Reinout Heijungs

Probability, Statistics and Life Cycle Assessment

Guidance for Dealing with Uncertainty and Sensitivity

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Reinout Heijungs
Department of Operations Analytics
Vrije Universiteit Amsterdam
Amsterdam, The Netherlands

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Preface

This book is devoted to the topic of what is often called 'uncertainty in LCA' including the ramifications into 'sensitivity in LCA'. The importance of these topics was stressed already in the early 90s, when the *Society of Environmental Toxicology and Chemistry* (SETAC) and the *International Organization for Standardization* (ISO) started to develop guidelines and standards for life cycle assessment (LCA). However, while the resulting texts mention that an uncertainty and sensitivity analysis needs to be carried out, they give few guidelines for how to actually do so.

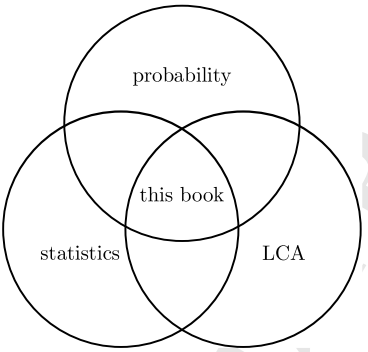
The results of this lack of guidance can be subdivided into two classes: positive and negative. On the negative side, we see that still many LCA case studies report results without or with only a very limited analysis of uncertainty and sensitivity. The positive side is that in the past 25 years a large number of articles, Ph.D. theses and reports have been published on the inclusion of uncertainty and sensitivity analysis in life cycle assessment. Sadly, these texts provide a fragmented picture. They all use their own terminology and notation, and they focus on specific elements. What is lacking is an embracing, coherent and critical treatment of the topics. This book aims to fill this gap.

At the same time, some of the publications that have appeared in the past 25 years are more valuable than others. This can be for practical reasons (e.g., issues related to computer time), but there are also more fundamental reasons. Uncertainty and sensitivity are topics that originate from considerations of probability and statistics. Any approach for dealing with uncertainty and sensitivity should therefore build upon the foundations of probability theory and statistics. That is much more than just the adoption of terms, symbols and equations, for standard deviations and similar concepts. It requires a complete reconsideration of the principles of LCA, based on probabilistic and inferential thinking. It is the author's experience that many LCA practitioners, long ago, took a course in these subjects, and now have forgotten most of it. That is unfortunate, because probability and statistics are fields that do more than just delivering a formula for a standard deviation. They provide a way of thinking, in terms of random variables, samples and estimation.

The lack of a solid background in probability and statistics is evident from several of the published documents. For instance, they frequently use terms like 'parameter',

'bias', 'error', 'confidence interval' and 'true value' in an incorrect way. The result is that the validity of some of these approaches can be doubted. But it requires a long path before we get to that point.

This book can be truly seen as discussing the three fields of the title: probability, statistics and LCA, but only to the extent that they are relevant in relation to each other. Graphically:



Or symbolically, as a pseudo-equation:

$$\text{this book} = \text{probability} \cap \text{statistics} \cap \text{LCA}$$

Readers interested in the general theories of probability, statistics or LCA should consult other books. Of course, in writing this book, the author has consulted such books, and reference will be provided.

Part I of the book is a primer. Indeed, one aim is to present in a concise, coherent and reader-friendly way the basic ingredients of probability theory and statistics, but not for the purpose of offering a basic textbook on probability or statistics. The purpose is to single out those topics that are relevant to the incorporation of uncertainty and sensitivity in LCA. Typical undergraduate textbooks on statistics are either highly mathematical or very thick, and they contain several aspects that are not directly relevant to our topic. For instance, moment generating functions and exponential smoothing are introduced in many such books, but we will not need them, and therefore skip them.

Part II is a critique. As a matter of fact, the author believes that a critical analysis is badly needed. The last decade or so, developments in uncertainty analysis of LCA have been going around in circles, author *B* building on what author *A* writes, and the other way around. As a result, we now see many strange things in the published articles: notation, terminology and concepts are blurred. We give just one example here: several authors in the field of LCA think that the squared geometric standard

deviation is the standard (or best, or only) way to address uncertainty. A fresh treatment, based on established foundations, is wanted, and that is exactly what this book offers.

Part III accumulates all findings into a guidance document: guidance for including the lessons from probability and statistics in LCA. It is, in contrast to the middle part, a constructive text.

The author has been teaching probability, statistics and LCA, and his emphasis in the field of LCA has always been the mathematical side. Few other people combine these three angles, and he feels it as a unique opportunity to edify a solid foundation for the treatment of uncertainty and sensitivity in LCA. His first steps in the study of uncertainty and sensitivity analysis (then phrased as reliability and marginal analysis) were published in 1994 (Heijungs (1994)). Of course, he has not been alone in conceiving this work. In particular, his (former) colleagues; Ph.D. students; and students Angelica Mendoza Beltrán, Arjan de Koning, Carlos Felipe Blanco, Evelyne Groen, Jeroen Guinée, Patrik Henriksson, Sietske Lensen, Stefano Cucurachi, Tristan Senga Kiessé and Valentina Prado have contributed substantially to the development of the ideas described in this book.

The ideas were—in part—previously published in papers, mainly Blanco et al. (2020a), Brandão et al. (2022), Cucurachi et al. (2016, 2022), Groen et al. (2014, 2016, 2017), Heijungs (1994, 1996, 2010, 2017, 2017a, 2017b, 2020a, 2021a, 2022b), Heijungs and Kleijn (2001), Heijungs and Suh (2002), Heijungs and Frischknecht (2005), Heijungs et al. (2005, 2016, 2017, 2019), Heijungs and Tan (2010), Heijungs and Lenzen (2014), Heijungs and Dekker (2022), Henriksson et al. (2015a, 2015b), Mendoza Beltrán et al. (2016, 2018a, 2018d), Senga Kiessé et al. (2022) and Wolf et al. (2017). But there are also several parts that were not published before. Moreover, these previous works have been reassessed and reworked into a consistent and coherent set-up.

All computations were performed in *Excel*, without any add-ins except from those that are available by default (*Analysis ToolPak* and *Solver Add-in*). This is important information, because it shows that all methods that are illustrated can be used without any specialized software. This also applies to the figures in this book. The large majority of graphs was made with *Excel*; only a few diagrams were made with *TikZ*.[1] The text itself was typeset in LaTeX, using *MikTeX*.[2]

The book itself has its beginnings in a seminar, *Probability, Statistics and the Environment*, that the author gave on May 9, 2017 at *Technische Universität Wien* (thanks go to Helmut Rechberger and Oliver Cencic for the invitation). The argument was later developed in a manuscript *Probability, Statistics and Industrial Ecology* that was sent to the *Journal of Industrial Ecology*. But it was found unsuitable for a journal due to its length and mainly pedagogical set-up (thanks go to Richard Wood for recommending this). So in the end the article was reworked into the present book, and indeed, the reader will agree that it was a bit too much for an article, even while the breadth went down from *Environment* to *Industrial Ecology* and then even further

[1] See https://www.ctan.org/tex-archive/graphics/pgf/.

[2] See https://miktex.org/.

down to *LCA*. The lock-down of the university from March 2020 onward gave the author the possibility to recluse and concentrate on writing it.

The book's title is a hint to von Mises' *Probability, Statistics and Truth* (Von Mises, 1939). The book, originally written in 1928 in German as *Wahrscheinlichkeit, Statistik und Wahrheit*, is a classic semi-popular exposition of the basic ideas of probability and statistics. Its title has inspired many authors for follow-ups: *Probability, Statistics and Mathematics*; *Probability, Statistics and Analysis*; *Probability, Statistics and Econometrics*; *Probability, Statistics and Estimation*, so inserting *Life Cycle Assessment* seemed to be appropriate. Essential to von Mises' argument is that probability and statistics are to be understood in the frequentist's sense: repeated observations from a phenomenon that is inherently variable. This book will continue along that line: LCA relies on data that display an inherent variability. As a result, probability theory is the only correct way to do LCA. There is no 'true' LCA result, and the methods developed in probability and statistics are essential reading for anyone involved in the theory and practice of LCA.

It seems appropriate to close this Preface with the remark in von Mises' Preface of 1939, which has unfortunately been removed in the second English edition that is available today (Von Mises, 1981). *Clear thinking, the scrupulous testing of all propositions by comparison with objective phenomena and the repudiation of all empty phrases may be rare qualities at the present time, but there are still some philosophers who endeavor to maintain these principles, and with such, I think, we shall easily find a common language.* Clear thinking, repudiating empty phrases and finding a common language are indeed what this book seeks to achieve.

Amsterdam, The Netherlands Reinout Heijungs

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