



Universiteit
Leiden
The Netherlands

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

Cucurachi, S.

Citation

Cucurachi, S. (2014, October 21). *Impact assessment modelling of the matter-less stressors in the context of Life Cycle Assessment*. Retrieved from <https://hdl.handle.net/1887/29300>

Version: Corrected Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/29300>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden

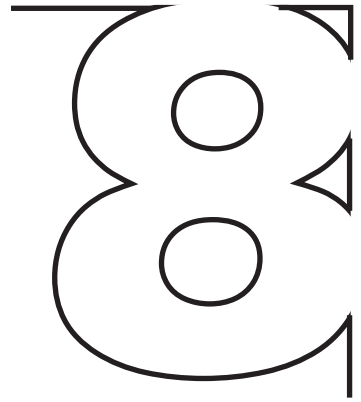


The handle <http://hdl.handle.net/1887/29300> holds various files of this Leiden University dissertation.

Author: Cucurachi, Stefano

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

Issue Date: 2014-10-21



**Answers
to the
research questions
and
concluding remarks**

Answers to the research questions and concluding remarks

1

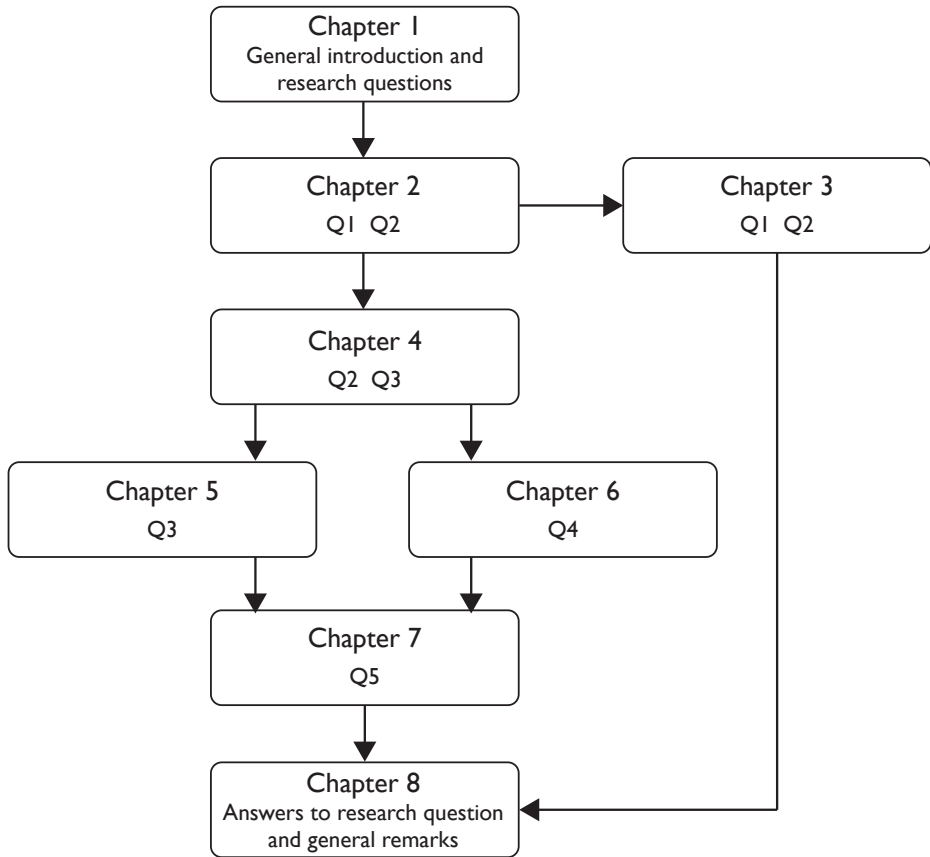
Introduction

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-modified 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 devise 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). A light-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 of 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-less 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.

References

- Althaus, H. J., de Haan, P., Scholz, R. W. (2009). Traffic noise in LCA. *The international journal of life cycle assessment*, 14(6), 560-570.
- Brandt, A. R. (2012). Variability and uncertainty in life cycle assessment models for greenhouse gas emissions from Canadian oil sands production. *Environmental science technology*, 46(2), 1253-1261.
- Curran, M. A. (1993). Broad-based environmental life cycle assessment. *Environmental science technology*, 27(3), 430-436.
- EC-JRC, 2011. Recommendations based on existing environmental impact assessment models and factors for life cycle assessment in European context. ILCD Handbook—International Reference Life Cycle Data System, European Union EUR24571EN. ISBN 978-92-79-17451-3. At http://lct.jrc.ec.europa.eu/assessment/assessment/projects#consultation_impact – accessed January 2013.
- Fang, K., Heijungs, R., de Snoo, G. R. (2014). Theoretical exploration for the combination of the ecological, energy, carbon, and water footprints: Overview of a footprint family. *Ecological Indicators*, 36, 508-518.
- Francis, C. D., Barber, J. R. (2013). A framework for understanding noise impacts on wildlife: an urgent conservation priority. *Frontiers in Ecology and the Environment*, 11(6), 305-313.
- Frischknecht, R., Jungbluth, N., Althaus, H. J., Doka, G., Dones, R., Heck, T., Spielmann, M. 2005. The ecoinvent database: Overview and methodological framework (7 pp). *The International Journal of Life Cycle Assessment*, 10(1), 3-9.
- Gaston, K. J., Bennie, J., Davies, T. W., Hopkins, J. (2013). The ecological impacts of nighttime light pollution: a mechanistic appraisal. *Biological Reviews*, 88(4), 912-927.
- GWEC, 2013. Global Wind Statistics—2012. Global Wind Energy Council, Brussels
- Heijungs, R. (1996). Identification of key issues for further investigation in improving the reliability of life-cycle assessments. *Journal of Cleaner Production*, 4(3), 159-166.
- Hölker, F., Moss, T., Griefahn, B., Kloas, W., Voigt, C. C., Henckel, D., Tockner, K. (2010). The Dark Side of Light: A Transdisciplinary Research Agenda for Light Pollution Policy. *Ecology Society*, 15(4).
- Holzman, D. C. (2014). Fighting noise pollution: a public health strategy. *Environ Health Perspect*, 122, A58.
- Hetherington, A. C., Borrion, A. L., Griffiths, O. G., McManus, M. C. (2014). Use of LCA as a development tool within early research: challenges and issues across different sectors. *The International Journal of Life Cycle Assessment*, 19(1), 130-143.
- Huijbregts, M. A. (1998). Application of uncertainty and variability in LCA. *The International Journal of Life Cycle Assessment*, 3(5), 273-280.
- Jeswani, H. K., Azapagic, A., Schepelmann, P., Ritthoff, M. (2010). Options for broadening and deepening the LCA approaches. *Journal of Cleaner Production*, 18(2), 120-127.
- Kight, C. R., Swaddle, J. P. (2011). How and why environmental noise impacts animals: an integrative, mechanistic review. *Ecology letters*, 14(10), 1052-1061.
- Lazarevic D., Buclet N., Brandt N. (2012). The application of life cycle thinking in the context of European waste policy. *J Clean Prod* 29–30:199–207.
- Lloyd, S. M., Ries, R. (2007). Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches. *Journal of Industrial Ecology*, 11(1), 161-179.
- Moore, C. B., Siopes, T. D. (2000). Effects of Lighting Conditions and Melatonin Supplementation on the Cellular and Humoral

Immune Responses in Japanese Quail *Coturnix coturnix japonica*. *General and comparative endocrinology*, 119(1), 95-104.

Müller-Wenk, R. (2004). A method to include in LCA road traffic noise and its health effects. *The International Journal of Life Cycle Assessment*, 9(2), 76-85.

Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., Rebitzer, G., 2004. Life cycle assessment Part 2: Current impact assessment practice. *Environ. int.*, 30(5), 721-739.

Pfister, S., Bayer, P. (2013). Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production. *Journal of Cleaner Production*.

Premalatha, M., Abbasi, T., Abbasi, S.A. (2014). Wind energy: Increasing deployment, rising environmental concerns. *Renewable and Sustainable Energy Reviews*, 31, 270-288.

Rosenbaum, R. K., Margni, M., Jolliet, O. (2007). A flexible matrix algebra framework for the multimedia multipathway modeling of emission to impacts. *Environment international*, 33(5), 624-634.

Sala, S., Farioli, F., Zamagni, A. (2013). Life cycle sustainability assessment in the context of sustainability science progress (part 2). *The International Journal of Life Cycle Assessment*, 18(9), 1686-1697.

Schmitt, J., Seidler, A., Diepgen, T. L., Bauer, A. (2011). Occupational ultraviolet light exposure increases the risk for the development of cutaneous squamous cell carcinoma: a systematic review and meta-analysis. *British Journal of Dermatology*, 164(2), 291-307.

Stewart, J., McManus, F., Rodgers, N., Weedon, V., Bronzaft, A. (2012). *Why Noise Matters*. Earthscan from Routledge.

Van Kamp, I., Davies, H. (2013). Noise and health in vulnerable groups: A review. *Noise health*, 15(64).

