehended. The analysis of the noise impacts, radio-frequency electromagnetic fields (RF-EMF) pollution, and ecological light pollution (ELP) allowed to test the provided guidelines and to check if the modelling effort should be increased for these categories. These stressors have been often referred to as missing in LCA, thus making the framework incomplete (Sala et al., 2013). The guidelines defined in the framework were tested on these matter-less stressors, though they are potentially applicable to any other stressor that is considered for inclusion in LCA. The three matter-less stressors at the centre of the analysis in this work of thesis represented a specific case of the way LCA could expand.

As recommended by the guiding framework presented in Chapter 2, the study of any impact should start with the analysis of the scientific evidence that has been collected through studies and repetitions. Although the three stressors have certain common features and are all defined by the physics of waves, the scientific evidence that supports the existence of potential harmful effects varies among them. In this sense, the presence of a report performed by a recognised international agency or of an objective and transparent scientific review of the evidence represent some of the pieces of scientific evidence that allow to discern between an impact for which the evidence is mature enough to construct an impact assessment model, and another for which more evidence should be available before engaging in a model development.

In Chapter 2 and Chapter 3 the case of the impacts of RF-EMF on biodiversity and humans are analysed in detail. A vibrant discussion on their possible health effects still holds in the field of RF-EMF: for instance on potential long term adverse health effects, such as cancer, but also on an the association between actual and perceived exposure to electromagnetic fields and non-specific physical symptoms in the general population.

As reported in Chapter 3, a number of scientific reviews regards the impacts of RF-EMF and of other types of electromagnetic radiation in the electromagnetic spectrum. The chapter presents a systematic review of the published scientific studies on the potential ecological effects of RF-EMF in the range of 10 MHz to 3.6 GHz. The evidence found in the literature confirmed that effects may be found at high as well as at low dosages compatible with real exposure situations. The possibility of determining clear dose-response curves is, thus, limited due to the high variation in the strength of the effect at similar frequencies. The analysis of the literature also highlighted how a lack of standardization and repetition of studies may limit the generalization of results. As the example of RF-EMF suggests, further developments in LCIA should be also tested in light of the consensus that they have reached in their scientific field. It is not unusual that theories and models in the environmental sciences are not supported by the full community of scientists. Therefore, experts from the specific field of science regarding the stressor should be involved to avoid a selective interpretation of the literature. This trend should be favoured in all new developments in the field of LCA.

For the case of noise, a sufficient body of evidence suggests that the mechanisms determining the impacts are clear for the case of humans and biodiversity. The analysis of the literature for the case of ELP advises that care should be taken to address the impacts on biodiversity, since a clear impact pathway has not yet been formulated. For the case of humans, of particular relevance for the field of LCA are the impacts related to occupational exposure (see e.g. Schmitt et al., 2011).

With respect to the computational structure of LCA (Heijungs and Suh, 2002), none of the stressors considered showed clear limitations that would not allow inventorying their relative emissions. On the impact assessment side, it would be possible to model the fate factor of the characterisation model for all the three matter-less stressors. For the case of RF-EMF and ELP, the modelling process could not proceed any further since Chapter 2 showed a lack of conclusive evidence. Different is the case of noise, for which more solid evidence has been highlighted in the literature, and for which the modelling of impacts could be based on the consolidated modelling practice of LCIA (see e.g. Pennington et al., 2004 and Rosenbaum et al., 2007).

For the case of any other stressor considered for the inclusion in LCA, a similar detailed analysis as shown in Chapter 2 and Chapter 3 would allow to identify those stressors to which priority should be given. Therefore, the analysis of any stressor should focus on the importance of the evidence, on its relationship with the computational structure of LCA, and of the strength of the consensus on the available evidence.

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

The study of the specialist literature may further discriminate for which target subject (e.g. humans, or other organisms), a model should quantify the impacts.

As shown in Chapter 2 and Chapter 4, the evidence available for the case of noise supports the development of a model that would consider the impacts of this matter-less stressor on humans and biodiversity. The impacts of anthropogenic noise have for long been studied both on humans (see e.g. Van Kamp and Davies, 2013) and wildlife (see e.g. Kight and Swaddle, 2011 and Francis and Barber, 2013). For the case of humans, the definition of a generic model is made possible by the availability of a common impact pathway. The knowledge of the direct effects (e.g. hearing impairment) and indirect effects (e.g. physiological alterations mediated by stress) of noise on humans support its inclusion in LCA. For the case of other species, a case-by-case analysis should be done in order to device the best possible exposure pathway to suit the needs and the evidence available for the different species. The evidence found in the literature suggests that these impacts need to be monitored to consider their possible inclusion in LCA.

For ELP a clear explanation of the mechanisms determining a certain effect on humans or other targets, and a consensus has not yet been found in the literature. The human effects have been analysed only in the occupational context of exposure, providing a limited application for LCA. The focus therefore should be on linking occupational impacts of ELP to those life cycles for which night shifts would be relevant.

The attention of scientists has focused mostly on the potential ecological impacts of ELP. The division of species across diurnal, crepuscular or nocturnal, is thought to have happened in order to avoid competition by specializing in a particular section along the light gradient (Gutman and Dayan, 2005; Gaston et al., 2013). A substantial proportion of species has adapted to be active during low-light conditions, with about 60% of mammals falling into this category (Holker et al., 2010). Predatory-prey activities driven by natural light cycles have been observed in taxonomically diverse species, from zooplankton and fish to lions (Gaston et al., 2013). Few studies have analysed the effect of artificial night light in altering the behaviour of certain species, or in restructuring the partitioning between species at different light conditions. Foraging activities have been seen to change for certain species as a response to the exposure of local area network (LAN). Alight-induced selection for non-light sensitive individuals (Holker et al., 2010) seems to regard species that have already evolved to utilise novel niches created by artificial light.

The melatonin-mediated effects of exposure have been found on the immune function of birds in laboratory studies (Moore and Siopes, 2000). Moreover, exposure to light at night may also function as a determinant of masking, which occurs when a light stimulus alters the endogenous clock of a species, determining e.g. a change in the distribution of activities between night and day (Gaston et al., 2013). Effects of artificial lighting have long been noticed also on plants. According to the latitudinal range of species, delay and promotion of flowering have been identified, as well as enhanced vegetative growth, or early leaf out, late leaf loss and extended growing periods, which could impact the composition of the floral community (Gaston et al., 2013). Though a growing amount of evidence on certain species is available, no common approach to the issue links to date an increased level of illumination to direct potential ecological effects and possible threshold levels of exposure. As discussed in Chapter 2, such evidence limits the possibility of tackling with a generic impact assessment model all impacts of ELP on biodiversity.

As showed, the lack of knowledge of the mechanisms by which RF-EMF affect humans and biodiversity alike would, at this moment, suggest desisting from the modelling of such impacts in LCA. Only direct heating has been confirmed, in fact, as an effect of the exposure to RF-EMF.

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

The evidence available in the literature, the mechanisms determining the propagation of sound waves, and the resulting impacts on humans suggested proceeding with the development of a characterisation model for the noise stressor. Though advancements are still needed in some key fields, the quantification of the impacts of noise on humans provided a sufficient starting basis to define first a generic theoretical framework in Chapter 4, and then to calculate the relative characterisation factors in Chapter 5. A limited number of proposals to include noise impacts in LCA were already available in the literature (see e.g. Muller-Wenk, 2004; Althaus et al., 2009). However, contrasting to the previous available modelling attempts, the proposed model aims at following the traditional characterisation scheme of LCA. In particular, the model considers sound emissions as the quantities to be inventoried in the inventory phase. By doing this, the model follows the computational structure of LCA and allows its application also for sound emissions. The conversion of sound emissions from the non-linear decibel scale to the linear Joule allows for the summation of contributions across a life cycle. The modelling scheme introduced in Chapter 4 and Chapter 5 allows overcoming some of the specificities of matter-less stressors, aligning their modelling to that of other stressors considered in LCA (e.g. toxic emissions). Furthermore, the introduction of a conversion function as described in Chapter 7 allows considering in LCIA matter-less stressors, but also opens the possibility of solving non-linearities for other potential stressors that are material (e.g. nano-materials).

Existing standards for the propagation and attenuation of sound emissions allowed defining a fate factor. An effect factor was, then, obtained considering the human perception of sound at different frequencies and different times of the day, and the people living in a certain location. The novelty of such a theoretical model is that it allows keeping the parallel between noise and other stressors in LCA without breaking the computational structure of LCA. In Chapter 5, the further specification of different compartments of sound emission and exposure to noise allowed to calculate characterisation factors that portray the most common archetypes needed for LCA studies. In order to allow for a local analysis of any context of emission and exposure spatially-explicit characterisation factors were provided in the form of maps. Such information may be combined with inventory data and used in LCA studies in which enough information is available on the context of emission. To support highly-localised studies a calculation tool was also presented in Chapter 5 to supply specific sets of characterisation factors to LCA practitioners.

The computational structure of LCA provides a methodological basis on which to build impact assessment models. It ensures that all results are comparable and that the relationship between a life cycle and a specific functional unit is maintained. The case of matter-less stressors shows that although such structure is rigorous, it may be adapted to specific needs of the mechanisms that determine a certain impact.

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?

Having defined a model and calculated characterisation factors, the work of this thesis moved to the investigation of the sources of uncertainty in the model, and to the further understanding of the dependencies among the model inputs and the output. The issue of uncertainty quantification is of fundamental importance for the trustability of LCA as a scientific tool, and of LCIA models as a trustable representation of a complex reality. This line or reasoning particularly counts for the cases of matter-less stressors, in which potential weakness of empirical data may be detected.

The increased use and popularity of LCA has, in fact, increased also the attention of users (e.g. policy makers) to the level of uncertainty that LCA results carry (Lloyd et al., 2007;

Lazarevic, 2012). Early in the history of LCA the matter of dealing with uncertainty in LCA was already pointed out and formalised in techniques (see e.g. Curran, 1993; Heijungs, 1996; Steen, 1997; Huijbregts, 1998). The analysis, propagation and communication of uncertainty have, after some years of latency, finally resulted also in an increased attention of LCA experts and developers of methods. More systematic approaches are popping up in the field and results of uncertainty analyses are presented along with LCA studies (see e.g. Brandt, 2012). The tendency of using single scores without uncertainty ranges will likely give way to a more robust representation of data, thanks to improved methods (see e.g. Henriksson et al., 2014), increased availability of background uncertainty data in databases such as ecoinvent (Frischknecht et al., 2005), and improved software with capabilities to perform uncertainty analysis and propagate uncertainty.

Therefore, a variety of techniques have been applied and used to deal with several aspects of the framework, from LCI to impact scores. Nevertheless, an aspect of LCA that still requires major attention is that of the uncertainty that the LCIA impact assessment models carry. Often interactions among model parameters are unknown and modellers have failed to conduct statistical analysis that address the sensitivity of their models.

The full development of a characterisation model, starting from the theoretical model (Chapter 4) through its operationalization and eventually to the calculation of characterisation factors (Chapter 5), provided the unique opportunity of testing the quality of the developed noise model from a statistical point of view. Chapter 6 as a result, presents a protocol based on the combination of global sensitivity analysis measures to study LCIA impact assessment models.

The results and ranking provided by the variance-based techniques allowed to study the model structure and to identify the strength of dependencies among the input parameters of the noise model. Given the multiplicative and interactive nature of the model, the results of the analysis did not allow to provide a conclusive statement on the importance of input parameters in driving the uncertainty of the output of the model (i.e. the calculated characterisation factor). However, the case of the noise model confirms that it is a combination of techniques that allows for a full comprehension of the interactions and for a better understanding of the individual importance of inputs influencing the output. Global techniques dealing with the entire distribution of the input and the output allowed to rank the inputs and to define a ranking of importance. Increasing our knowing on the (relative) importance of inputs allows for a better understanding of the noise model, and may help in determining in which areas the model should be improved in the future.

The proposed measures, previously often overlooked by the LCA community, allow for an efficient analysis of models of great complexity. The protocol sets the basis for a rigorous analysis of LCIA models, and presents a series of techniques that may be also used in other contexts of the LCA framework, in order to understand which inputs drive uncertainty in models (e.g. which LCI inputs drive the uncertainty of the impact score the most). The protocol contributes to make LCA more robust scientifically and to present to the community of LCA users a variety of tools that are ready available in the specialist sensitivity analysis community.

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

The development of a characterisation model, the calculation of suitable characterisation factors as archetypes or maps, and the thorough analysis of the model alone do not immediately guarantee that a model is applicable in practice. Hence, they do not ensure that the in-depth study, which led to the proposed noise model will be actually used by practitioners conducting LCA studies. In particular, this is the case of unusual impact categories such as those regarding matter-less stressors, for which more information is needed to classify and inventory emissions. The case of noise is exemplifying here, since the way sound emissions are inventoried requires introducing an extra step in the usual practice of LCI. A function is needed to translate the non-linear decibel into a linear joule. This function operates a transformation that is based on the time a unit process is working for the functional unit taken into consideration. To show the practical relevance of newly developed LCA models (whether or not regarding matter-less stressors), a case study in which the model is used and tested is insightful for potential future users.

A case study was therefore used to demonstrate the applicability of the noise model to LCA studies. The specific case of wind turbines was chosen to highlight the link that matter-less stressors have with emerging or relatively new technologies. Wind turbines, moreover, are considered one of the most promising sources of renewable energy. This type of energy is likely to increase its presence in the years to come. The intermittency of supply, in fact, has not stopped wind energy from finding the favour of policy makers, environmental activists and the majority of citizens alike. In the period 2004-2011 the installed wind generating capacity reached 190 gigawatts (GW) globally, outpacing any other renewable energy installed during the same period (GWEC, 2013).

Such a level of future development requires the LCA community to intervene and measure the potential future impacts of the wind power generators across their life cycle. Among the impacts that these systems have, noise is one of the most lamented ones (Premalatha et al., 2014). The availability of a noise model allowed modelling the impacts due to sound emissions in the whole life cycle of wind turbine systems. While due to the lack of the appropriate modelling capability to account for the impacts due to noise, earlier studies had not sufficiently considered the operation phase of the wind turbines, this work of thesis, in turn, includes it in the analysis.

The definition of a generic model allows accommodating any source of emissions of sound, being it static or mobile. The application of the model to the case of wind power generators contributed to show that the model is applicable to real cases, and to show that not only mobile sources are accountable for noise impacts, but also static emissions, such as the wind power generators. The model allows incorporating for the first time in LCA the impacts due to sound emissions determining noise in a life cycle, overcoming the methodological limitations of previous modelling efforts and linking the modelling of the impact category noise to the computational structure. The topic of "traffic noise", "transportation noise", or "noise due to mobility" has for years been mentioned as still lacking from LCA (see e.g Muller-Wenk, 2004). In fact, the results presented in Chapter 7 show that when scaled to a functional unit the noise impacts due to the transportation phases in the life cycle are diluted and do not always contribute significantly to the impacts. The majority of the noise impacts are, in fact, due to the operation of the system.

The application of the model in a real case study allowed further understanding of its functioning. A variety of configurations were analysed in relationship to a common functional unit of 1 kWh. Linearizing to the functional unit has the advantage of allowing for the comparison of systems with a similar goal and scope, but with different processes involved in their life cycle. In real cases, it would be interesting to consider the case of a group of wind power generators with similar nominal powers operating at the same time (i.e. a wind park), compared to one generator operating under similar local conditions. In this sense, we may compare the performance relative to noise impacts of six generators with a nominal power of 500 kW against one generator with a nominal power of 3000 kW. Applying directly the model, one would scale the sound emissions of six generators to the functional unit of 1 kWh and compare the resulting impact to that of the 3000 kW generator. Such an approach would still result in the park of six generators performing worse, in terms of the noise impact score, than the single generator. However, the total impact would be similar to that of one single 500 kW generator, due to the scaling to the functional unit and to the time-based transformation introduced. This result confirms that sound emissions are a rather local type of stressor. Therefore, in order to compare the wind park of six generators with the single 3000 kW generator it is needed to gather data directly on the sound emissions (thus the sound power) of the park together. The direct scaling (i.e. multiplying the emission in joule for one 500 kW generator by six to obtain the total wind park emission) would not yield realistic results. This point of attention may also count for other matter-less stressors.

Chapter 7 concludes that the claim that a wind power generator produces none or negligible emissions during the use-phase cannot be maintained, simply by the sheer quantification of noise impacts that are also paramount during the use-phase of this product. Similarly, other emerging technologies may present impacts in the upstream and downstream processes that are currently neglected.

Further modelling efforts would be needed to improve the model and to reduce the uncertainty of the process of transition from the midpoint to the endpoint level. Such transition requires to carefully studying the link between the exposure of a human target to sound and the potential health effect that such exposure statistically determines (see also Chapter 5 on the matter). Moreover, at the current evolution of the model, the personal preferences of people and their personal subjective predisposition to like or dislike a certain noise are included only through the concept of frequency-specific characterisation factors and penalties. Even though studies suggest that it is possible to state that certain noises at certain frequencies and loudness levels will be affecting any subject (Stewart et al., 2012), future developments of the model may add a statistical relationship to personal perceptions based on available knowledge in the literature.

3
Conclusions and future outlook

This thesis focused on matter-less stressors and on how to deal with their specific features in relationship with the framework of LCA. The lack of analysis of impacts that results from non-material stressors, such as sound, which have for years been excluded from LCA studies, may be a limiting factor for the framework as a whole. Across the life cycle of many products such underdeveloped impacts are present and could change the result of those studies, highlighting different hotspots than those brought forward by the existing LCA studies.

The process of development of an impact assessment model that is described in this work, from the selection of the suitable candidates for inclusion, to the testing of inputs, outputs and the results of the developed model provides an account of how any new impact category should be approached in LCA. If LCA needs to expand and include new stressors, then the chapters of this thesis may be considered as important step-by-step considerations for such endeavour.

During the course of the chapters, at various times it is highlighted that it should be kept in mind during the modelling process that typically only the developer of a model has specialist detailed knowledge of the stressor and model under study, and not necessarily the practitioner. A characterization model, in fact, is usually taken from the literature, or has been selected in a LCA software as part of a comprehensive impact assessment method, and is only implicitly considered by the practitioner. For the matter-les stressors described in this thesis, specific physical properties apply and need to be taken into account also at the LCI phase. A more accurate knowledge of the impact assessment models by both practitioners and LCA modellers, will be necessary also to understand and to use the newly-developed models until the available software will be updated. Therefore, a community of educated practitioners will be fundamental for the success of the future developments in LCA, and LCA developers have a role to play in the responsibility to achieve such community.

A further point of attention regards the necessity of LCA to deal more and more with stressors that determine highly-localised and temporally-variable impacts. This thesis has been conducted as part of the LC-IMPACT project (www.lc-impact.eu). In this project, a number of improvements have been proposed to make the results of LCA representative for a broader set of conditions of emission and exposure. Characterisation factors have been produced to the level of detail of map cells of a side in the range of few metres. Outside this project, developers of LCIA models have also worked in the last years to incorporate spatial and temporal variability in the impact assessment models (see e.g. Pfister and Bayer, 2013 for the case of the water footprint). In Chapter 5, such effort has been done also for the case of noise impacts.

An increased spatial definition and complexity are desirable for an environmental assessment tool, such as LCA, that aims to be the reference in the environmental assessment of products, and contributes to better reflect the reality that it tries to model. The application of such models certainly empowers the LCA framework giving the possibility to users to portray any possible context of emission, exposure, fate, and effect. However, from a practical perspective it will increasingly be a challenge to gather enough inventory information to perform a complete LCA study. The selective use of blocks of the LCA framework in the form of e.g. the carbon footprint or the water footprint (see Fang et al., 2014 for a review) will be needed in all cases in which a full LCA study is out of the scope of the analysis. It should not be forgotten that LCA may be used in combination with other environmental assessment tools and analyses of impacts. The limits of LCA should therefore be recognized and it should not be the tool to hammer all nails. LCA has a great deal of benefits and advantages, but traditional risk assessment may be more appropriate than LCA for all applications in which a very detailed modelling of the predicted impacts is needed for a specific highly-localised case. In this sense, the strengthening of collaborations with other communities of the environmental sciences would be advantageous (see e.g. Huijbregts, 2013 on the matter).

For the matter of uncertainty in LCIA models and, overall, in the framework, developers should provide precise guidelines and protocols, and only LCA studies complying to those guidelines should be recommended for consideration to policy and decision makers. The effort of stressing the framework of LCA and questioning its scientific robustness should not be given up, in order to avoid the risk of communicating results that carry an unnecessary level of uncertainty. We should actively look for close collaborations also with experts in the field of statistical analysis to enrich the scientific foundation of LCA. Last, for many of the (matter-less) stressors that are analysed in LCA the involvement of expert knowledge from other fields of science is highly advisable as a support to the modelling phase of any impact assessment models. In this way, LCA developers avoid the risk of a selective use of the literature and it would guarantee a full comprehension of the scientific evidence.

The community of LCA scientists should take the lead and adopt all measures necessary to guarantee a bright future for LCA. Though LCA may increasingly improve its broadness and scope, it is the solidification of its scientific foundation that will guarantee its status as a trustworthy and reliable assessment tool, but, more importantly, as a legitimate scientific discipline.

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8

Synopsis

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

In the last three decades, the Life Cycle Assessment (LCA) framework has grown to finally establish itself as the leading tool for the assessment of the environmental impacts of product systems. A series of scientific publications, standard guidelines and handbooks contributed to found the scientific basis of LCA and to set the standards for conducting LCA studies. LCA studies are now conducted around the globe both in and outside the academia and also used as a basis for policy making.

The widespread diffusion of LCA has not halted the attempt to continuously improve the theories and models that are still underdeveloped or not yet developed. A series of challenges are still ahead of LCA and are polarizing the attention of the researchers in the field. In particular, the focus of LCA scientists has been recently put on the matter of increasing the completeness and representativeness of impact assessment models and of reducing the uncertainty of these models and their results.

LCA is in continuous evolution, and so are the impact assessment models that are used in the Life Cycle Impact Assessment (LCIA) phase of LCA. There is no formal best set of impacts to include in the LCIA phase when conducting a study. Moreover, recent proclamations on LCIA recommend further increasing the modelling effort to include in LCA the impact of those stressors (i.e. pressures on the environment) that are still outside of the framework.

Now that LCA is able to treat a wide variety of stressors and that the science behind existing and established impact assessment models is more solid, LCA modellers may work on deepening and broadening LCA. Of the missing links in LCIA, of particular interest for their specificities are those stressors that are not related to the standard extraction/emission pattern, thus they do not relate to the extraction of a certain quantity of matter or to the emission of matter to the environment. These stressors may be defined in this acceptation as matter-less. At the core of thesis are, in particular, three matter-less stressors that have been considered under-developed, that share common physical properties, and are often co-occurring. The stressors in question are sound emissions, radio-frequency electromagnetic emissions and light emissions. These three matter-less stressors were used to guide the analysis in this thesis and 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?

In Chapter 2 we developed a stepwise approach to analyse which stressors and impacts should be prioritized when modellers are evaluating how to improve LCA. We showed that in order to enlarge the spectrum of stressors that are considered in LCIA, it is necessary to carefully analyse if a certain stressor is suitable for inclusion in LCA, thus to analyse its impacts throughout the life cycle of a product system. Moreover, it is fundamental to verify that the strength of the evidence that scientists in the specialist domain of that stressor have managed to collect is sufficient and uncontested. We proposed a stepwise approach that allows setting a priority on which stressors are ready to be modelled in LCA. The approach was tested on the particular case of the three matter-less stressors analysed in this thesis, though it may be applied to any new impact category in LCIA.

Chapter 3 complements the analysis proposed in Chapter 2. For the case of radio-frequency electromagnetic radiation, in fact, it was necessary to directly gather information on the impacts by means of an unprecedented review analysis. Through this work the evidence available in the literature on the ecological impacts of radio-frequency electromagnetic fields on biodiversity was studied. Such a review was available for the case of human targets, but a work of classification and analysis of the strength of the evidence was not available for the case of non-human targets. The analysis allowed classifying the evidence, and evaluating statistically the presence of trends between the exposure to the radio-frequency radiation and its relative effects.

The review of the literature conducted in Chapter 3, combined with the information presented in Chapter 2, allowed to conclude that the knowledge that is available on the impacts of radio-frequency electromagnetic fields, both on humans and biodiversity, does not suggest that their impacts should be considered in LCA. Thus, it was the sheer absence of evidence, rather than the physical properties of electromagnetic waves, that blocked the modelling process. Similar conclusions were presented for the case of ecological light pollution: the current state of knowledge does not allow modelling the complete impact pathway both for the case of humans and biodiversity.

For the case of sound emissions and noise impacts, the analysis of the evidence and of the physical properties of sound waves showed that the modelling effort should be strengthened. In particular, the literature shows that solid and uncontested evidence is available for the case of noise impacts on humans, though extra research should be conducted to verify the modelling effort necessary to characterise the impacts of sound on biodiversity. We proceeded, therefore, with the modelling of sound emissions and noise impacts on humans.

In Chapter 4 we proposed a theoretical framework to allow the inclusion of sound emissions and noise impacts on humans in LCA. A midpoint impact assessment model was proposed. At the Life Cycle Inventory (LCI) phase of LCA, we showed the way to inventory sound emissions from any sound-emitting source, being it static or mobile. Based on the physical properties of sound, and on the knowledge gathered from the expert literature we inventoried elementary flows of sound based on their frequency, the time of the day on which they occurred, and the location of emission. The unit of the inventory is joule, a unit of sound energy, which makes, unlike the non-linear decibel, sound emissions additive and directly comparable. Furthermore, a characterisation model was proposed to characterise the inventoried sound emissions. Such model matches the common LCIA practice for toxicants and uses a fate factor and effect factor to calculate characterisation factors for the noise impacts on humans. A common standard for the propagation and attenuation of sound emissions was adapted to the need of LCA, and to the defined LCI phase.

In Chapter 5 we operationalised the proposed model, expanded it, and moved on to the calculation of actual characterization factors, based on the theoretical definition. At this stage, a series of considerations were made on the level of spatial refinement that characterization factors should have. We decided to provide the future users of the characterisation factors for noise impacts on humans the possibility to choose the necessary level of refinement based on the available information on the context of emission. Archetypal contexts of emission were defined in order to represent the most common frequencies, times, and location of emission. A total of 248 characterisation factors was calculated for the defined archetypal contexts. Characterisation factors were calculated also for the case of unspecified contexts of emissions. Furthermore, spatially explicit maps of characterisation factors were produced, using for each of the parameters defined in the characterisation model a 10 by 10 km map for the EU. To support also the needs of a practitioner that would have complete information on all sound emissions in a life cycle, we introduced the possibility for users to calculate custom characterisation factors by means of a simple calculation sheet. According to the information available, the practitioner may choose to use 10-by-10-km maps and/or archetypal characterisation factors, or, alternatively, define site-specific customised characterisation factors.

In Chapter 5, we touched upon the issue of uncertainty in impact assessment models, which is of great importance not only for the matter-less sound emissions, but more broadly for anyone working with impact assessment models in LCA and integrated assessment models in other fields of the environmental sciences. In Chapter 6 we further investigated the application for this purpose of a variety global sensitivity tools. Through the study of the developed characterisation model for noise impacts, we defined a protocol to regularly conduct uncertainty and global sensitivity analysis of characterisation models. An ensemble of techniques was proposed and compared and the results of its application to the noise model were analysed in light of the impacts that such techniques may have in the whole field of LCA. We showed that the structure of models and the importance of model inputs in determining the uncertainty of the output may only be fully analysed if a standard protocol that carefully follows the available statistical techniques is used.

Once the model was developed and its uncertainty analysed, we moved onto applying it directly to a representative case study. In Chapter 7, we re-examined the findings in previous chapters and tried to generalise the experience obtained with the "sound/noise model" to any other matter-less stressor candidate for inclusion in LCA. We gave indications on how to deal with the LCI of matter-less stressors and on how to deal with their characterisation. The case study of wind turbines was used to test the developed characterisation model in a system that is often associated with sound emissions, in particular during its operation phase. Although more than a hundred LCA studies analysed the environmental performance of such systems, sound emissions and their impacts were always neglected. The case study showed that it is possible to use the proposed characterisation model and to characterise sound emissions throughout the entire value chain of wind turbines, from the extraction of resources to their disposal.

The research questions answered by this thesis, although applied to the specific case of matter-less stressors, provide a number of sparks to foster future improvements of LCA. The criteria for selection defined allow consciously prioritizing those stressors that should put first to enlarge the scope of LCA. The thesis proved that not all stressors need to be tackled by LCA. The case of sound emissions and noise impacts may prove paradigmatic to treat any new development in LCA, regarding or not matter-less stressors. We showed that LCA should not be the tool to deal with all possible issues and all possible environmental analyses: LCA has its limits. Some may be improved by further research, some other need to be tackled by LCA in combination with other decision-support tools. In order to make LCA a more trustable means of environmental analysis, experts from the fields of sciences that are relevant for LCA should be directly involved in the development of models and methods. We showed a practical example for the case of global sensitivity analysis: the expertise from the field of LCA was combined with that of the field of statistics. Only such approaches may really empower LCA and increase its trustworthiness.

Samenvatting

Modellering van de effectbepaling van niet-fysieke stressoren in de context van levenscyclusanalyse

In de laatste 30 jaar heeft LCA zich ontwikkeld en gevestigd als het meest gebruikte instrument om de milieu impact van product systemen te analyseren en beoordelen. Verschillende wetenschappelijke publicaties, gestandaardiseerde richtlijnen en handboeken liggen aan de wetenschappelijke basis van LCA en hebben bijgedragen aan de internationale standaard ISO 14040 voor de uitvoering van LCA studies.

LCA studies worden nu wereldwijd zowel binnen als buiten de de academische wereld uitgevoerd en daarnaast ook gebruikt in de ontwikkeling en totstandkoming van beleid. Hoewel de toenemende verspreiding en toepassing van LCA een continue verbetering van niet of onderontwikkelde aspecten niet in de weg staat, bestaan er nog veel uitdagingen in de ontwikkeling van LCA.

Recentelijk is de aandacht van LCA wetenschappers aan het verschuiven naar verbeteren van de representativiteit van impact assessment modellen en het verminderen van de onzekerheid rondom deze modellen die worden gebruikt in de Life Cycle Impact Assessment (LCIA) fase van LCA.

Er bestaat geen formeel vastgestelde lijst van impacts die in de LCIA fase worden opgenomen bij de uitvoering van een een LCA studie. Bovendien wordt er steeds meer belang gehecht aan de opname van impacts van stressors (i.e. verschillende soorten factoren die de leefomgeving beïnvloeden) die nu nog niet in een LCA kader geplaatst kunnen worden.

Nu meerdere stressors en de achterliggende wetenschappelijke impact modellen onderdeel uitmaken van LCA beginnen LCA wetenschappers zich te richten op het verbreden en verdiepen van LCA. Specifieke interesse gaat naar die impacts die niet te relateren zijn aan fysieke emissie of opname. Omwille van bovenstaande eigenschap kunnen deze stressors als matter-less stressors gedefinieerd worden. Centraal in dit proefschrift staan drie matter-less stressors, die in de realiteit vaak tegelijkertijd aanwezig zijn, vergelijkbare fysische eigenschappen vertonen en bovendien binnen het LCA kader als onderontwikkeld worden beschouwd, De betreffende stressors zijn geluidsemissie, radio-magnetische emissie en licht emissie. Deze stressors zijn leidend voor de analyses in dit proefschrift, waarin de volgende onderzoeksvragen centraal staan:.

Q1. Hoe kunnen we er zeker van zijn dat de kennis van bepaalde impacts veroorzaakt door een bepaalde stressor voldoende is om deze stressor op te nemen in een LCA onderzoekskader?

Q2. Hoe kunnen we beoordelen op welke target subjects (bv. de Mens) we ons het beste kunnen richten tijdens het modelleringsproces?

Q3. Hoe kunnen matter-less stressors worden gedefinieerd binnen de mathematische structuur van LCA?

Q4. Hoe kunnen we de modelstructuur, de afhankelijkheden tussen de verschillende inputs in het model en de relatieve invloed van de verschillende inputs op de output van een karakterisatie model in LCIA het beste bestuderen?

Q5. Hoe kunnen we de wetenschappelijke validiteit van een nieuw karakterisatie model beoordelen en gebruikers van LCA in de praktijk begeleiden wanneer zij deze in LCA studies willen inzetten?

In hoofdstuk 2 wordt een stappenplan uiteengezet waarmee beoordeeld kan worden welke stressors en impacts van belang zijn wanneer modelbouwers onderzoeken hoe LCA verbeterd kan worden. We laten zien dat wanneer we het spectrum van stressors die centraal staan in LCIA willen uitbreiden, het noodzakelijk is om zorgvuldig na te gaan of een bepaalde stressor voldoende geschikt is voor LCA om haar impacts op basis van het volledige productiesysteem te analyseren.

Daarnaast is het van groot belang dat wetenschappers voldoende en onderbouwd wetenschappelijk bewijs in handen hebben dat de betreffende stressor een bewezen impact heeft op de leefomgeving. Er wordt een stappenplan voorgesteld dat een prioritering mogelijk maakt van nieuwe stressoren in LCA. De kwaliteit van dit stappenplan is getest met betrekking tot de voorgenoemde drie matter-less stressors, maar het stappenplan is ook te hanteren bij andere nieuwe impact categorieën in LCIA.

De inhoud van hoofdstuk 3 is complementair aan de benandering en analyse die voorgesteld wordt in hoofdstuk 2. Om een voorbeeld te geven, met betrekking tot de stressor radio- en elektromagnetische straling was het bijvoorbeeld noodzakelijk om eerst meer informatie te verzamelen van de impacts van deze stressor , door middel van een review studie welke nog niet eerder was uitgevoerd. In deze review study in Hoofdstuk 3 is de beschikbare wetenschappelijke kennis verzameld over de ecologische impacts van radio- en elektromagnetische velden op biodiversiteit. Een recente review gericht op de effecten op de mens was reeds beschikbaar, maar een hoog kwalitatieve studie ten aanzien van de ecologische impacts op andere levende organismen dan de mens, was er nog niet.

De analyse in Hoofdstuk 3 tracht de beschikbare wetenschappelijke resultaten op hun kwaliteit te beoordelen en door middel van statistische methoden zijn de aanwezige trends tussen de blootstelling aan radio straling en haar relatieve effecten op niet humane doelen besproken.

Uit de literatuur studie in Hoofdstuk 3, en de informatie die wordt besproken in Hoofdstuk 2 kunnen we concluderen dat de huidige beschikbare kennis van radio- en elektromagnetische velden , en diens impacts op zowel de mens als de biodiversiteit, vooralsnog niet voldoende is om vast te kunnen stellen dat deze stressor binnen LCA bestudeerd zou moeten worden.

Het gaat in dit geval dus om de afwezigheid van voldoende wetenschappelijk bewijs en niet de fysieke eigenschappen van elektromagnetische golven, die de noodzakelijke informatie voor het modelleringsproces binnen LCA belemmert. Vergelijkbare conclusies worden getrokken met betrekking tot licht-vervuiling: Zowel met betrekking tot haar effecten op de mens als op de biodiversiteit in het algemeen, staat de huidige status van de wetenschappelijke literatuur over deze stressor niet toe een volledige inventarisatie te kunnen doen van de impacts van deze stressor in LCA

Wanneer we kijken naar geluidsemissie, dan kunnen we stellen dat de literatuur analyse en de studie van de fysieke eigenschappen van geluidsgolven laten zien dat er voldoende aanleiding is om het modelleringsproces voor deze stressor verder te intensiveren. De beschikbare literatuur laat in het bijzonder zien dat er solide en onbetwistbaar bewijs is voor de invloed van geluid op de mens, meer onderzoek is echter nodig om ook de impacts van geluid op de biodiversiteit te kunnen karakteriseren binnen LCA.

Het vervolg van dit proefschrift richt zich daarom verder op de modellering van geluidsemissies en -impacts op de mens.

In Hoofdstuk 4 wordt een theoretisch kader gepresenteerd waarmee het mogelijk is om geluidsemissie en geluidshindereffecten op de mens te analyseren en vast te stellen binnen LCA. Hierbij wordt een midpoint impact assessment model gehanteerd. In de Life Cycle Inventory (LCI) fase in LCA, is een manier ontwikkeld om geluid afkomstig van welke statische of bewegende geluisbron dan ook, op te nemen in het model. Gebaseerd op fysieke eigenschappen en de beschikbare wetenschappelijke kennis hierover in acht nemend, is besloten om geluidsemissie te meten op basis van haar trillingsfrequentie, de tijd van de dag wanneer de emissie plaatsvindt, en de locatie van de emissie..

Als eenheid voor de inventory uitkomst is gekozen voor de joule als eenheid van geluidsenergie welke, anders dan het geval is bij de non-lineaire eenheid decibel, ons in staat stelt verschillende geluidsbronnen samen te kunnen bekijken in één model of deze juist met elkaar te vergelijken. Bovendien wordt een karakterisatie model voor gesteld welke de geëmitteerde geluid emissie omzet in een impact. Dit model is gebaseerd op de reguliere LCIA praktijk met betrekking tot toxische stoffen en gebruikt een fate factor en een effect factor om karakterisatie factoren te berekenen voor geluidsimpacts op de mens.

In Hoofdstuk 5 is het voorgestelde model voor geluidsemissies geoperationaliseerd, uitgebreid en verder ontwikkeld voor het berekenen van de karakterisatie factoren, gebaseerd op de theoretische definities. In deze fase zijn een aantal overwegingen gemaakt met betrekking tot de ruimtelijke precisie die de karakterisatie factoren zouden moeten hebben. Er is besloten de toekomstige gebruikers van de karakterisatie factoren zelf de mogelijkheid te geven te kiezen tussen verschillend detail niveaus gebaseerd op de beschikbare informatie en context van de studie. Daartoe zijn context-gebaseerde archetypen gedefinieerd welke de meest voorkomend geluidsfrequenties, tijden en locaties omvatten. Een totaal van 248 karakterisatie factoren is berekend voor deze hiervoorgenoemde archetypische contexten. Karakterisatie factoren zijn ook berekend voor niet nader gespecificeerde contexten van geluidsemissie. Daarnaast worden er visuele kaarten van karakterisatie factoren gepresenteerd, waarbij voor elke parameter die gedefinieerd wordt in het karakterisatie model een kaart met een precisie van 10 vierkante meter is gebruikt op basis van data uit de EU. Om de gebruiker die de beschikking heeft over vrijwel alle geluidsemissies in een levens cyclus te ondersteunen, hebben we de mogelijkheid ontwikkeld voor gebruikers om casus specifieke karakterisatie factoren te berekenen door middel van een simpel rekenoverzicht. Afhankelijk van de beschikbare informatie, kan de gebruiker kiezen tussen de 10 bij 10 kilometer kaart en / of gebruik te maken van archetypische karakterisatiek factoren, of er juist voor te kiezen om zelf gebiedsspecifieke karakterisatie factoren te berekenen.

In Hoofdstuk 5 wordt aandacht besteed aan onzekerheidsfactoren in de impact assessment modellen. Gegeven de relevantie van dit onderwerp, niet alleen voor matter-less geluidsemissie maar voor welke stressor dan ook die wordt onderzocht door middel van impact assessment modellen in LCA of geïntegreerde assessment modellen in andere onderzoeksvelden binnen de milieuwetenschappen, wordt in Hoofdstuk 6 het gebruik van verschillende global sensitivity tools verder onderzocht, om de onzekerheidsfactoren van de modellen die gebruikt worden in LCIA, te kunnen identificeren. Op basis van de studie naar het characterisation model of noise impacts, is een protocol opgesteld om onzekerheids- en global sensitiviteitsanalyses standaard op te nemen bij de ontwikkeling van karakterisatie modellen.

Een verscheidenheid aan technieken met betrekking tot het geluid karakterisatie model en de resultaten hiervan is naast elkaar gelegd en geanalyseerd om te zien welke invloed dergelijke technieken kunnen hebben op het gehele LCA onderzoeksveld. We laten zien dat het belang van de structuur van het model en het relatieve aandeel van de model inputs op de mate van onzekerheid in de uitkomsten, alleen ten volle geänalyseerd kan worden wanneer er een standaard protocol wordt gevolgd, die via de juiste weg gebruik maakt van de beschikbare statistische technieken. Na de ontwikkeling van het model (Hoofdstuk 4) voor geluidsemissie en een daaropvolgende analyse om de mate van onzekerheid in het model te kunnen bestuderen, is het model hierna getest op basis van een representatieve case study, namelijk een case studie naar windturbines.

In hoofdstuk 7 onderzoeken we opnieuw de bevindingen in voorgaande hoofdstukken en beoordelen we de mate waarin inzichten die opgedaan zijn door middel van het nieuwe model voor geluidsemissie, gegeneraliseerd kan worden naar andere matter-less stressors die in de toekomst mogelijk in LCA worden opgenomen. We geven aanwijzingen hoe om te gaan met matter-less stressors in het LCA onderzoekskader en gerelateerde uitdagingen met betrekking tot het karakterisatie process. De casestudy naar windturbines is gedaan om het ontwikkelde karakterisatie model te testen, binnen een productiesysteem, waar geluidsemissies gerelateerd zijn aan de operationele fase.

Hoewel meer dan honderd LCA studies zich hebben gericht op de milieu impacts van deze relatief nieuwe energie productie systemen zijn geluidsemissies en gerelateerde impacts hierbij altijd veronachtzaamd. Deze studie laat zien dat, uitgaande van verschillend windturbine karakteristieken, het mogelijk is om de impacts van geluidsemissies op de mens te kwantificeren, en dat verschillende systemen met elkaar vergeleken kunnen worden op basis van deze resultaten. De case studie laat overtuigend zien dat het mogelijk is om het ontwikkelde karakterisatie model in te zetten in LCA en de impacts van geluidsemissies te kwantificeren, waarbij het gehele proces van de extractie van natuurlijke hulpbronnen tot de afbraak van restproducten mee wordt genomen.

Het doel van dit proefschrift was om te onderzoeken hoe matter-less stressors opgenomen kunnen worden in LCA. De onderzoeksvragen die worden beantwoord in dit proefschrift, ook al zijn deze met name gericht op matter-less stressors, zorgen voor een aantal belangrijke stappen voorwaarts om de verbetering van het LCA onderzoekskader een impuls te geven. De gegeven selectie criteria stellen ons in staat om op rationale wijze te kunnen beslissen welke stressors het meest in aanmerking komen om de reikwijdte van LCA te vergroten. Dit proefschrift laat ook zien dat niet alle stressors per definitie opgenomen hoeven te worden in LCA

Echter, de case studie van geluidsemissie in dit proefschrift kan beschouwd worden als paradigmatisch als het gaat om hoe nieuwe stressors, matter-less of niet, bestudeerd en al dan niet opgenomen kunnen worden in LCA. We laten zien dat LCA niet per definitie het instrument is dat in alle gevallen, alle mogelijke milieukundige analyses vorm kan geven: LCA kent haar beperkingen. Sommige van deze beperkingen kunnen worden weggenomen door verder onderzoek, andere kunnen ondervangen worden door LCA in combinatie met andere milieu analyse instrumenten. Om LCA een betrouwbaarder instrument voor milieukundige analyses te maken, is het noodzakelijk dat experts uit aanverwante wetenschapsgebieden, direct betrokken worden in de ontwikkeling van (nieuwe) modellen en methoden. Een praktisch voorbeeld hiervan is de globale sensitiviteitsanalyse die gedaan is in dit proefschrift. De expertise binnen het wetenschappelijke kader van LCA is gecombineerd met expertise uit het wetenschapsveld van de statistiek.

Curriculum Vitae

Stefano Cucurachi was born in 1985 in Copertino, Italy. He comes from the heel of the Italian boot, in the region of Apulia. He graduated from Liceo Classico Giuseppe Palmieri of Lecce, a secondary school specializing in classical studies, in 2003. From 2003 to 2006 he studied Industrial engineering at Universitá LIUC- Carlo Cattaneo in Italy. Following on from this, he continued his studies with a Master's degree in Industrial Engineering with a dissertation focusing on the search of Pareto optimality between decisions driven by LCA and decision driven by financial and managerial pressures in a company environment. The MSc in Industrial Engineering was awarded in 2008. Stefano continued his academic training at the University of Kent in the UK where he completed in 2009 a Master's degree in Management Science and Logistics. His dissertation focused on the application of mathematical models to environmental problems, and in particular on the development of a statistical model to evaluate the cost of fixing fish-passage barriers in watersheds. During the course of his university studies Stefano further lived in England and Canada, in which he completed two academic years as an exchange student. After the completion of his studies, Stefano started an internship in the R&D and logistics units of Xerox Co. in Milan, Italy. In close contact with the top management of the Italian unit of the company, he developed protocols for the recovery of end-of-life machinery returning after the end of lease contracts. He started in May 2010 his experience at the CML Institute of Environmental Sciences of the University of Leiden where the work that is presented before you was developed. For the last two years Stefano has also been an active member of the SENSE research school and has sat in the PhD council of the research school.

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