CHANCES AND LIMITS OF STATISTICAL METHODS TO CAPTURE UNCERTAINTIES IN LIFE CYCLE ASSESSMENT

CHANCEN UND GRENZEN STATISTISCHER METHODEN ZUR ERFASSUNG VON UNSICHERHEITEN IN DER ÖKOBILANZIERUNG

Helen Hein, Joachim Schwarte

Institute of Construction Materials, University of Stuttgart

SUMMARY

Statistical methods are often used in life cycle assessment (LCA) to analyse uncertainty. These are very well suited for random uncertainties, but reach their limits in the case of fuzzy data, systematic deviations or sometimes also in the case of high uncertainty or complexity of the systems under investigation. Fuzzy logic is suitable for fuzzy data. This theory can also be combined with statistical methods. However, the growing interest in life cycle assessments, also outside the expert circle, bears the risk that the complex results based on such methods are misinterpreted. A practicable and easily understandable methodology is to record uncertain values as intervals, whereby the interval widths of the results reflect their (un)certainty, as it were.

ZUSAMMENFASSUNG

Statistische Methoden werden in der Ökobilanzierung (LCA) häufig zur Analyse von Unsicherheit eingesetzt. Diese sind für zufällige Unsicherheiten sehr gut geeignet, stoßen jedoch bei unscharfen Daten, systematischen Abweichungen oder mitunter auch bei hoher Unsicherheit bzw. Komplexität der untersuchten Systeme an ihre Grenzen. Für unscharfe Daten eignet sich die Fuzzylogik. Diese Theorie kann auch mit statistischen Methoden kombiniert werden. Das wachsende Interesse an Ökobilanzen auch außerhalb des Expertenkreises birgt jedoch die Gefahr, dass die komplexen Resultate auf Basis solcher Verfahren missinterpretiert werden. Eine praktikable und einfach verständliche Methodik ist die Erfassung unsicherer Werte als Intervalle, wobei die Intervallbreiten der Ergebnisse gleichsam deren (Un-)sicherheit spiegeln.

1. INTRODUCTION

There are a number of theoretical methods and a wealth of published approaches for analysing uncertainty in life cycle assessment (cf. [1, 2]). One statistical method used in practice, implemented in well-known LCA programmes and thus available and widely known, is Monte Carlo simulation. It is used to numerically estimate the probability distribution of the results on the basis of random numbers. Other methods based on statistical considerations are, for example, analytical methods such as the Gaussian error propagation law derived from the first-order Taylor series expansion.

Both methods - the Monte Carlo simulation as well as the Gaussian error propagation law - are suitable for the calculation of random uncertainties; however, they reach their limits of validity for certain types of uncertainty and are limited with regard to the level of the existing uncertainties or the scope of the systems to be examined (cf. [3, 4, 5]). In this article, the two statistical methods are compared. Both methods are less suitable for estimating the uncertainty of purely fuzzy data, which is why a methodology for handling fuzzy data is presented and the combinability of this with statistical methods is discussed. The last chapter is devoted to the significance of the results of life cycle assessments when the uncertainties are analysed with the methods presented.

2. STATISTICAL METHODS IN LIFE CYCLE ASSESSMENT - SUITABILITY AND COMPARISON

Monte Carlo simulation is a numerical method with which samples can be generated via distribution functions of each individual input in order to estimate the uncertainties in the results. For this purpose, the type of distribution function and the necessary parameters must be determined (cf. [4, 5]). The inputs are randomly varied in large numbers and an ecological balance is carried out each time. With the sample resulting from the calculated results, statistical key figures can be determined, such as the standard deviation or the interquartile range. The analytical procedure requires an assumption of the variances of the inputs, with which the standard deviation can then provide information about the uncertainties in the results of an ecological balance.

The necessary information must often be estimated for both methods, since only little information is available about the individual input parameters. One method that should make it possible to estimate the variance of an input is the Pedigree method (cf. [6, 7]). Assuming a normal distribution, uncertain data can be assigned to different factors with regard to different criteria (such as completeness or reliability) - the lower the quality of these criteria, the higher the resulting variance of the input.

According to [3, 4, 5], both statistical methods are suitable for the calculation of randomly varying uncertainties, but are not or only to a limited extent suitable for the assessment of systematic deviations. Monte Carlo simulation can reduce uncertainties due to variability very well, but depending on the number of runs and the complexity of the systems, the computing time can be very long, so that the practicability of this procedure is then reduced. Analytical methods, on the other hand, require less information about the uncertainties and comparatively very little computing time. However, only uncertainties of limited magnitude can be estimated reliably; the relative uncertainty should not be too large compared to the parameter. Ciroth showed in [3] that the analytical formulas of first and second order can sometimes be suitable for the estimation of systematic errors, but not always. He therefore recommends direct correction of the input data in the case of systematically estimated deviations. Uncertainties of missing or incomplete data cannot be adequately captured with either method - in short, information that is also known as fuzzy data.

3. FUZZY DATA: POSSIBILITIES OF COLLECTION AND COMBINABILITY WITH STATISTICAL METHODS

LCA often requires information from manufacturers or experts that is uncertain and can only be formulated vaguely. Such information is also referred to as fuzzy data. A simple example of fuzzy information is a colour gradient with a continuous transition (cf. Fig. 1); however, it can also be found in complex situations, such as scenario-based climate projections (cf. [8]).

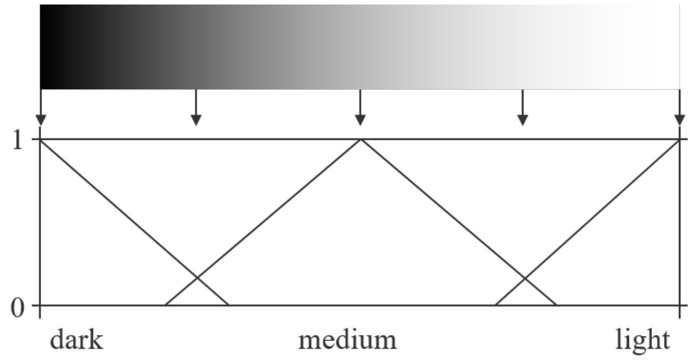

Fig. 1: Fuzzy sets "dark", "medium" and "light" and degrees of membership of a continuous colour gradient.

With these complex models uncertainties also play a major role, the results of which are fuzzy, which must also be taken into account in the presentation of results in order to avoid misunderstandings (cf. Fig. 2). Fuzzy logic is suitable for capturing such uncertainties, where information can belong to different quantities to a certain degree. The fuzzy logic was also investigated in [10, 11] for use in life cycle assessment - where the membership functions were assumed to be linear in a simplified form. The support set and the kernel are defined in terms of intervals. The former represents the pessimistic limit to the impossible, while the kernel represents the optimistic limit to the possible.

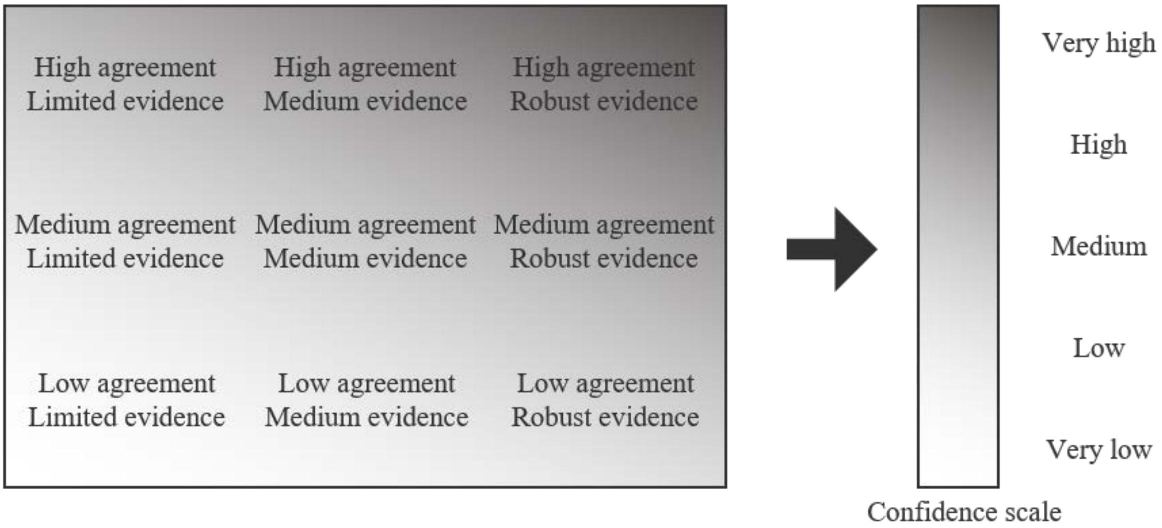

Fig. 2: Confidence scale with continuous transitions for assessing uncertainty of climate projections depending on agreement and evidence of findings. Own representation, based on [9].

Real variables can be variable *and* fuzzy at the same time. The statistical methods can be combined with the fuzzy theory (cf. [12]). The results are then presented in the form of fuzzy statistical values, which must also be understood as such.

4. LCA RESULTS: RISK OF (MIS)INTERPRETATION

A large number of very different data from many scientific fields flow into a life cycle assessment - thus mean values, medians, estimated values, comparative data, assumptions, etc. come together. Pohl therefore recommended for figures used in life cycle assessments:

"In fact, each of them must be accompanied by a footnote disclosing where it comes from and how it is interpreted [...]." ([11], p.81, note: translated into German).

The results of life cycle assessments are often used in political decision-making processes or made available to the public for marketing purposes. In this context, it is important that the uncertainties associated with the quantified results are also communicated in a comprehensible way outside the circle of experts. Clear communication of the degree of plausibility of calculated, ecological environmental impacts is all the more important in view of the increasingly important role that sustainable and ecological development plays in society and the economy. The authors therefore consider interval-based life cycle assessment to be a suitable procedure in which uncertain values are recorded as intervals (cf. [13]) and uncertain results of the LCA are also output as intervals and only compared as intervals, since discrete individual values are dispensed with.

5. CONCLUSION

Statistical methods are very well suited for estimating random uncertainties in LCA, especially if sufficient information is available that is additionally required for the methods. If, however, the existence of fuzzy data or systematic deviations cannot be ruled out, the use of intervals instead of discrete individual values is a good way to take uncertain data into account. This is a practicable procedure, since only the additional input of interval limits is required. Moreover, the results in the form of intervals leave little room for misunderstanding. The interval widths are considered a measure of the uncertainty contained - they visualise the uncertainties contained in the results in an understandable way. This transparent presentation can also prevent wrong decisions outside the scientific community based on misinterpreted or inadequately documented results of LCAs.

REFERENCES

[1] HEIJUNGS, R.; HUIJBREGTS, M.A.J. (HRSG.): *A Review of Approaches to Treat Uncertainty in LCA, 2004*

[2] IGOS, E.; BENETTO, E.; MEYER, R. ET AL.: *How to treat uncertainties in life cycle assessment studies?* In: The International Journal of Life Cycle Assessment 24 (2019), Heft 4, pp. 794-807

[3] CIROTH, A.: *Fehlerrechnung in Ökobilanzen*. Berlin, Technische Universität Berlin, Dissertation, 2001

[4] HEIJUNGS, R.: *On the number of Monte Carlo runs in comparative probabilistic LCA*. In: The International Journal of Life Cycle Assessment 25 (2020), Heft 2, pp. 394-402

[5] HEIJUNGS, R.; LENZEN, M.: *Error propagation methods for LCA—a comparison*. In: The International Journal of Life Cycle Assessment 19 (2014), Heft 7, pp. 1445-1461

[6] FRISCHKNECHT, R.; JUNGBLUTH, N.; ALTHAUS, H.-J.; DOKA, G.; HECK. T.; HELLWEG, S.; HISCHIER, R.; NEMECEK, T.; REBITZER, G.; SPIELMANN, M.; WERNET, G.: *Overview and Methodology. ecoinvent report No. 1*. Swiss Centre for Life Cycle Inventories, Dübendorf, 2007

[7] WEIDEMA, BP.; BAUER, C.; HISCHIER, R.; MUTEL, C.; NEMECEK, T.; REINHARD, J.; VADENBO, CO.; WERNET, G.: *Overview and methodology*. Data quality guideline for the ecoinvent database version 3. Ecoinvent Report 1 (v3). The ecoinvent Centre, 2013

[8] HILLERBRAND, R.; SCHNEIDER, C.: *Unwissenschaftlich weil unsicher? Unsicher weil wissenschaftlich!* In: Jeschke, S.; Jakobs, E.-M.; Dröge, A. (Hrsg.): *Exploring Uncertainty*. Springer Fachmedien Wiesbaden, Wiesbaden, 2013, pp. 151-177

[9] IPCC, 2012: *Summary for Policymakers*. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., et al. and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 1-19

[10] ROŠ, M.: *Unsicherheit und Fuzziness in ökologischen Bewertungen – Orientierungen zu einer robusten Praxis der Oekobilanzierung*. Zürich, ETH Zürich, Dissertation, 1998

[11] POHL, C.E.: *Auch zu präzis ist ungenau – Unsicherheitsanalyse in Oekobilanzen und Alternativen zu "use many methods"*. ETH Zürich, Diss., 1999

[12] VIERTL, R.: *Fuzzy Daten und Stochastik*. In: Seising, R. (Hrsg.): *Fuzzy Theorie und Stochastik – Modelle und Anwendungen in der Diskussion*, Computational Intelligence. Vieweg+Teubner, Wiesbaden, 1999, pp. 244-250

[13] HEIN, H.; SCHWARTE, J.: *Products in early development phases: ecological classification and evaluation using an interval arithmetic based calculation approach*, World Academy of Science, Engineering and Technology, International Journal of Energy and Environmental Engineering, Band 13, Nr. 5, 2019, pp. 368-374