Francesco Pomponi · Catherine De Wolf
Alice Moncaster *Editors*

Embodied Carbon in Buildings

Measurement, Management, and Mitigation

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Foreword

The significance of embodied carbon in buildings has been recognised only relatively recently. Early attempts to quantify the carbon implications of specific construction materials were noble and served to identify the very real challenges in determining with any confidence the true figures of embodied carbon. The number of variables was daunting, and the postulation of generalised figures for individual materials served only to demonstrate the unreliability of depending on the values for any particular setting.

More recently, there has been a drive internationally to improve the understanding of embodied carbon in materials and in the whole cycle of construction and operation. As buildings become more energy-efficient, the embodied carbon component becomes more significant in the decision-making process for environmentally responsible design.

The publication of this book on embodied carbon in buildings could not be more timely. As research proliferates into the many different facets of the topic, the authors have brought together contributions which together cover the key questions to be addressed in a digestible and accessible form. Tackling management, measurement and mitigation in the three sections of the book is most impressive, and by dealing with uncertainty, much of the scepticism of life cycle analysis and its past in confusion and unreliable data can be dispelled. The geographical coverage globally is invaluable, and the authors have been assiduous in bringing such a diverse collection of contributions together in a single volume.

Pomponi, De Wolf and Moncaster, who are all eminent in this field, can be very proud of this seminal publication.

Professor Peter Guthrie

Peter Guthrie, OBE, FREng, was appointed the UK's first professor of engineering for sustainable development at the University of Cambridge in 2000. A civil engineer with geotechnical specialisation by background, for the first half of his career, Peter worked as a practising engineer on infrastructure projects, working extensively in Africa and Asia as well as on major UK projects such as the Channel Tunnel Rail Link and London 2012 Olympic Park. In 1980, Peter founded RedR Engineers for Disaster Relief, and in 1994, he was awarded an OBE. With a passion for integrating social and environmental considerations into engineering design, since 2000 he has led research at Cambridge that enables engineers to deliver more sustainable outcomes. In recent years, a particular focus of his has been on improving the understanding of energy efficiency in buildings and the challenges (financial, social and environmental) faced in delivering significantly lower carbon emissions from building stock. His other main focus is on resilience in infrastructure.

The Editors

Dr Francesco Pomponi is the Vice Chancellor's Fellow at Edinburgh Napier University. Francesco leads the Resource Efficient Built Environment Lab (REBEL) in Edinburgh, a group of scientists addressing the issue of resource scarcity and their efficient use from a multi-disciplinary point of view. Francesco's expertise lies with life cycle assessment, embodied carbon and circular economy, and he moved to academia after 6 years in industry as engineer and project manager. He is part of the newly launched Annex 72 of the International Energy Agency and has recently chaired the 'Life Cycle Assessment and Carbon Accounting' Forum of the International Passive and Low Energy Architecture Conference and the 'Design for Sustainability' Track of the International Sustainable Development Research Society Conference. He is a fellow of the RSA, a member of the IET and a fellow of the HEA. An associate member of St Edmund's College University of Cambridge and of Cambridge Architectural Research (CAR), Francesco regularly collaborates with practitioners and researchers from South and Central America, Africa, Europe and of course the UK.

Dr Catherine De Wolf is a Marie Sklodowska-Curie postdoctoral fellow from the European Commission and a Swiss Government Excellence Scholar at the Swiss Federal Institute of Technology in Lausanne (Ecole Polytechnique Fédérale de Lausanne, EPFL) where she works on low-carbon structural design within the Structural Xploration Lab (SXL). She also worked as a researcher at the University of Cambridge while obtaining her PhD in building technology at the Massachusetts Institute of Technology (MIT), after studying both civil engineering and architecture at the Vrije Universiteit Brussel and Université Libre de Bruxelles. She closely collaborated with leading engineering firms including Arup, Ney & Partners and Thornton Tomasetti on embodied carbon assessment in buildings. This led to her nomination on the board of the Carbon Leadership Forum and the launch of the Structural Engineers 2050 Commitment Initiative.

Dr Alice Moncaster is a senior lecturer in engineering at the Open University. She remains a visiting fellow at the University of Cambridge, where she was previously a lecturer in engineering and director of the IDBE masters course, and a fellow of Newnham College. The move to academia followed 10 years in industry as a civil/structural engineer, during which time she became increasingly concerned about the responsibility of the construction sector for climate change. Alice's research focuses on reducing the ecological impacts of the built environment. She led the research group Cambridge University Built Environment Sustainability (CUBES) as part of the Centre for Sustainable Development at Cambridge between 2010 and 2017 and has been the UK participating expert on the International Energy Agency Annex 57, and now Annex 72, since 2012.

Introduction

Embodied carbon is, to some extent, an odd beast. Its importance is evident and the beneficial consequences of its reduction undeniable. We know that the built environment is a major source of our carbon excesses, yet most policies focus only on part of the picture by capping operational energy consumption, for the use of buildings. We also know that the Intergovernmental Panel on Climate Change (IPCC) has warned that carbon reductions are needed now, not in 30 years' time. Lowering the immediate emissions related to current building construction and demolition, the embodied carbon, is an obvious way to do so. In recent years, research on embodied carbon has therefore increased.

Many fields of research develop steadily over the years, led by a small and coherent community of experts. Others quietly die, as the world moves on. Yet, for a very few topics, a moment comes when the world suddenly wakes up to their importance, and interest and attention start to snowball. This is such a moment for the subject of this book, the greenhouse gas emissions resulting from the construction of buildings. Within this snowballing, of industry consultancies producing tools, of manufacturers benchmarking their products, of academics working together on major projects and even of the rumblings of political and regulatory change, there is, however, a real danger that the knowledge will become so dispersed that any real progress will be lost. Instead of forming a coherent body of work to inform policy and evoke real change in how we construct our built environment, we run the real risk of finding ourselves in a meaningless avalanche of disconnected ideas. This book, therefore, sets out to perform a vital task – to extract coherence, not chaos, from this outpouring of intellectual endeavour.

Following the Paris Agreement, many nations have revamped their carbon plans, climate change drafts and carbon reduction targets. However, most governments remain stuck on the same single track of promoting operational energy efficiency in buildings, seemingly reluctant to acknowledge that this ignores an essential part of the picture. More energy-efficient buildings may reduce energy use and carbon emissions in the long term, but without a parallel focus on embodied energy and carbon, the real savings that could be made right now are lost, often instead resulting in an increase in short-term impact. Without a holistic understanding of the data, a sincere estimate of the uncertainties and an appreciation of the impact of human behaviour – both of occupiers and of constructors – this is a gamble with the future of our environment.

We hope, therefore, that we have succeeded in representing, within this one volume, a persuasive argument for the importance of including embodied emissions in all aspects of construction. The argument is constructed over the first three sections through the main areas of debate over the *measurement* of embodied carbon, the key concepts of its *management* and a comprehensive overview of the *mitigation* strategies being proposed and enacted. The final section acknowledges that there are geographical differences in both context and approach, providing an overview of the state of knowledge and practice across regions of the world.

Correct understanding of estimates is an essential starting point in the embodied carbon debate. If we cannot agree on our numbers, the conversation is prevented from moving forward. The first section, therefore, includes three chapters dedicated to uncertainty analysis, each of which offers novel and diverse points of view on the topic. The section also features chapters on the embodied carbon of different structural materials as well as the inclusion of some uncommon variables in embodied carbon assessments, such as surface albedo.

The management section is perhaps the most diverse in the book and the one with the greater interdisciplinary outlook. It features chapters looking at early design tools, others aimed at bridging the current gap between research and practice and some looking at the significance of life cycle stages often neglected in embodied carbon assessments as well as the identification of carbon hotspots.

The third section on mitigation is the natural conclusion of the 'embodied carbon journey' offered in the book. In other words, now that we know how to quantify embodied carbon and that we have also learned how to manage it, how can we actually reduce it? The section features a diverse set of chapters, looking at novel opportunities offered by the principles of a circular economy, sustainable technologies and optimisation strategies at both material and building levels.

Views from different regions of the world conclude the book, and we are very proud of the broad coverage we managed to achieve. This section includes contribution from Australia, a world leader in embodied carbon, Africa, North and South America, Europe and China. We strongly believe all chapters offer a stimulating learning opportunity for all those interested.

We hope that this book will succeed in its aims: to educate and enthuse both practitioners and scholars, to provide a comprehensive starting point for the novel researcher in the field and to act as an essential reference source for everyone working on this topic. Most of all, we hope to have created a document that collates, connects and makes sense of the current state of knowledge and that identifies clearly the questions still to be answered.

We believe that bringing together key researchers in this area has already started the process of creating a virtual global community highlighting and validating their different views while acknowledging the similarity of the challenges we are facing. We hope that both readers of and contributors to this book will return to their work with renewed spirit and positivity, in the recognition that together we form a strong, passionate community working together to create real change towards a low-carbon future.

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Part I
Measurement

Chapter 1
Uncertainty Analysis in Embodied Carbon Assessments: What Are the Implications of Its Omission?

M. A. Mendoza Beltran, Francesco Pomponi, J. B. Guinée, and R. Heijungs

Introduction

Embodied carbon assessments of buildings are methodologically similar to the more well-known and standardized life cycle assessment (LCA) focused on the quantification of carbon emissions throughout the life cycle of buildings. Generally, this type of studies results in single-point estimates, based on deterministic data, which in many cases represents an average numerical output which embeds no information on the likelihood, significance or variability of that value. In comparative studies, for instance, when the performance of two buildings is compared, the LCA point value results are superposed and directly compared. The allegedly less environmentally detrimental alternative is chosen without considering the risk of making a wrong decision.

Such deterministic assessments have many associated uncertainties. For instance, inventory data for complex systems such as buildings is variable and sometimes non-existent, undetermined and ambiguous. Also, methodological choices are made during the different phases of LCA, introducing uncertainty in the results particularly in comparative contexts. Yet, many LCAs and embodied

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carbon assessments of buildings lack uncertainty analysis that address the presence of these sources of uncertainty and that accompany and enrich the interpretation of results.

This chapter will provide the reader with an overview of uncertainty analysis in LCA, from the rationale to the methodological challenges through to the increased usefulness of the results in comparison with point value assessments. This chapter will reflect on the consequences of disregarding uncertainty in LCA and attempt to explain how uncertainty analysis interacts with decision-making and how it can benefit and facilitate environmentally conscious decisions.

Meanwhile, a large body of literature is available on how to conduct an uncertainty analysis in LCA. Diverse techniques and methods that can be suited to address uncertainty in different applications and contexts are already part of the existing literature. Although we will provide reference to seminal literature and key studies for the less experienced reader, this chapter will not focus on the technical details for implementing an uncertainty analysis. Rather, we investigate the consequences of abstaining in the practice of uncertainty analysis in LCAs of buildings. Thus, we focus in the comparison of a deterministic LCA and an LCA with uncertainty analysis.

Uncertainty in LCA

Certainty is the idea of confidence, assurance and accuracy about our knowledge of the truth. Certainty and truth exist, evading discussions on philosophical scepticism that are self-defeating as denying their existence is already accepting a truth with certainty (Briggs 2016). The idea of uncertainty is based upon the existence of truth by acknowledging there is something that is but cannot be fully known. Uncertainty does not exist in objects themselves, aside from the sense of existence, but only in our mind or intellect (Briggs 2016). Therefore, it is our incapacity to know the truth that underlines uncertainty. In fact, there are many ways to treat uncertainty, but probability is one of the most used ones. Probability is the language of uncertainty that explains the limitations in our knowledge of the truth (Briggs 2016). This is why many fields of knowledge have relied on probability to help treat this limitation, and the field of LCA is no exception, as will be shown below.

Uncertainty has been researched for about 30 years in LCA. The increased attention that LCA received during the 1990s as a tool to describe environmental impacts of products in the broad sense came along with criticism about the drawbacks of this decision support framework used by governments and companies (Udo de Haes 1993). One of the major limitations are uncertainties around it (Finnveden 2000; Ross et al. 2002), which threaten the reliability of decision-makers on the results and recommendations from LCAs. Guinée et al. (1993) mentioned that: “A valuation of environmental profiles without an assessment of the reliability and validity of the results, is of little value”.

Some of the first dedicated research to uncertainty treatment in LCA appeared during the 1990s. Uncertainty analysis in LCA was defined by Heijungs (1996) as “the study of the propagation of unintentional deviations” in order to understand “those areas where product and process improvement lead to the highest environmental gain”. Similarly, Huijbregts (1998a, b) identified the usefulness of uncertainty analysis in LCA to help decision-makers judge the significance of the differences in product comparisons, options for products improvements or the assignment of eco-labels. Weidema and Wesnæs (1996) were the first to describe and apply data quality indicators (DQIs), semi-quantitative numbers providing information about the quality of the data, and data quality goals (DQGs), the desired quality of the data, in an LCA context. This methodological development known as the “pedigree-matrix” in LCA jargon, inspired by the purely qualitative proposal of Funtowicz and Ravetz (1990), is one of the most widely applied techniques to semi-quantitatively address uncertainty of data in LCA. This method was later incorporated in the ecoinvent database (Frischknecht et al. 2007). DQIs enabled early probabilistic approaches to account for data uncertainties and LCA models evolved from deterministic models to stochastic models characterized by probability distributions (Kennedy et al. 1996).

Yet only until the end of the 1990s and beginning of the twenty-first century, a general framework that distinguished various types of uncertainty and variability in LCA was proposed and further studied (Huijbregts 1998a; Björklund 2002). These frameworks are of particular importance as they differentiate various types of uncertainty and variability in LCA as well as recognize that different types of uncertainty and variability might require different treatment (Huijbregts 1998b). The types of uncertainty and variability are (according to a combination of Huijbregts 1998a; Björklund 2002):

- Parameter uncertainty: data inaccuracy, data gaps and unrepresentative data
- Uncertainty due to methodological choices
- Model uncertainty
- Epistemological uncertainty
- Spatial variability
- Temporal variability
- Sources and objects variability
- Mistakes

While uncertainty refers to lack of knowledge about the truth (Briggs 2016), variability makes reference to inherent differences within a population attributable to natural heterogeneity of values (Björklund 2002). Therefore, while uncertainty can be reduced, variability cannot be reduced but only better estimated, for instance, with better sampling (Björklund 2002). In the interest of brevity, from here on we use uncertainty to refer to both uncertainty and variability types together.

Types of Uncertainty

Although a detailed description of each type of uncertainty falls beyond the scope of this work, a very brief explanation of some uncertainty types is provided to exemplify what they entail. We ask readers to consult Björklund (2002) for a detailed description of each type of uncertainty.

Parameter uncertainty has been associated to data inaccuracy (Huijbregts et al. 2001), unavailability and to unrepresentative data (Björklund 2002). This is uncertainty due to, for example, wrong inventory data, missing data or data that refers to different technologies, places or temporal resolutions than the intended one. *Methodological choice uncertainty* is due to the unavoidable choices of practitioners along the phases of LCA on topics like functional units, system boundaries (Tillman et al. 1994), allocation methods (Weidema 2000; Guinée and Heijungs 2007), impact categories and characterization methods and factors (Huijbregts 1998b; Finnveden 1999). *Model uncertainty* refers to simplification aspects of LCA such as aggregation and the modelling aspect of LCA, for example, linear and non-linear models (Heijungs and Suh 2002), derivation of characterization factors (Björklund 2002) or estimation of emissions with exogenous specialized models. *Variability* refers to intrinsic fluctuations of a numerical property (Björklund 2002) such as the yield of a hectare of arable land. *Epistemological uncertainty* emerges from the lack of knowledge on system behaviour, for instance, when modelling future systems (Björklund 2002).

Approaches to Deal with Uncertainties in LCA

Different types of uncertainty in LCA may require different types of treatment. There are different approaches to deal with uncertainties in LCA. In certain cases, the aim is to reduce uncertainty in order to generate a more reliable assessment and therefore, better support for decision-making. In other cases, the aim is to reflect the uncertainty of the result as an extra piece of information to the decision-maker. In general, the main approaches to different types of uncertainty are (Heijungs and Huijbregts 2004) the scientific, the constructivist, the legal and the statistical approaches. These approaches use additional research, consensus or agreement, authority and probability and statistics to deal with uncertainty. From these approaches, only the statistical approach explicitly incorporates uncertainty in the outcomes of LCA (Heijungs and Huijbregts 2004).

Statistical approaches to parameter uncertainty have led to sophisticated methods to quantify input uncertainties (Heijungs and Frischknecht 2005; Bojacá and Schrevens 2010; Henriksson et al. 2013; Ciroth et al. 2013; Muller et al. 2014; Qin and Suh 2016), to propagate such uncertainties through the LCA model (Imbeault-Tétreault et al. 2013; Groen et al. 2014; Heijungs and Lenzen 2014), to interpret outputs with uncertainty (Heijungs and Kleijn 2001; Prado-Lopez et al.

2014, 2015; Henriksson et al. 2015; Cucurachi et al. 2016) as well as to approaches that deal with all the above (Hung and Ma 2009; Andrianandraina et al. 2015; Gregory et al. 2016; Wei et al. 2016).

Dealing with uncertainty due to methodological choices in LCA has mostly been approached by the constructivist and legal approach. Consensus among stakeholders on the choices or predefining (ISO 2006) or mandating the choices reduces uncertainty in the outcomes (Heijungs and Huijbregts 2004) and increases comparability of studies. Environmental Product Declaration (EPD) schemes as well as Product Category Rules (PCRs) are examples of such approaches to deal with uncertainty due to choices (Del Borghi 2013). More recently, statistical and mathematical approaches to treat choice uncertainty have been proposed too (Jung et al. 2013; Cruze et al. 2014; Mendoza Beltran et al. 2015; Hanes et al. 2015). These incorporate the effects of uncertainty due to the different choices on the outcomes.

For model uncertainties, statistical approaches have been published (Padey et al. 2013; Andrianandraina et al. 2015). Typically, these treat parameter and model uncertainty simultaneously.

Within the different approaches, a large number of tools to deal with uncertainty in LCA are available (Table 1.1).

Regardless of the availability of the different tools and the widely agreed recommendation that dealing with different sources of uncertainty in LCA is a vital step to increase reliability on LCA results, few studies apply any method for such purpose (Ross et al. 2002; Lloyd and Ries 2007). It appears that the latest literature review of LCAs including uncertainty was performed by Lloyd and Ries (2007), which despite being about a decade ago is the best available. This study reviewed 400 journal publications and 2000 websites resulting from the search terms uncertainty or variability and LCA and published up to 2004. They narrowed down their review to 24 studies, from which about half contained applications in specific sectors and the rest focused on method development. From the case study articles, only two focus on the building sector (Chevalier and Tfino 1996; Huijbregts et al. 2003). Since the review of Lloyd and Ries (2007), the trends have not changed (Pomponi and Moncaster 2016). Despite of the addition of the DQI pedigree and its associated uncertainty estimation to the ecoinvent data, and the incorporation of methods for uncertainty propagation in mainstream software, such as SimaPro and OpenLCA, doing such an analysis is still more an exception than a rule. Although, including a preliminary uncertainty analysis in LCA studies is nowadays simpler than ever.

LCAs of Buildings with Uncertainty Analysis

A recent review by Pomponi and Moncaster (2016) focused on LCAs and embodied carbon studies of buildings. This review classified 77 studies according to the life cycle stages taken into account, among other characteristics. The stages were specified as in the BS EN 15978 framework (Fig. 1.1). Pomponi and Moncaster

Table 1.1 Main sources of uncertainty in LCA and some techniques and methods to treat them

Type Tools	Parameter uncertainty	Model uncertainty	Uncertainty due to choices	Spatial variability	Temporal variability	Sources and objects variability
Scientific approach						
Additional measurements	x					x
Scenario modelling		x	x	x	x	x
Non-linear modelling		x				
Multimedia modelling		x		x		
Constructivist approach						
Expert judgements/peer review	x		x			x
Rules of thumb	x					
Legal approach						
Standardization	x		x			
Prescription of specific methods (e.g. ILCD)	x		x			
Statistical approach						
Probabilistic simulation	x		x			x
Data quality indicators	x			x	x	x
Uncertainty importance analysis (global sensitivity analysis)	x	x	x	x	x	x
Classical statistical analysis	x			x	x	x
Bayesian statistical analysis	x			x	x	x
Sensitivity analysis	x	x	x	x	x	x
Interval arithmetic	x			x	x	x
Correlation and regression analysis	x					x

Adapted from Huijbregts (1998a), Björklund (2002), and Heijungs and Huijbregts (2004)

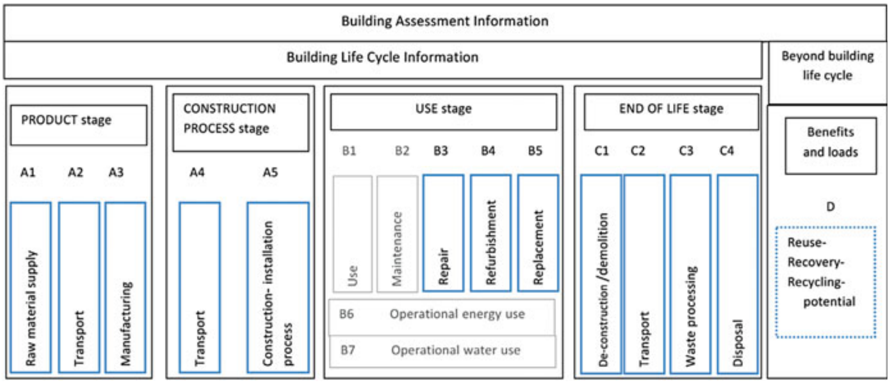

Fig. 1.1 BS EN 15978 framework

(2016) showed that most studies exclude or ignore uncertainty analysis and have a short-sighted approach to the life cycle of buildings, i.e. many only include manufacturing stages and few include impacts during occupation (use stage) or end-of-life.

There are, however, a few recent studies that include some treatment of uncertainty. These are studies where mostly a large number of scenarios has been assessed, therefore producing a range of results that convey a level of uncertainty (Pomponi et al. 2015, 2016). Alternatively, they use Monte Carlo simulations to propagate parameter uncertainty (Blengini and Di Carlo 2010; Heeren et al. 2015; Hoxha et al. 2017; Pomponi et al. 2017). In the case of Heeren et al. (2015), a comprehensive sensitivity analysis has been enriched with information about the assumed distributions of parameters, as well as correlation between parameters and outputs, allowing a much deeper interpretation of combined effects of materials used and energy demand of buildings, as well as of trade-offs in the results. The authors modelled a high-number of combinations resulting from different samplings of certain parameters per life cycle stage. Their findings are therefore in the form of a range of results with statistical description (e.g. mean, standard deviation, quartiles), and this certainly helps a more informed decision-making process.

Despite the existence of these more recent studies that include some handling of uncertainty, it is atypical for LCAs in the building sector to formally consider uncertainty. The first study which accounted for parameter, methodological choices and model uncertainties in the building sector is that by Huijbregts et al. (2003). The authors focused on two insulation alternatives for a Dutch one-family dwelling and developed and tested a methodology that takes into account parameter uncertainty through Monte Carlo (MC) simulations and scenario and model uncertainty by means of resampling different scenarios and model assumptions iteratively. Their results indicated that all types of uncertainty influence the outcomes of their study, thereby showing that the three sources of uncertainty should be evaluated and accounted for simultaneously.

The other example is the study by Vieira and Horvath (2008). The authors approached uncertainty differently, in a more qualitative fashion. However, their work also aims at reducing uncertainty in LCAs of building by eliminating some of the value judgements used in common approaches for allocation. The authors map differences in uncertainty between attributional and consequential LCAs. They tested their approach by comparing the outcomes of both approaches applied to concrete in a typical US building frame, concluding that neither appeared to yield more complete results.

The Inclusion of Uncertainty Analysis in LCAs

As shown in the literature review, studies taking into account uncertainty in LCAs of buildings are scarce. Those studies do treat uncertainty by means of scenarios and statistical approaches and display a range of different outcomes. Scenarios are mainly applied to show the effect of parameter, methodological choices and model uncertainty. Otherwise, MC simulation is used as a propagation method for uncertainty in model parameters and for inventory data (Huijbregts et al. 2003; Heeren et al. 2015).

Given that the main aim of this study is to understand what uncertainty analysis adds to LCA, we illustrate the difference between a deterministic LCA and an LCA including uncertainty analysis. For such purpose, we complemented a deterministic LCA of a household in the UK (Monahan and Powell 2011) to include uncertainty of life cycle inventory data by means of the protocol of Henriksson et al. (2013) using additional secondary data. We further propagate this source of uncertainty in the inputs to the outputs using MC simulations. Finally, both deterministic and uncertainty analysis LCA results are presented for comparing the outcomes of both approaches for the same household. Below we present the implementation of the illustrative case.

Illustration Case Implementation

We build on the case and inventory data published by Monahan and Powell (2011). The choice for this specific study follows mainly two reasons: the clear availability of inventory data and the simplified approach to implement the carbon emissions, which is typical for embodied carbon assessments of buildings. Monahan and Powell (2011) implemented carbon intensities for the full supply chains of materials used in the construction phase without an actual representation of the supply chain processes. A more classic approach to implement the life cycle of products, used in other LCAs, connects the inputs of foreground processes to background processes from LCA databases or from other secondary data sources which do include varied and interconnected processes in the supply chains. The study by

Monahan and Powell (2011) is an embodied carbon assessment for a household in the UK. The functional unit for this study is the external, thermal envelope of a three bedroom, semi-detached house with a total footprint area of 45 m^2 and a total internal volume of 220 m^3. The phases of the life cycle included in the system are product and construction stages according to Fig. 1.1.

From Monahan and Powell (2011), we use the quantity of materials used in construction as well as we calculate the average embodied carbon coefficient (ECC) for each material (Table 1.2). Using three data points, i.e. the average, the low estimate and the high estimate for the ECC per material, the weighted average, overall dispersion parameter phi (Heijungs and Frischknecht 2005) and the assumed distribution were calculated following the protocol and decision tree from Henriksson et al. (2013). Using these parameters, we implemented the system in the CMLCA software (http://www.cmlca.eu/). We used 1000 MC simulations to propagate uncertainties in the inputs to the outputs. Only carbon emissions are included in the inventory. Results are presented at the inventory level for carbon emissions to air.

Results

Figure 1.2 shows the embodied carbon content per material used in the construction in tons of carbon dioxide. Figure 1.3 shows the percentage of the contribution of each material to the total embodied carbon per household. These two figures correspond to our implementation of the system of Monahan and Powell (2011). Both results are very similar as expected.

Results including inventory data uncertainty estimates for the total embodied carbon content per household are shown in Fig. 1.4. Not only do these outcomes show there is variability in the total embodied carbon (i.e. from 18 to 67 tons of CO_2/household), but they also show the frequency in which different results are likely to be obtained. The average embodied carbon is still around the result for the deterministic LCA, i.e. 35 tons of CO_2/household.

The contribution of each group of materials to the total embodied carbon was calculated. Figure 1.5 shows these results for each group of materials and 1000 MC simulations. This analysis enables improved identification of processes that require data refinement. Alternatively, if data is considered already as the best available as possible, technological improvements can be identified that would lead to higher mitigation of emissions. For example, Fig. 1.3 shows that waste treatment is responsible for 12% of carbon emissions; however, Fig. 1.5 shows that this could be as high as 30%.

Table 1.2 Inventory data for household constructed in the UK

Category	Material	Quantity (kg) Monahan and Powell (2011)	Emissions ($kgCO_2$) Monahan and Powell (2011)	Average ECC ($kgCO_2$/kg [a]) Monahan and Powell (2011)	Average ECC pedigree-matrix Weidema and Wesnæs (1996)	Low estimate of ECC[a]	Low ECC pedigree-matrix Weidema and Wesnæs (1996)	High estimate of ECC[a]	High ECC pedigree-matrix Weidema and Wesnæs (1996)	Weighted mean ECC [overall dispersion] Henriksson et al. (2015)	Distribution
Metals	Aluminium	260	2140	8.23	[1,1,1,1,1,4]	2.12	[2,3,2,2,3,5]	10.93	[2,3,2,2,3,5]	7.7 [0.58]	Lognormal
	Steel	251	956	3.81	[1,1,1,1,1,4]	1.54	[2,3,2,2,3,5]	3.98	[2,3,2,2,3,5]	3.48 [0.42]	Lognormal
Minerals	Brick	2264	1175	0.52	[1,1,1,1,1,4]	0.18	[2,3,2,2,3,5]	0.55	[2,3,2,2,3,5]	0.471 [0.47]	Lognormal
	Cement	2023	798	0.39	[1,1,1,1,1,4]	0.222	[2,3,2,2,3,5]	0.86	[2,3,2,2,3,5]	0.44 [0.62]	Lognormal
	Concrete	56,651	9863	0.17	[1,1,1,1,1,4]	0.05	[2,3,2,2,3,5]	0.22	[2,3,2,2,3,5]	0.16 [0.55]	Lognormal
	Gypsum plaster	1349	413	0.31	[1,1,1,1,1,4]	0.22	[2,3,2,2,3,5]	0.43	[2,3,2,2,3,5]	0.32 [0.33]	Lognormal
Openings	Windows	1277	1996	1.56	[1,1,1,1,1,4]	1.384	[2,3,2,2,3,5]	3.42	[2,3,2,2,3,5]	1.82 [0.5]	Lognormal
	Doors	142	246	1.73	[1,1,1,1,1,4]	1.23	[2,3,2,2,3,5]	2.69	[2,3,2,2,3,5]	1.8 [0.39]	Lognormal
Plastics	HD polyethylene	56	90	1.61	[1,1,1,1,1,4]	1.58	[2,3,2,2,3,5]	2.11	[2,3,2,2,3,5]	1.68 [0.18]	Lognormal
	LDPE	29	72	2.48	[1,1,1,1,1,4]	1.97	[2,3,2,2,3,5]	3.1	[2,3,2,2,3,5]	2.5 [0.23]	Lognormal
	Poly-isocya-nate insulation	187	561	3.00	[1,1,1,1,1,4]	1.384	[2,3,2,2,3,5]	3.18	[2,3,2,2,3,5]	2.78 [0.38]	Lognormal
	Polythene	146	285	1.95	[1,1,1,1,1,4]	1.89	[2,3,2,2,3,5]	2.58	[2,3,2,2,3,5]	2.04 [0.19]	Lognormal
	PUR insulation	195	585	3.00	[1,1,1,1,1,4]	1.23	[2,3,2,2,3,5]	3.11	[2,3,2,2,3,5]	2.74 [0.42]	Lognormal