SCORELCA

STUDY N° 2019-01

DEALING WITH PARTICLES IN THE METHODS FOR LIFE CYCLE IMPACT CHARACTERIZATION

Summary

August 2020

Scientific coordinators* & co-authors

Benoît Bulliot*, Magdalena Czyrnek-Delêtre*,
Isaure Adam, Clément Lefort et Alexis Burguburu

I Care & Consult, 28 rue du 4 Septembre, 75002 Paris

SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.

✓ This work has been supported by ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie) www.ademe.fr

Introduction

The consideration of particulate matter in LCA is based on the development of methods that allow the integration of research results related to the health and environmental impacts of particulate matter into the life cycle assessment framework. The first work that has made it possible to take into account particles in LCA dates back to the end of the 1990s with the work of Hofstetter (1998).

Since then, the consideration of particles has gradually evolved in parallel with the progress of scientific knowledge on the impact of particles.

However, to date, the available LCA methods for characterizing impacts have significant limitations in addressing the health and environmental issues associated with particles. Although the "Particulate Matter" impact category is classified as I (robust) by the ILCD, the recommended method, UNEP 2016, does not cover all aspects of these impacts nor all types of particles.

On the other hand, scientific knowledge has progressed considerably, as shown by the recent work of ANSES on the impact of particles according to their composition and origin. However, in order to take this knowledge into account in LCA, it is necessary to be able to quantify these impacts on health and the environment with sufficient precision.

The objective of this study is therefore to identify how the health and environmental impacts of particles in LCA and non-LCA are taken into account, and then to provide recommendations for a better consideration of particles in LCA in order to assess their environmental impacts in a more accurate and robust way.

These recommendations tackle good practices for practitioners on the one hand and specific recommendations to be implemented by method developers on the other. Illustrations of these recommendations are also proposed on simple cases of LCA.

I. Typology and impacts of particles

1. Particle typology

The particles are mainly characterized by their size: coarse, fine and ultrafine particles, to each of these sizes are associated origins, compositions and characteristics summarized in the table below

Particles	Ultrafine particles ($PM_{0,1}$)	Fine particles (PM2,5)	PM10 and coarse particles
Formation	Nucleation/condensation	Accumulation/Nucleation/condensation	Break-up of large solids/droplets
Composition	Sulfate Elementary carbon Metal compounds Low volatility organic compounds	Sulfate, nitrate, ammonium, and hydrogen ions Elementary carbon, Low and medium volatility organic compounds Metals compounds	Oxides of crustal elements (Si, Al, Ti, Fe), mineral dust Pollen $CaCO_3$, $CaSO_4$, NaCl, sea salt
Sources	High temperature combustion Atmospheric reactions of primary, gaseous compounds	Combustion of fossil and biomass fuels Atmospheric oxidation of NO2, SO2, and organic compounds, including biogenic organic species	Fly ash from uncontrolled combustion, Suspension from disturbed soil, construction and demolition Road dust, Tire, brake pad debris Ocean spray
Atmospheric half-life	Minutes to hours	Days to weeks	Minutes to hours
Travel distance	<1-10km	10 à 100 km	< <1 to 10s of km (100s to 1,000s of km in dust storms)
Solubility	Not well characterized	Largely soluble	Largely insoluble or with low solubility
Penetration into the respiratory system	Alveoli; passage through the alveolar-capillary barrier	Terminal bronchioles and alveoli; passage through the alveolar-capillary barrier	Bronchioles

Table 1 : Synthesis of particle characteristics by size

2. Health impacts of particles

The REVIHAAP[1] study of the WHO indicates that majority of existing studies quantifying the impact of particulate matter deal with the effects of long-term (mortality and morbidity) and short-term (morbidity) exposure to PM2.5.

WHO points out that there exist quantitative studies for specific health impact aspects that are based on other types of particles (e.g. PM10, coarse fraction of PM10, soot carbon and sulphate), however, the study emphasizes that the health impact assessment will be most comprehensive when considering PM2.5 as a whole. Alternative methods of risk quantification cannot be added together since the effects are not independent, moreover it does not seem true that a particle defined by its source or its composition would allow a better assessment of toxicity than this mass approach using PM2.5.

Another important aspect to consider when assessing the impact of particulate matter is that the concentration-risk (C-R) relationship is not necessarily linear over the range of concentrations to which the human population is exposed.

3. Climate change impacts of particles

Quantitative assessment of the impact of particulate matter on climate change still has several limitations despite scientific progress:

At present, aerosols remain the main source of uncertainty in the assessment of climate change impact, although progress has recently been made. The reasons for this uncertainty are that the properties of particles, as well as those of the clouds with which particles interact, vary substantially on a much finer scale than is currently possible to incorporate into climate models.

In addition, the direct radiative forcing of particles has a regionally heterogeneous impact on hydrological changes and air mass circulation patterns.

There is also uncertainty and variability in the impact of particulate matter due to complex feedback effects of the climate system, including the influence of weather on particulate emissions and formation as well as their lifetime.

From a quantitative point of view, impact measurements via the Global Warming Potential (GWP) and the Global Temperature Potential (GTP) was developed for different time horizons. However, these factors have been developed at the level of particulate matter for primary particles (Organic Carbon and Black Carbon) and at the level of precursors of secondary particles (NO_x, SO_2, VOC, CO).

It should be noted that these factors have large uncertainties which illustrate the difficulties of assessing the effect of aerosols on climate.

4. Impacts of particles on the ecosystems

Measuring the impacts of particulate matter on the ecosystem requires a detailed understanding of the deposition process of the particles. Besides, quantification of the impacts of PM with sulphur and nitrogen on ecosystems can only be made by considering the whole cycle of these elements. As a consequence, the specific impact of particulate matter is currently not quantified.

It also appears that the impact of PM on the ecosystem is more dependent on particles chemical composition than on the size and the total mass of the particles.

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[1] REVIHAAP – Review of evidence on health aspects of air pollution, WHO/Europe, 2013 - https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report

II. LCA bibliography

1. Indicators associated with particulates emissions

The life cycle assessment methods used in this study are as follows:

- ILCD 2011 (International Life Cycle Data)
- ReCiPe 2016
- Impact World + 2019
- EF3.0 method (PEF) based on the method developed by UNEP/SETAC

The first stage of this bibliographical work consists in identifying, for each of the methods selected, which indicators take into account particulate matter when assessing environmental impacts.

Particulate Matter / Respiratory Inorganics category only considers particles, regardless of the method studied.

In particular, Climate Change category does not consider the impact of particulates at all at present, even though they have an effect on climate change. To date, Near-Term Climate Forcers (NTCFs) are not characterized by any LCA method. The IPCC report provides factors for GWP100 as well as for GWP20 which are not implemented in current methods.

2. Theoretical analysis of the consideration of particles in LCA Particulate Matter indicator

2.1. Impact Pathway

Particulate Matter indicator links particulate matter emissions to the human health impact (end-point). To characterize this health impact, a pathway impact is defined.

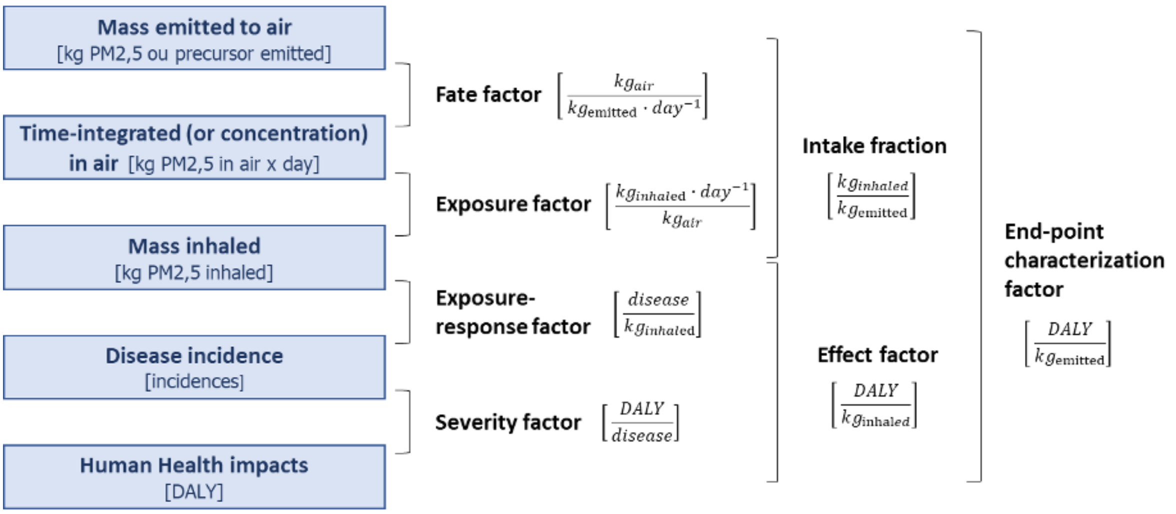

Figure 1 : Impact pathway characterizing human health effects from exposure to particulate matter in LCA (Adaptation of Haes et al., 2002 et Jolliet et al., 2004)

This indicator therefore links the amount of particulate matter or precursors emitted to a measure of population health damage expressed in DALYs (Disability-Adjusted Life Years), a measure of the number of years of healthy life lost due to illness or premature death.

The characterization factor (CF) can be expressed as the product of a fate factor (FF), an exposure factor (EF), an exposure-response factor (ERF) and a severity factor (SF):

$$CF = FF \cdot EF \cdot ERF \cdot SF$$

The product of the fate factor and the exposure factor is generally referred to as the *intake fraction* : $iF = FF \cdot EF$.

2.1.1. Intake Fraction

The intake fraction reflects what fraction of an emitted amount of particulate matter will eventually be inhaled by the population. The following figure provides a theoretical illustration of fractional intake.

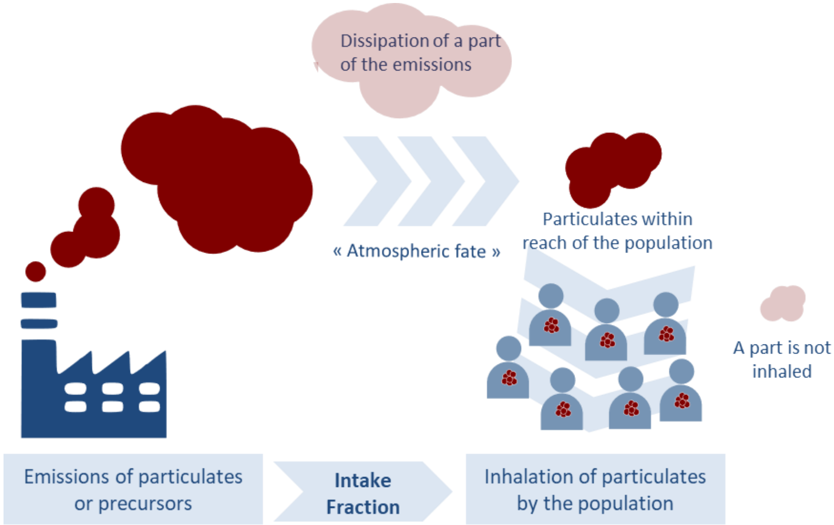

Figure 2 - Theoretical illustration of the intake fraction

Particles or precursors are emitted into the air. This mass of pollutant in the air evolves according to meteorological parameters and some of it is naturally dissipated over time. Once within reach of the population, a certain part of this mass of pollutant in the air is inhaled by the population. This part inhaled depends in particular on population density.

The fraction intake is defined as follows:

$$iF_p = \frac{Cumulative\ population\ intake\ (kg)}{Total\ pollutant\ emission\ (kg)}$$

In order to calculate iFs, LCA researchers use chemical transport models to simulate the fate of particles in the atmosphere, and couple this with data on population exposure to particles (population density, inhalation rate ...). Two approaches exist to perform iFs calculations:

- The **spatialized approach**, which consists in decomposing the calculations by region by considering the local conditions of each region (with a more or less fine grid).

- The **archetype approach**, which allows to gather many local conditions into a few typical conditions. In the methods analyzed here, archetypes on emission height (which has an influence on the fate factor) and population density (which has an influence on the exposure factor) are used.

Chronology of the development of intake fraction values and LCA methods

The development of the methods analyzed in this study has been done in continuity with the development of iFs values. Thus, the methods were based on iFs values from the scientific literature available at the time they were developed. The following figure illustrates the chronology of iFs and LCA method publications.

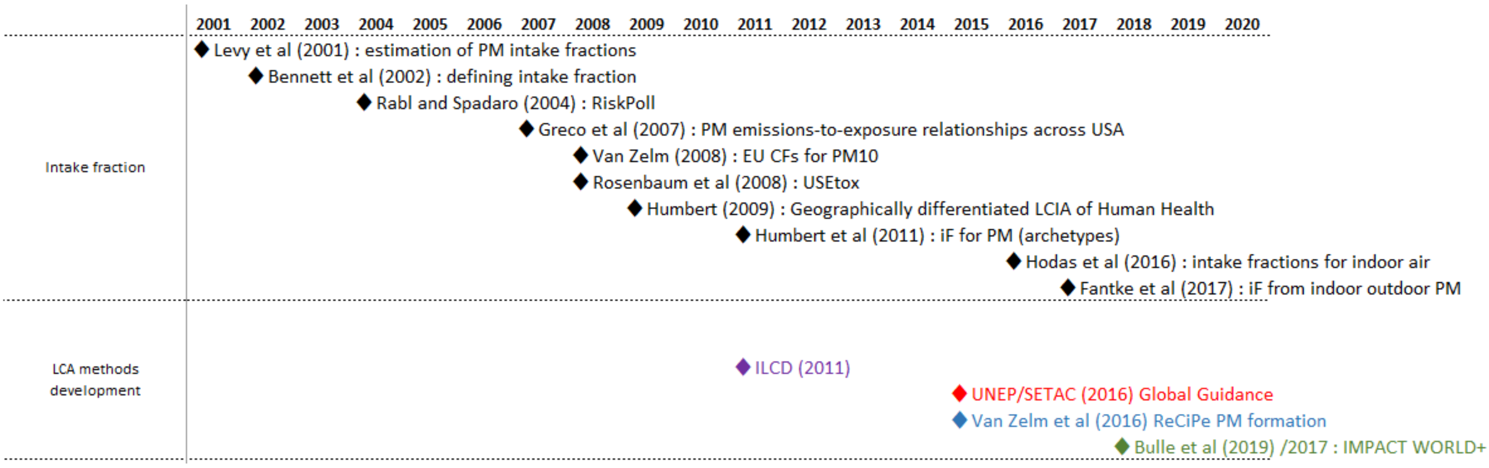

Figure 3 - Chronology of Intake Fractions and LCA Methods Publications

Several characterization models were developed and proposed iFs between 2004 and 2008. In 2009, Humbert synthesized these developments and detailed further the proposed archetypes. These factors are used in the ILCD method. They are then updated and consolidated in 2011, before being used in the Impact World+ method and the UNEP/SETAC method. The ReCiPe method is based on spatialized factors developed independently by Van Zelm and colleagues in 2008 and 2016.

Factors and parameters

PM10 do not have their own factor, but the PM10 iF is a ratio that corresponds to the fraction of PM2.5 in PM10. The fraction used for this calculation is not the same in all methods: ILCD and EF3.0 use a factor of 23%, while Impact World+ uses a factor of 60%. ReCiPe does not propose a factor for PM10.

The intake fraction also makes it possible to describe exposure to so-called "secondary" PM2.5 caused by precursor emissions. The precursors considered are the same for the four methods analyzed here: nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ammonium (NH_3).

Finally, indoor emission sources are not considered at present time. Nevertheless, developments are ongoing on the subject and some iFs have been developed but are not integrated into the operational methods implemented in the LCA tools now.

2.1.2. Exposure-reponse factor

The exposure-response factor (ERF) links exposure (amount inhaled by the population) to impacts on the health of the population.

Methodology for calculating the ERF

To calculate the ERF, researchers rely on the results of epidemiological studies coupled with statistical data on particulate matter exposure and mortality on a larger scale in order to obtain the most general ERF possible.

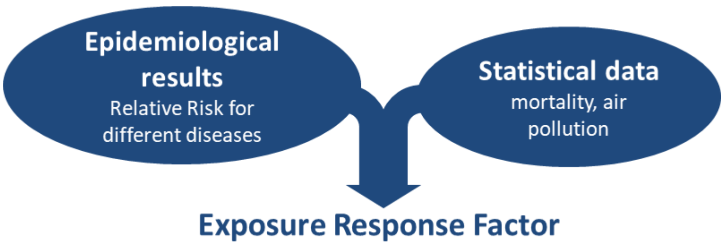

Figure 4 - Illustration of ERF calculation by LCA researchers

The ERF obtained therefore depends on determining parameters such as:

- the dose-response function considered, which represents the health effect as a function of exposure to particulate matter. It can be linear or non-linear, and thus take into account the initial exposure or not.

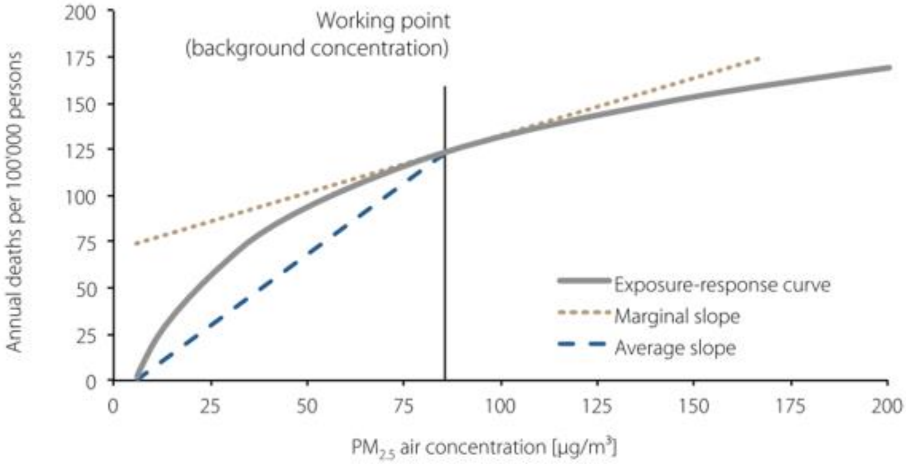

Figure 5 - Illustration of a non-linear dose-response function

- the diseases considered
- the epidemiological source used

Figure 6 illustrates the different epidemiological sources and diseases considered on which the ERF calculation of each LCA method is based.

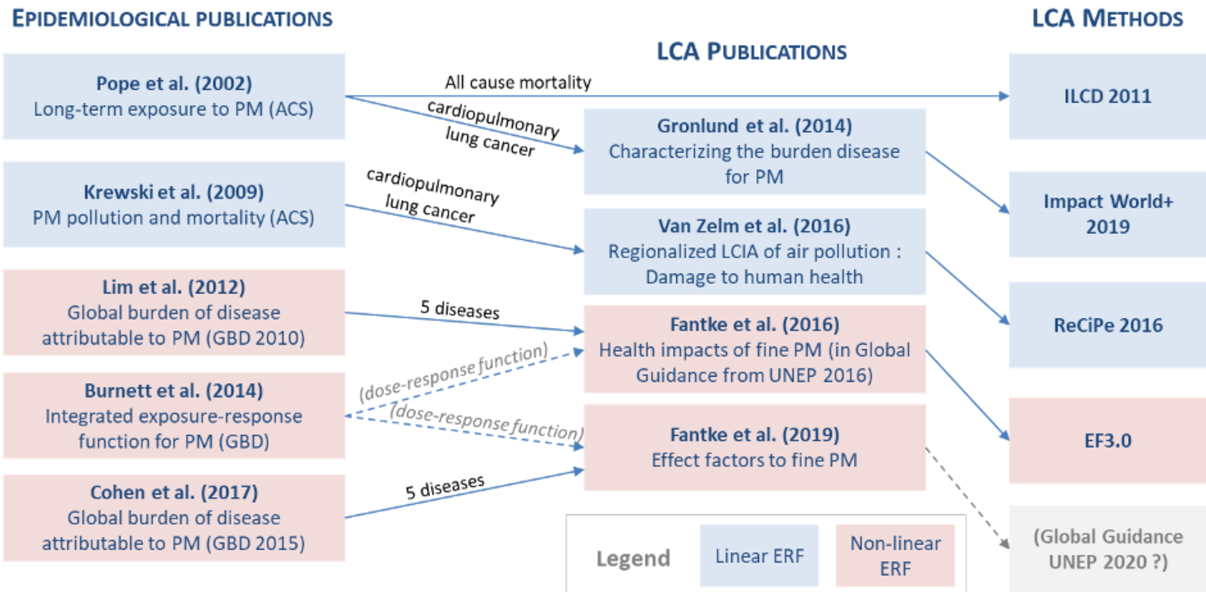

Figure 6 - Illustration of the different epidemiological sources used for the calculation of the ERF in LCA methods

Only the UNEP/SETAC method adopted by the JRC in the EF3.0 method uses a non-linear dose-response function. Furthermore, while the ILCD method considered all-cause mortality for the calculation of ERF, Impact World + and ReCiPe methods consider only cardiopulmonary diseases and lung cancers whereas EF3.0 method goes a little further by considering five diseases[2].

2.1.3. Severity Factor

The exposure-response factor is used to estimate the number of cases of disease in a population exposed to particulate matter. The severity factor (SF) is used to estimate the severity of these health effects, expressing them as a single unit called DALY (Disability-Adjusted Life Years).

To calculate the SFs, researchers also rely on epidemiological studies and statistics on the mortality and morbidity associated with each disease considered in the particulate characterization.

EF3.0 does not propose an end-point characterization factor, so it does not use SFs.

[2] Ischemic heart disease, cerebrovascular disease, lung / bronchus / tracheal cancer, chronic obstructive pulmonary disease in adults (≥25 years), and lower respiratory tract infections in young children (≤5 years).

2.2. Overview of the methods

	ILCD	ReCiPe	IMPACT WORLD +	PEF
Substances characterized	PM10 NH_3 PM2,5 NO_x SO_2	PM2,5 NH_3 NO_x SO_2	PM2,5 NH_3 PM10 NO_x SO_2	PM2,5 NH_3 PM10 NO_x SO_2
Indicators and units	**Mid-point** : up to iF expressed in kgPM2.5 eq **End-point :** in DALY	**Mid-point :** up to iF expressed in kgPM2.5 eq **End-point :** in YLL	**Mid-point :** up to iF expressed in kgPM2.5 eq **End-point :** in DALY	**Mid-point :** up to ERF expressed in *disease incidence* **End-point :** no end-point
Archetypes	3 archetypes : *urban ground* *Non-urban or from high stack* *Unspecified*	No archetype. Spatialized calculation based on a grid.	3 population density archetypes : *Urban* *Rural* *Remote* 3 height of emission archetypes : *High stack* *Low stack* *Ground level* + unspecified archetype crossed with all other archetypes	2 population density archetypes : *Urban* *Rural* 4 emission height archetype : *Very high stack* *High stack* *Low stack* *Ground level* + archetype *unspecified*
Diseases considered	All-cause mortality Chronic bronchitis	Cardiopulmonary diseases Lung cancer	Cardiopulmonary diseases Lung cancer	Ischemic heart disease, cerebrovascular disease, lung / bronchus / tracheal cancer, chronic obstructive pulmonary disease in adults (≥25 years), and lower respiratory tract infections in young children (≤5 years).
Epidemiological study(s) for ERF	ACS (Pope et al 2002) et Kuenzli et al 2000.	ACS (Krewski et al 2009).	ACS (Pope et al., 2002).	GBD 2010 (Lim et al., 2012)
Dose-response function	Linear	Linear	Linear, based on Gronlund et al., 2014 study	Non linear, based on Burnett et al 2014 study
Epidemiological study(s) for SF	ACS (Pope et al 2002) et de Kuenzli et al 2000.	World health statistics 2015, WHO (World Health Organization)	GBD 2010 (Lim et al., 2012)	GBD 2010 (Lim et al., 2012)
PM10 consideration	23% of PM2,5 factor	-	60% of PM2,5 factor	23% of PM2,5 factor
Unspecified factor	Unspecified PM2,5 is an average factor	-	Unspecified PM2,5 is an average factor	Unspecified PM2,5 is characterized by the worst factor

MAIN RESULTS

- Only the health effect of PM2.5 is currently characterized in LCA, all methods being based on the assumption that PM10-2.5 has no demonstrated effect on human health.
- No method considers a finer particle size than PM2.5, which means that all PM2.5 are characterized in the same way regardless of their size.
- Emission sources and chemical composition of particulate matter are not considered.
- There are two approaches to the location of emissions: an archetype approach dealing with typical conditions of population density and emission height, and a spatialized approach. However, spatialized factors are not always available in LCA tools; only ReCiPe uses the latter approach.
- The archetypes currently considered in operational methods do not include an indoor archetype to date, although this is developed in the recent UNEP publication.
- The health effects considered vary from one method to another, according to the source epidemiological studies used, and the type of mortality considered: all-cause or specific mortality. Only ILCD uses all-cause mortality. The other methods characterize between 2 and 5 diseases.
- The effect of particulate matter on health can be modelled using two approaches: a linear versus a non-linear dose-response function. The latest models propose a non-linear approach.

3. Practical analysis of the consideration of particles in LCA Particulate Matter indicator

3.1. Presentation of methods granulometry

EF3.0, IMPACT WORLD+, ILCD 2011 and ReCiPe methods patterns are shown in the final report. Those patterns provide a broader view of the structure of methods.

There is a characterization factor at the end of each branch. The dotted lines are not part of the branches; they indicate an existing archetype equivalent to the archetype to which it is attached.

3.2. Use of the *unspecified* archetype

When an emission of particles or precursors is entered into the LCA software without knowledge of the emission conditions, the unspecified archetype may be used, instead of more precise archetype. Depending on the method, different approaches were used to allocate a factor to “unspecified” cases.

EF 3.0	Conservative approach : higher factor
Impact World +	Average approach: weighted average of total number of factors
ILCD	

3.3. Comparison of end-point characterization factors

The figures below present a comparison of end-point factors between ILCD, Impact World+ and the UNEP method (on which the mid-point of EF3.0 is based) for flows that are likely to be used often: the PM2.5 flow with the urban ground and rural high stack archetypes, and the NH_3, NO_x, and SO_2 precursor flows with the urban and rural archetypes. The ReCiPe method is not compared here because its end-point factor is not expressed in the same unit (YLL).

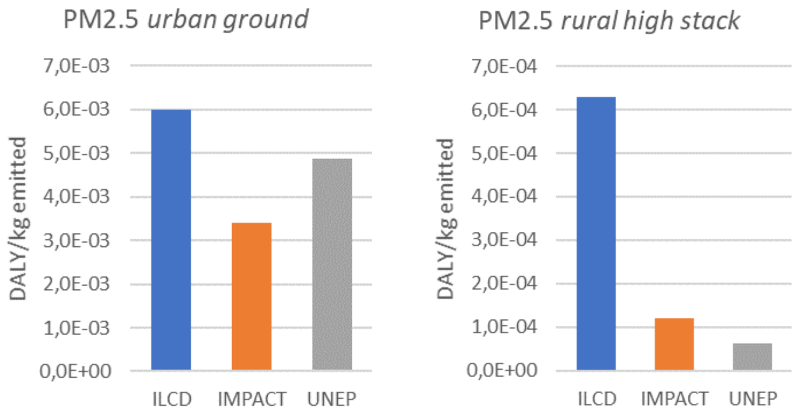

Figure 7 - Comparison of end-point CFs of PM2.5 urban ground and PM2.5 rural high stack

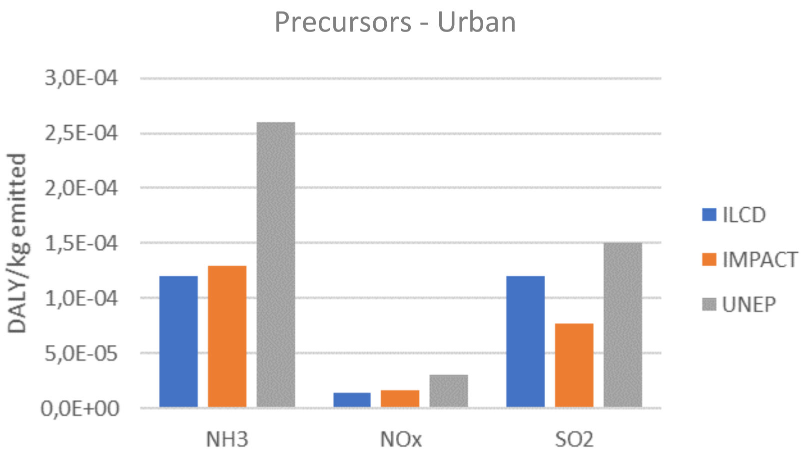

Figure 8 - Comparison of precursor end-point CFs with the urban archetype

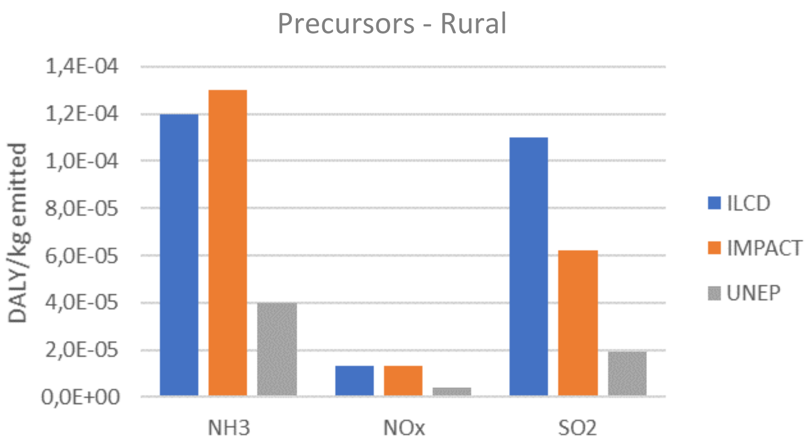

Figure 9 - Comparison of precursor end-point CFs with rural archetype

The three figures above show that the impact of the different emissions (of primary PM2.5 or precursors, in urban or rural areas) are not of the same order of magnitude, once again reflecting the importance of the archetypes, and vary significantly from one method to another.

For the PM2.5 rural high stack flow, the factor used by ILCD covers higher variety of conditions (archetype rural or from high stack) and in overall, is more impacting in terms of exposure than other methods. The CF of ILCD is therefore higher.

For the other flows, ILCD has fairly low intake fractions, which were revised and increased during the development of Impact World + and UNEP factors. Impact World + and UNEP use intake fractions that are close or identical for precursors.

In contrast, for effect factor, ILCD considers a much higher effect factor, due to the consideration of all-cause mortality in epidemiological studies, unlike Impact World + and UNEP, which only considered a few specific causes.

UNEP factors are higher than Impact World + factors on urban flow and lower on rural flow for both PM2.5 and precursors, even if intake fractions are very close. As UNEP considered a non-linear dose-response function, the effect factor depends on the archetype used, it is generally above that of Impact World + for urban emissions and below that of Impact World + for rural emissions. Note that there is an inconsistency in the UNEP factors between rural and urban, as the dose-response function explained by UNEP describes a lower additional health effect for a higher initial exposure. The problem is not the dose-response function itself, which can be applied between two specific locations and will correctly give the highest health response at the lowest concentration location, but the use of two separate sources of concentration data used to parameterize the rural and urban archetypes. This will be corrected in the next factors to be published by Peter Fantke at the end of 2020.

In the end, the CFs are close between ILCD and Impact World + (except for PM2.5 rural high stack where ILCD is higher). The UNEP CFs are lower for the rural archetypes, higher for the urban precursors, and between Impact World + and ILCD for PM2.5 urban ground.

III. Recommendations

1. Particulate Matter

1.1. Recommendations to practitioners

In order to assess the adaptations to be made by practitioners to take better account of particulate matter, the recommendations are based on the main steps of the ISO 14040-44 LCA standard.

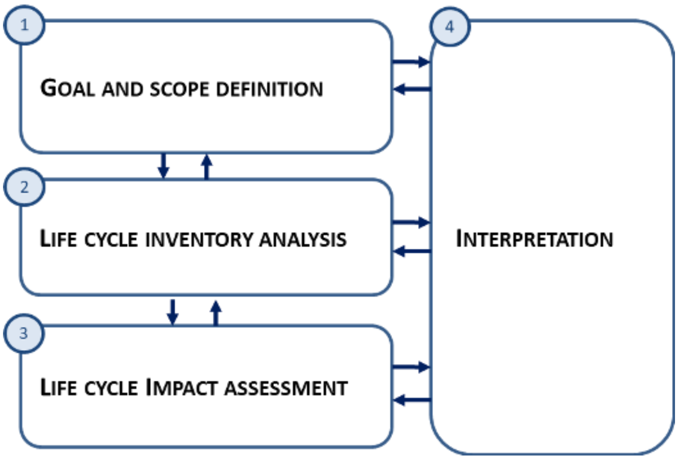

Figure 10 : LCA steps according to ISO 14040-44

1.1.1. Goal and scope definition

Identified issues	Recommendations
• Particulate matter subject **poorly considered** when defining the goal and scope of the study	• Identify whether the **subject of particulate matter is important**, and if so, at which stage(s) of the life cycle - Adjusting the level of detail needed on data collection - Define relevant life cycle boundaries

1.1.2. Life cycle inventory

- **Data collection**

Identified issues	Recommendations
• Risk of **double counting** (PM10 - PM2.5) • Lack of precision in the collected data (emission conditions, ...) • Data not collected (identification upstream of the collection of important steps) • Flows available in LCA tools but not characterized in all methods • Lack of hypothesis formulation on the part of the practitioner	• Conducting an in-depth collection: - Potentially emitting life cycle stages must be identified - The source of the data must be known - Conditions of emission must be identified (related to archetypes) • Checking that the selected flows are well characterized • Making assumptions where data are missing, including on emission conditions

- **Identification of emitting processes**

Identified issues	Recommendations
• Use of generic processes: - Databases don't always have sufficient information - Adaptation of generic processes can be done but is rarely performed by LCA practitioners	• Identify life cycle stages, and processes that are sources of emissions • Question the archetypes used by the generic processes • Adapt the inventory to address generic process inaccuracies

1.1.3. Life cycle impact assessment

- **Selection of indicators and characterization models**

Identified issues	Recommendations
• Different methods available: - Different model assumptions - More or less conservative models - Models with archetypes or with spatial factors - Overall lack of practitioner knowledge of the methods limitations	• Need for the practitioner to be aware of the advantages and limitations of each method in order to choose the most appropriate one for his or her study.

Methode	Comment
ILCD	Globally obsolete particulate method in view of the data used, the available archetypes and subsequent developments. Some key points: - In the absence of knowledge of emission conditions, an average approach is adopted - The number of archetypes is limited: only high pop and low pop - The factor for PM10 is lower than for the Impact World + method (23% of the CF PM2.5 against 60%): this value is less conservative and less consensual a priori.
IMPACT WORLD+	This method is positioned as a complete method with more recent data than ILCD. The numerous archetypes, if well used, allow a relatively fine analysis. Some essential points: - This is one of the most accurate methods, especially in the case where specific information on the emission conditions is accessible because many archetypes are available. - The only method that allows an exhaustive combination of archetypes: very useful if the information on the emission conditions is imperfect (knowledge of the emission height but not of the location for example). - In the absence of the information on the emission conditions, an average approach is adopted. - The data are nevertheless less recent than those used for the PEF method, especially for the effect factor, which is lower than for PEF (fewer diseases considered, etc.). - PM10 are characterized with a value of 60% of PM2.5, which seems to be a consensus today.

EF3.0	Most advanced methodology in the approach with more recent data, more diseases considered, a non-linear dose response function for more precision for high concentrations, etc. Nevertheless, a problem in the homogeneity of the data considered leads to inconsistent factors for the rural archetype, which is an important limitation. Some essential points: - This is one of the most precise methods in the case where we have a detailed knowledge of the emission conditions because many archetypes are available, but the problem with the "rural" factors strongly mitigates this point. - In the absence of information on emission conditions, a conservative approach is adopted. - The factor for PM10 is lower than for the Impact World + method (23% of the CF PM2.5 against 60%): this value seems less conservative and less consensual.
ReCiPe	ReCiPe proposes a spatialized approach, which differs greatly from other methods. • A spatialized inventory is necessary - To be used only if the LCA tool includes spatialized factors or integration of spatialized factors is necessary.

1.1.4. Life cycle interpretation

- **Results analysis**

Identified issues	Recommendations
• Lack of awareness of the Particulate Matter indicator among LCA practitioners: inadequate or non-existent interpretation • Uncertainties and limitations in the characterization of particulate matter not sufficiently considered in the interpretation of impact results	• LCA is an iterative process: it is necessary to question the results and in particular the contributing processes in order to refine/modify the inventory. • Need to develop training for LCA practitioners

- **Verification**

Identified issues	Recommendations
• An error in the choice of flow has a strong influence on the impact results. (Ex: orders of magnitude x100 between PM2.5 urban ground and PM2.5 rural high stack)	• Perform one or more sensitivity analyses on particulate emissions - Identify inaccurate data - Identify the parameter to be varied ▪ Quantitative flow data ▪ Particulate type ▪ Archetype used

1.2. Technical recommendations for other actors

1.2.1. Development of characterization factors

Identified issues	Recommendations
• No indoor factors in current operational LCA methods • The latest developed indoor factors only concern emissions related to cooking and heating • Choice of archetypes sometimes difficult due to lack of information on conditions (height of emissions, population density) • The phenomenon of limiting precursors is not considered at the moment	• Deepen the development of indoor factor • Investigate the possibility of developing indoor factors for other emission sources. • Study the option of archetypes related to emission sources (by sectors) • To deepen and integrate the phenomenon of limiting precursors

Ongoing developments

In Peter Fantke's latest papers[3] the authors proposed new intake fractions and new effects factors, including indoor factors. These two articles will be combined in 2020 to propose new characterization factors, integrating indoor factors and correcting the current inconsistency between rural and urban factors.

1.2.2. Database development

Identified issues	Recommendations
• Sometimes imprecise inventories of particulate emissions. • Not all archetypes available in the methods are available in the databases.	• Work with databases to integrate more accurately the archetypes so that the finesse of the methods can be deployed effectively.

1.2.3. Development of LCA tools

Identified issues	Recommendations
• Spatialized characterization factors not available in some LCA tools	• Implement in the LCA tools all the spatialized characterization factors developed in the methods.

[3] Fantke et al. 2017 and Fantke et al. 2019

1.3. Governance recommendations to LCA stakeholders

Identified issues	Recommendations
• Characterization factors that are sometimes difficult for practitioners to understand • Several research groups are developing CFs, sometimes in parallel: -> disparities between particulate characterization methods, for example in the vocabulary and units used.	• Develop cooperation between the different actors in order to make the methods more intelligible to practitioners (e.g. UNEP factors included in the PEF). • - Improve transparency regarding the calculation assumptions and theory used for the development of the factors and methods of characterization.

2. Other indicators

2.1. Climate Change

Identified issues	Recommendations
• No impact of particulate matter considered in current methods • Existence of factors through IPCC GWP100 or GWP20 of NTCFs: not implemented in current methods and rarely added manually by the practitioner. •	Practitioner: • Refine data collection to break down the inventory by composition • Add these fluxes to the modelling and associate the characterization factors with them based on IPCC GWP100 and GWP20 values. • Assess the impact on climate change by ensuring that a sensitivity analysis is conducted using GWP20 factors. Developers: • Integrate characterization factors based on IPCC values

2.2. Ecosystems

Air Quality data on the impact of particulate matter on ecosystems are not yet mature enough to make LCA recommendations on this topic.

Conclusion

The first part of this study provided a state of the art on the way in which particulate matter is understood in terms of air quality and identified the associated issues, particularly in terms of public health. The second part of the study provided an exhaustive state of the art of how they are taken into account in current LCA methods and identified, in summary, their current limitations.

This consideration is based on the development of methods that make it possible to integrate research results on the impact of particulate matter on health and the environment. The first work that made possible to include particles in LCA dates back to the late 1990s with the work of Hofstetter (1998). Since then, thanks to scientific research on the impact of particles on health on one hand, and advances in the development of LCA methodologies on the other, different methods have emerged, presented in various scientific publications.

However, the available LCA methods for characterizing impacts have certain limitations in addressing the health and environmental issues associated with particulate matter, while at the same time, existing methods are often poorly harnessed by LCA practitioners.

This study has thus shown that there is a double challenge in taking into account particles in LCA, which is reflected in the recommendations made:

- A challenge to improve existing methods: current methods still have certain shortcomings, particularly in terms of integrating the impact of particles in indoor air, phenomena associated with the formation of secondary particles, the articulation of archetypes, etc., which require further research to make existing factors more robust and to be able to consider a greater number of situations;
- A challenge for improving LCA practices: practitioners today have a relatively poor grasp of the Particulate Matter methods and the first degree of improvement in considering particles in LCA is in the hands of LCA practitioners. While further development of more robust factors is essential, it will be of little effect, if the methods are poorly exploited by the practitioner. Thus, it is particularly important to develop training on this topic so that the LCA community can become more competent in a comprehensive way.

Finally, these improvements in factors and practices require a more cross-cutting dialogue between the different actors at several levels:

- At the level of method developers, for better coherence between the different works, better readability for the practitioner and greater transparency on methodological choices;
- At the global level of LCA stakeholders: method developers, databases, tool designers and practitioners, so that progress can be integrated in a coherent and cross-cutting manner.