FROM RESOURCES TO A PRODUCTS: WHICH ENVIRONMENTAL IMPACTS FOR THE ECOSYSTEM?

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Abstract

For more than one hundred years the industrial revolution explodes all over the world through the different technologies. All these technologies were developed to help and increase the human conditions in providing new products. However, this development demands more and more resources (e.g. energy, water, raw materials) and generates many undesirable consequences with our over consumptions and the industrial systems used for the production.

With the development of the research in human health and on the ecosystems, one has capable to assess our potential negative impacts. It exists many model in order to assess the environmental impacts (environmental impacts are on the ecosystem and on human health), one of the most famous methodology is the Life Cycle Assessment (LCA) [1] [2] that is managed by the standard ISO 14040 and ISO 14044. However, even if this methodology is well-known, this one presents many limitations.

Introduction

Since the 60^{s}, and the development of the approach of the life cycle and since the end of the 90^{s} with the standardization of the LCA [3], many companies believe in this methodology in order to evaluate and understand the environmental impacts of a product. Even if many methodologies have been developed, LCA is now the most common used in order to assess the environmental impacts of a product. The LCA can't be to evaluate the environmental impacts of a company, but this methodology is a product approach.

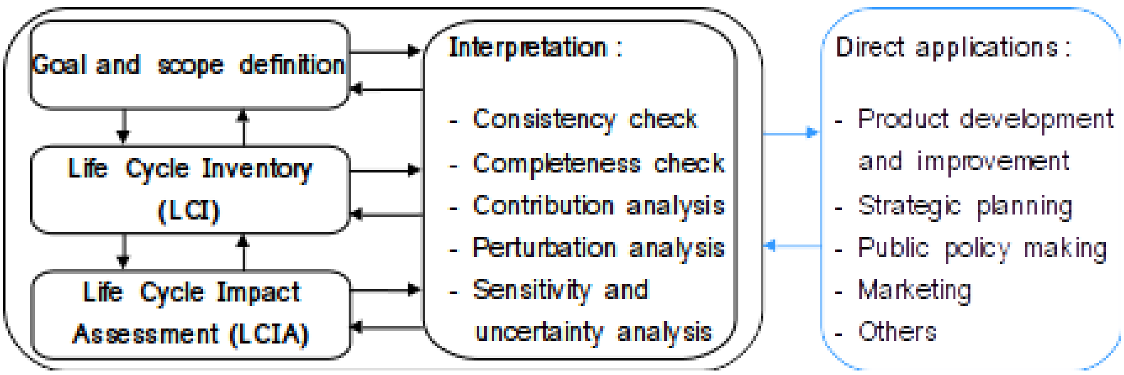

Illustration 1: Scope of the LCA

The main principles of the LCA is that one needs consider the whole life cycle of the product, from the extraction of the raw materials to the end of life of the product (end of life means the potential treatment in the end of life of the product, e.g. landfilled, incinerated, recycled,…). Also, one needs to consider several environmental indicators (e.g. Global Warming Potential, Ozone Layer Depletion,…), usually, in LCA studies, one can find around 10 indicators [4]. This multi-criteria approach is crucial, considering the life cycle and several environmental indicators, one avoids the environmental impact transfer. One of the last important principles, is the importance to include all the components of the product, even the additional components like the consumables one (e.g. coffee filters if one studies a coffee machine, fuel if one studies a car,...)

The step of LCIA (see Illustration 1) proposes many indicators (*CI*) that can reflect the environmental impacts based on the inventory data (balance of Inputs and Ouputs of the studied system, represented by the step of LCI in Illustration). In this case each indicator is calculated following this equation:

$$CI = \sum_{i=1}^{n} M_i \times CF_i \quad (1)$$

where:

- *CI* is the impact score for the considered category,
- CF_i is the specific characterization factor for the substance *i*, that expresses the potential impact of M_i,
- M_i that represents each single elementary material flow contributing to the total impacts.

The general framework of the calculation model is usually modeled as follow:

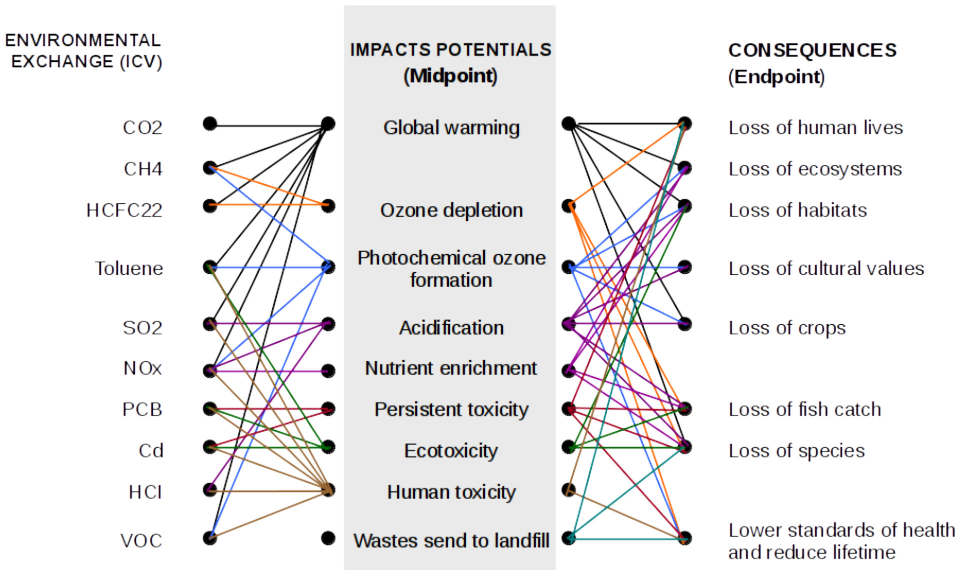

Illustration 2: calculation model principle [3]

The environmental exchange represents the masses of the substances (M_i) in equation (1), then the arrows represent the characterization factor Cf_i. One can identify two kinds of indicators, “Midpoint” and “endpoint”. It is assumed that all elements are concerned by the Midpoint level, the fact is that the concentration f each substances can have a potential environmental effect. Then, one can have the endpoint level, where one focuses to the consequences of the potential environmental impacts (identified in midpoint level) [5] [6]

One of the most famous criteria is the Global Warming Potential using the methodology proposed by the Inter Governmental Panel on Climate Change (IPCC) [7], but one can find also some methods to evaluate the potential human toxicity and ecotoxicity of different compartments (air, water and soil) [3]. Today, the European Commission recommends to follow USEtox [8] as a model concerning the human health and the ecosystem impacts. In 2004, a Take Force on Toxic Impacts launched in Prague under the auspices on the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC).

USEtox model

USEtox proposes several Characterization Factors (CF) for organic and non-organic substances for categories of indicators (human toxicity and ecotoxicity). The calculation of CF_e for the ecotoxicity is based on three parameters:

$$CF_e = FF \times XF_e \times EF_e \quad (2)$$

where:

- FF (Fate Factor expressed in day) is the residence time of the substance in a compartment (air, water, soil),
- XF_e (Expose Factor, dimensionless) represents the bioavailability of a chemical and can be represented by the fraction of the chemical dissolved in the compartment,
- EF_e (Effect Factor in PAF.m^3.kg^{-1}) reflects the change in the potentially affected fraction (PAF) of species due of the change in substance concentration in the compartment.

For each parameters, it is necessary to have a large database containing a various properties data for each substances (e.g. molar mass, solubility, partitioning coefficient between *n*-octanol and water). In the latest version of USEtox 2016 [9], one can find 27 inorganics (e.g. silver, copper, selenium) and 3077 organics (e.g. ethanol, atrazine).

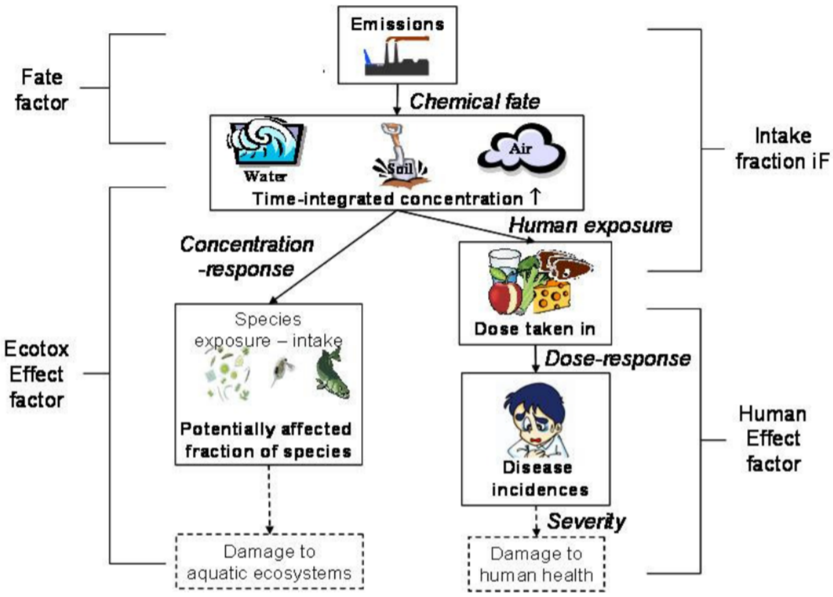

Illustration 3: Main Steps of the USEtox assessment [18]

Limitations

With LCA methodology, one can then compare the environmental impacts of different products and give some recommendations to redesign the product and reduce the impacts. However, many limitations have been identified with the non consideration of the temporal and spatial [10] [11] [12] aspect for all indicators and specifically for USEtox, one can also add the non consideration of a real data about the exposure factor for human. Up to now, one assesses XF_e with animals experimentations.

LCA is now a recognized methodology but the uncertainty of the results can be very high and even, sometimes, non identified. Also, many substances are unknown, especially in new technology like the health impact of the nano components [13] [14].

Case studies

Case study 1:Toxicity Assessment of Nanoparticles [15]

The applications of USEtox model on nanocomponents are not common at all. Today, only few articles used USEtox model to assess ecotoxicological or/and human toxicological CFs on nanoparticules have proposed.

Illustration 4 visualizes the applications of USEtox model in nanotechnology. It is clear that the development tendency of the USEtox model in nanotechnology is to include the nano-specific behavior into the calculation of CF of ENPs.

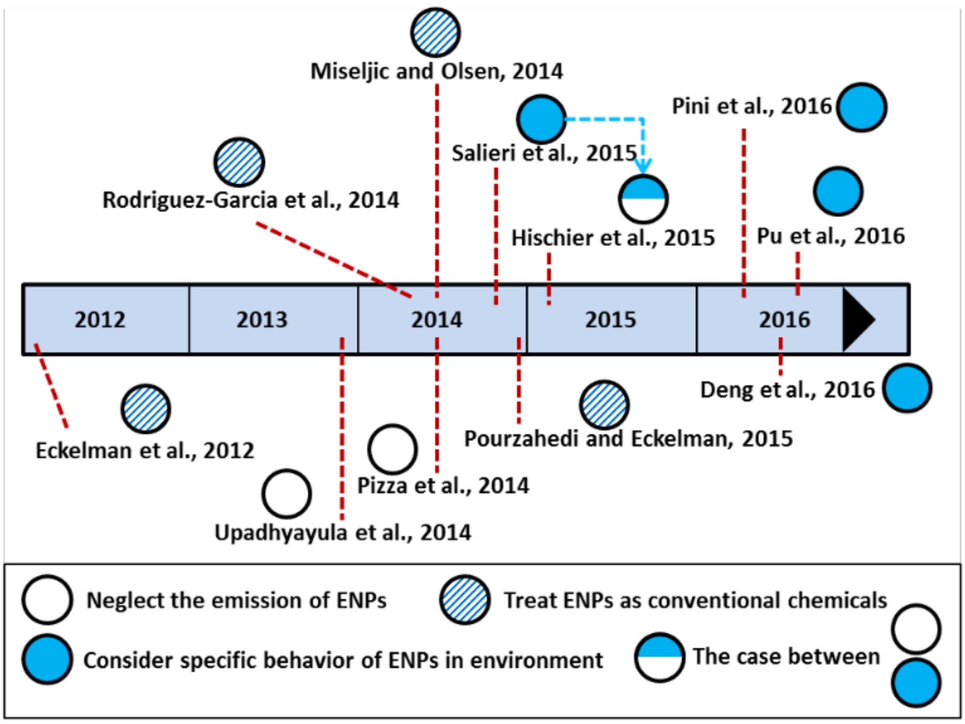

Illustration 4: The applications of USEtox model in evaluation the toxicity of nanoproductsaccording to the year published [15]

In order to determine the characterization factor of nanoparticules, we have used the neutrophils of pig. The many similarities between pig and human (genetics, physiology, anatomy, etc.) make pig as an excellent animal biomedical model for human [16]. For example, Meurens et al. highlighted that there were numerous advantages of the pig model for vaccine development and the use of pigs could acquire new knowledge on both animal and human health [17]. Then we have adapted the Fate Factor (*FF*) of USEtox in order to assess the new characterisation factor.

Also, in this study, we have proposed a regional characterization factor. The results propose a large difference between the different considered regions. The Illustration shows the results for the freshwater ecotoxicity.

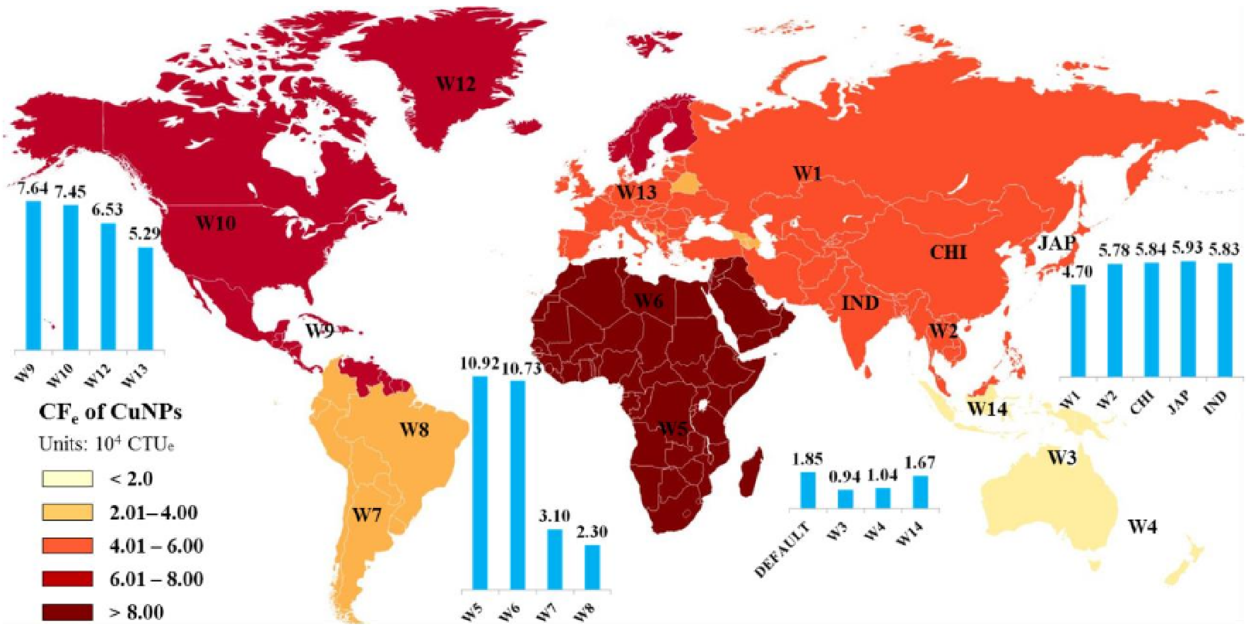

Illustration 5: World map of the CuNPs characterization factors (CFs), with histograms indicatingthe variation between the numerical values (Units: 10^4 CTU e) of 17 worldwide regions(one default region and 16 sub-continental regions) [14]

The method in USEtox model has been modified to adapt to the toxicological data from exposing porcine neutrophils to CuNPs. An extensive collection of the ecotoxicological data of ENPs from literatures is performed to calculate the ecotoxicological effect factors. Finally, the regionalized non-carcinogenic human CFs of CuNPs and freshwater ecotoxicological CFs of 14 ENPs have been proposed. It is noteworthy that the CFs proposed in this study should be classified as “indicative” in terms of USEtox model because the relatively high uncertainty in addressing fate, exposure and effects of metal or inorganic chemical.

It is demonstrated that the fate of ENPs in freshwater has important influences on the toxicity of ENPs and should be considered in the toxicity assessment of ENPs. The proposed CF values fill the gaps between toxicity testing and environmental modeling. These regionalized CFs values can be used in the future LCA, when assessing the impacts of products containing ENPs to human and ecosystem.

Case study 2: Toxicity Assessment of metals

Metals are the main nonorganic pollutants of extractive, manufacturing and chemical industries. Metals are considered as important in life cycle impact assessment in case of their high level of toxicity to humans and ecosystems [19].

Existing LCIA models (CML 1992, Eco-Indicator 95, IMPACT 2002+, TRACI, USEtox, etc.) allow to calculate the metals negative impact but there are still a lot of uncertainties connected with it [20]. As in general, as in case of metals impact assessment, the using of different LCIA methods may then lead to disparate results [21] [23].

Among all models USEtox is recommended as the best model for LCIA on human toxicity. This model provides the database with 28 metals for each compartment for non-cancerogenic effect and 17 for cancerogenic effect calculation, that is representable in comparison with other models, but its uncertainties regarding metals are still high [24].

One of the limitations connected with metals is lack of experimental data expressing the bioaccumulation of chemicals into the substrate as meat and milk. In USEtox model the metals accumulation is provided by plenty of literature references [25] [26], but these references nowadays are not representable. Plus, the model for calculation of transfer factor from environmental media to substrate in case of metals assessment is irrelevant [27] [28]. Thus, is purposed that using the measured by chemical analysis (INAA, ICP-MS, etc.) concentrations of metals in the “polluted medium” as meat and milk, provides the same information as transfer factor about metals content in the organs but in the more accurate way.

Thus, it is purposed to change the equation of human indirect exposure which expresses the contact between the human organism and polluted media (e.g. meat):

$$XP_{xp,i}^{inderect} = \frac{C_{Cr,pork} \times IR_{xp} \times P}{\rho_i \times V_i} \quad (3)$$

Calculation human exposure factor with indirect pathway

The expected results of the Characterization factor calculated with measured concentrations of chemicals in contaminated media should represent a more realistic reflection of the impact of the enterprise on the region under study. In this case, we purpose to use the own experimentation data or references of other research works, but these sources should be connected or with studied areas or reflect the same level of ecological tension on the population. This way leads to avoid the minimization of results of calculation of the Characterization factor.

Conclusions

Today, it is a good way of research where biologist, chemist, mechanics area merge to improve these parameters in order to reduce the uncertainty and be sure about results obtained. These researches are crucial to reduce our environmental impacts, but one of the main difficulty, is to correlate the different research area. The users of the LCA methodology are usually the designers but based on models developed by biologists, chemists and so on.

Integrating the results of environmental studies into different stages of life-cycle assessment helps to eliminate system limitations. The results of interdisciplinary research allow us to more accurately assess the level of anthropogenic tension and develop recommendations for the sustainable development of enterprises that are the main source of negative impacts.

References

[1] EPLCA and J. R. Center, “European Platform on Life Cycle Assessment Newsletter / info update No 9,” JRC, 2008.
[2] J. Valkama and M. Keskinen, “Comparison of simplified LCA variations for three LCA cases of electronic products from the ecodesign point of view,” in *Proceedings of the 2008 IEEE International Symposium on Electronics and the Environment*, Washington, DC, USA, 2008, pp. 1–6.
[3] J. B. Guinée, *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Springer, 2002.
[4] ILCD, *ILCD Handbook International reference Life Cycle Data System Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors*. International Reference Life Cycle Data System (ILCD) Handbook, 2011.
[5] H. A. Udo de Haes, S. Kotaji, A. Schuurmans, and S. Edwards, *Life-Cycle Impact Assessement: Striving Towards Best Practice*. Society of Environmental Toxicology and Chemistry, 2002.
[6] M. Hauschild, R. K. Rosenbaum, and S. I. Olsen, Eds., *Life cycle assessment: theory and practice*. Cham: Springer, 2018.
[7] P. Forster *et al.*, *Changes in Atmospheric Constituents and in Radiative Forcing. Climate Change 2007: The Physical Science Basis*. Cambridge university press, 2007.
[8] R. K. Rosenbaum *et al.*, “USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment,” *The International Journal of Life Cycle Assessment*, vol. 13, no. 7, p. 532, Oct. 2008.
[9] P. Fantke *et al.*, “USEtox® 2.0 Documentation (Version 1.00),” USEtox® Team, 2017.
[10] J. W. Owens, “Life-Cycle Assessment: Constraints on Moving from Inventory to Impact Assessment,” *Journal of Industrial Ecology*, vol. 1, no. 1, pp. 37–49, 1997.
[11] J. W. Owens, “Life-Cycle Assessment in Relation to Risk Assessment: An Evolving Perspective,” *Risk Analysis*, vol. 17, no. 3, pp. 359–365, 1997.
[12] T. Perminova, N. Sirina, B. Laratte, N. Baranovskaya, and L. Rikhvanov, “Methods for land use impact assessment: A review,” *Environmental Impact Assessment Review*, vol. 60, pp. 64–74, Sep. 2016.
[13] Y. Pu, B. Laratte, R. S. Marks, and R. E. Ionescu, “Impact of copper nanoparticles on porcine neutrophils: ultrasensitive characterization factor combining chemiluminescence information and USEtox assessment model,” *Materials Today Communications*, vol. 11, pp. 68–75, Jun. 2017.
[14] Y. Pu, F. Tang, P.-M. Adam, B. Laratte, and R. E. Ionescu, “Fate and Characterization Factors of Nanoparticles in Seventeen Subcontinental Freshwaters: A Case Study on Copper Nanoparticles,” *Environmental Science & Technology*, vol. 50, no. 17, pp. 9370–9379, Sep. 2016.
[15] Y. Pu, “Toxicity Assessment of Engineered Nanoparticles,” Université de Technologie de Troyes, 2017.

[16] D. Bréa *et al.*, “The pig as a model for investigating the role of neutrophil serine proteases in human inflammatory lung diseases,” *Biochemical Journal*, vol. 447, no. 3, pp. 363–370, Nov. 2012.
[17] F. Meurens, A. Summerfield, H. Nauwynck, L. Saif, and V. Gerdts, “The pig: a model for human infectious diseases,” *Trends in Microbiology*, vol. 20, no. 1, pp. 50–57, Jan. 2012.
[18] M. A. J. Huijbregts *et al.*, “USEtox - User Manual,” USEtox® Team, 2010.
[19] Gloria, T., Russell, A., Atherton, J., Baker, S. and Cook, M. (2006). Ecological Toxicity Methods and Metals. An examination of two case studies (8 pp + 1). The International Journal of Life Cycle Assessment, 11(1), pp.26-33.
[20] Pini, M., Bondioli, F., Montecchi, R., Neri, P. and Ferrari, A. (2017). Environmental and human health assessment of life cycle of nanoTiO2 functionalized porcelain stoneware tile. Science of The Total Environment, 577, pp.113-121.
[21] Dreyer, L., Niemann, A. and Hauschild, M. (2003). Comparison of Three Different LCIA Methods: EDIP97, CML2001 and Eco-indicator 99. The International Journal of Life Cycle Assessment, 8(4), pp.191-200.
[22] Owsianiak, M., Laurent, A., Bjørn, A. and Hauschild, M. (2014). IMPACT 2002+, ReCiPe 2008 and ILCD’s recommended practice for characterization modelling in life cycle impact assessment: a case study-based comparison. The International Journal of Life Cycle Assessment, 19(5), pp.1007-1021.
[23] Monteiro, H. and Freire, F. (2012). Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods. Energy and Buildings, 47, pp.572-583.
[24] Pizzol, M., Christensen, P., Schmidt, J. and Thomsen, M. (2011). Impacts of “metals” on human health: a comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA). Journal of Cleaner Production, 19(6-7), pp.646-656.
[25] IAEA International Atomic Energy Agency 2010: Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, International Atomic Energy Agency, Vienna
[26] Allison JD, Allison TL 2005: Partition Coefficients for Metals in Surface Water, Soil, and Waste. EPA/600/R-05/074, United States - Environmental Protection Agency
[27] Rosenbaum RK, Margni MD, Jolliet O (2007): A flexible matrix algebra framework for the multimedia multipathway modeling of emission to impacts. Environment International 33: 624-634