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

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Synopsis

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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.