Christoph Scope, Patrick Ilg, Stefan Muench, Edeltraud Guenther

Uncertainty in life cycle costing for long-range infrastructure. Part II: guidance and suitability of applied methods to address uncertainty

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Uncertainty in life cycle costing for long-range infrastructure. Part II: Guidance and suitability of applied methods to address uncertainty

Authors: Scope, Christoph; Ilg, Patrick; Münch, Stefan; Günther, Edeltraud
Technische Universitaet Dresden, Faculty of Economics, Chair of Environmental Management and Accounting,
Muenchner Platz 1/3, 01062 Dresden, Germany

Corresponding author: Günther, Edeltraud, Chair of Environmental Management and Accounting, TU Dresden, 01062 Dresden, Germany. Tel.: +49 351 463 34313
E-mail address: ema@mailbox.tu-dresden.de

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Cover letter to the reviewers

Dear reviewers

Please find following the manuscript "Uncertainty in life cycle costing for long-range infrastructure. Part II: Guidance and suitability of applied methods to address uncertainty" by Scope, C., Ilg, P., Münch, S., and Günther, E. that we would like to submit for publication in the International Journal of Life Cycle Assessment.

The paper is the second part of a series, succeeding "Uncertainty in life cycle costing for long-range infrastructure. Part I: Identified sources and methods to address uncertainty" that is also submitted in the International Journal of Life Cycle Assessment.

To our knowledge, this is the first paper series providing a comprehensive literature review that identifies and categorizes different sources and methods of uncertainty in Life Cycle Costing for infrastructure. This article extends Part I of the series by further inquiring into two issues. First, it includes a combined analysis of uncertainties and methods to address them in LCC calculations. It thus addresses the suitability of methods. Second, it assesses which types of uncertainty were neglected in previous literature.

We would like to give you some further information on our submission:

- The comprehensive review was conducted by predefined selection criteria, strict application of the search terms, using a well-documented review protocol, and double coding by three authors enhancing intercoder reliability.
- We provide useful information for planners, users, and builders in evaluating life cycle costs of infrastructure projects.
- As suggested in the Author Information Pack, the manuscript was sent to a language editing service to ensure correct scientific US English.

Should you require further information, please do not hesitate to contact us. We look forward to hearing from you.

Yours faithfully,

Christoph Scope, Patrick Ilg, Stefan Münch, and Edeltraud Günther

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1 Introduction

Infrastructure is an important pillar for every economy (Morcous and Lounis 2005; Terzi and Serin 2014). However, the long lifespan of projects in this sector is a challenge for infrastructure planners (Truffer et al. 2010; Albogamy and Dawood 2015). In particular, cost estimations for long-term projects are often not precise and have frequently been proven inaccurate in the past (Kostka and Anzinger 2015). Life Cycle Costing (LCC) is a promising tool to improve cost estimations of long-term projects (Goh et al. 2010; Swarr et al. 2011; Simões et al. 2013). Nevertheless, uncertainty in LCC has been discussed in previous literature (Gluch and Baumann 2004; Cole et al. 2005; Kayrbekova et al. 2011). It is argued that LCC practitioners should systematically consider the impact of uncertainties on LCC results (Greenberg et al. 2004; Lindholm and Suomala 2007; McDonald and Madanat 2012). Previous literature on uncertainty in LCC calculations has focused on selected sources of uncertainty and how to handle them (Budnitz et al. 1997; Goh et al. 2010; Xu et al. 2012). To the best of our knowledge, no holistic analysis on how to treat different uncertainties in LCC calculations has been published to date.

The present series consists of two parts. In Part I, a systematic overview and categorization of uncertainties in LCC calculations is presented and is recommended for better understanding of the fundamental concepts of uncertainty. However, it also became apparent that further research was necessary. This article extends Part I of the series by further inquiring into two issues. First, it includes a combined analysis of uncertainties and methods to address them in LCC calculations. It thus addresses the suitability of methods. Second, it assesses which types of uncertainty were neglected in previous literature. Consequently, this article addresses the following two research questions:

1) What methods can be used to address uncertainties in LCC calculations?
2) What methods to deal with uncertainty have been insufficiently addressed in previous research?

By summarizing the overall findings, Part II provides guidance for LCC practitioners and decision makers based on risk management to further integrate uncertainties in future applications of LCC as well as in management practice. Reasoning for the latter, Erkoyuncu et al. (2011) diagnose a lack of "work on integrating the whole process of uncertainty identification, quantification, response and management strategies". Decision makers are often not involved in the analyzing process and are not familiar with applied methods to address uncertainties. As Ciuffo et al. (2012) argues, decision makers can be confused when confronted with results. Thus, Part II further aims to provide guidance for a science-based and practical application of uncertainty analysis that is integrated within risk management in accordance with ISO 31000 (2009) and IEC 62198 (2013) as demanded by Pappenberger and Beven (2006). The integration is interesting because, with the availability of modern software packages, conducting probabilistic analyses no longer requires mathematical sophistication, (Bolger 1996). The ability of using methods to address uncertainties requires guidance on how to interpret, implement, and communicate uncertainty insights into management routines (Heidmann and Milde 2013). The systematic overview of the subject provides this guidance to interested readers who are willing to improve reliability of their own LCC calculations and applications.

This paper is structured as follows. Section 2 contains a brief overview of the applied methodology. Section 3 presents a holistic assessment of the suitability of methods to address sources and types of uncertainty (Section 3.1). That includes a discussion of potential methods that have not been sufficiently used in previous research on LCC for infrastructure (Section 3.2). Furthermore, it is evaluated if learning from Life Cycle Assessment (LCA)

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and Life Cycle Sustainability Assessment (LCSA) applications is feasible and relevant to filling these gaps (Section 3.3). An integrated approach based on risk management is further suggested to build a bridge from LCC analysts to decision makers (Section 3.4). Section 4 concludes and reflects on the validity and reliability of overall findings from this analysis.

2 Methods

To set up a common understanding of key terms, three short but concise definitions follow, equivalent to Part I. LCC is defined as "an economic method for assessing all (direct, indirect, internal, and external) costs and revenues (cash flows) arising within a defined life cycle considered important to the investment decision and project evaluation" (Ilg et al. 2015). Infrastructure is understood as buildings and constructions utilized for energy supply and distribution, transportation, waste and water treatment (ASCE 2015). The term 'uncertainty' hereby represents all uncertainty and variability in LCC, while keeping in mind the various sources and types of uncertainty. In a narrower sense, 'uncertainty' refers to uncertain outcomes lacking good probability information (Park and Sharp-Bette 1990a). Uncertainty in that wider sense also includes 'risk', i.e. outcomes not known with certainty but with probability information (Park and Sharp-Bette 1990a). Essentially, sources of uncertainty are categorized twofold: in aleatoric and epistemic uncertainty as well as parameter, model, and scenario uncertainty.

Using a systematic literature review, we gathered and synthesized relevant studies applying uncertainty analysis in LCC for infrastructure following Cooper (1982) as well as Fink (2013), Mayring (2003), and Seuring and Müller (2008). Arguments of Zamagni et al. (2012) referring to the subjective conclusions were considered. The review consisted of four steps: selecting research questions and bibliographic databases, applying practical and methodological screening, as well as synthesizing results. Whereas Part I focused on categorizing identified sources and methods to address uncertainties, Part II concentrates on integrating both spheres. The latter included assessing the suitability of methods, exploring usage patterns, drawing parallels to other life cycle based methods, and summarizing best practices. The necessary content analysis was realized by using MAXQDA, a qualitative data analysis software program. After the initial identification of sources of uncertainty, each article was screened on applied methods to address uncertainty. Based on findings from the systematic review, each article is encoded with sources of uncertainty discussed and methods applied. Sources are then categorized into epistemic and aleatoric nature and the so-called PMS system (parameter, model, and scenario uncertainty). The four classes of methods are deterministic, probabilistic, possibilistic, and others. The results of the integration are presented in Table 1 in Section 3. For a more detailed description of the methodology, including search terms and screening information, see Section 2 of Part I.

In order to fill existing research gaps of applied methods to address types of uncertainty within LCC, a second study pool related to LCA and LCSA was scrutinized. LCA is seen as a systematic, analytical process for assessing the environmental implications of product systems over their entire life cycle (ISO 14040:2006; ISO 14044:2006). LCSA is best described as a transdisciplinary integration framework for methods and models close to the field of integrated assessment (Guinée et al. 2011). Working step one of our systematic literature review was modified to include keywords ('life cycle ass*', 'life cycle anal*', 'life cycle sustainab*', 'sustainab* ass*') instead of LCC related expressions. In addition, the keyword 'review' was added to further restrict the study pool. Applying practical screening (English, no limit on publication year, no ranking minimum, infrastructure as topic) as step two, there were 48 studies considered relevant, after delimiting 148 from a pool of 196 studies, and adding 6 by means of cross reference (Crane 1969). In step three, methodological screening, the rule-based

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procedure for content analysis was unchanged as compared to the LCC studies. It was transparently documented and encoded with MAXQDA. The systematic approach, the repeated formal analysis by all three authors, and a pre-defined coding scheme ensure objectivity of the research process. Coding differences were analyzed and dissipated case by case. Intercoder reliability was tested by having all the authors encode the same articles. Only minor discrepancies were observed.

The following Section 3 summarizes the results, representing step four of the systematic review.

3 Results and Discussion

Categorization of sources, as shown in Part I of our series, aims to differentiate epistemic from aleatoric as well as parameter, model, and scenario uncertainty. This helps to choose the appropriate type of method to address uncertainty. Similarly, the classification of methods pursues a generic decision for its application on the respective type of data. Depending on the characterized source of uncertainty, an appropriate method can display, explain, and (or) reduce uncertainty. In Section 3.1, empirically applied methods in LCC to address different sources of uncertainty are illustrated and their suitability is discussed. Section 3.2 then analyzes research gaps understood as yet missing methods in the context of LCC for infrastructure or a missing framework to integrate various methods into management practices. In the end, Section 3.3 presents and evaluates learning potentials from LCA and LCSA to fill these gaps.

3.1 Suitability of applied methods to address uncertainty

It is each analyst's work to assess the overall level of uncertainty, which is often denominated as propagating uncertainty in LCA studies (e.g. Lloyd and Ries 2007), caused by each input parameter, the model structure, and the model context within the LCC modeling. The process of identifying appropriate methods is surely of iterative character. The following order of working steps can therefore be seen as suggestion. A possible way to standardize this approach is laid out in Section 3.4.

First and foremost, the application of methods depends on data availability and related type of data (see Figure 1). Initially, the type of data on hand leads to the appropriate class of method. Tangible and certain data is an ideal case seldom found in real-life problem sets. If enough tangible data (historic, estimated, comparable, confounding, etc.) is available but uncertain and random, sophisticated probability models can be applied. In that case, a new data collection allows for the opportunity to gain knowledge about the parameters' true probability distributions functions. Otherwise, methods to either fill data gaps by means of modeling or restrictive assumptions for probability distribution functions (e.g. triangular shaped) may be appropriate. If only unrepresentative data is available, methods should be used that adapt data to local, i.e. specific, circumstances. In case of intangible data (but not limited to), intuitive or possibilistic methods, like expert elicitation and fuzzy sets, are recommended. Overall, LCC calculations most likely contain all classes of methods for data estimation scattered among different parameters: deterministic, probabilistic, and possibilistic.

[Insert here Figure 1]

In a second step, screening routines like Sensitivity Analysis should be applied in order to check each LCC calculation for hot spots regarding uncertainty. As introduced, overall uncertainty is partly caused by chosen input parameters. Sensitivity Analysis is a means to study effects on outputs through arbitrary changes in inputs (Reap et al. 2008a), thereby helping to rank the influence of each input by importance. This is necessary at an

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early stage when uncertainty is rather difficult to quantify. Due to limited resources (funding, time, computer power, man power, expertise of analysts, and skills among the decision-makers), each LCC practitioner has to weigh and balance the efforts to newly measure or estimate data points based on models. According to Schmidt (2003), these circumstances complicate the interpretation of LCC results and, hence, should only be conducted by experts. Resuming, a first screening such as this allows for iterative deepening of uncertainty analyses concentrating on identified hot spots.

In a third step, suitable and appropriate methods need to be tested to address the identified hot spots as well as relevant model and scenario uncertainties. Björklund (2002a) summarized that a suitable tool "must lead to an actual improvement of data inventory routines, model insight and results presentation, as well as be of help to decision makers." As mentioned before, a lack of integrated views on the diverse and numerous sources and methods makes it difficult to choose the appropriate one. Table 1 combines all reviewed sources and methods in an attempt to ease that process. An 'x' displays an applied method for specific sources as identified from the study pool. An 'o' extends the table by marking methods as capable of addressing these sources. The latter is suggested by the authors of this review.

Table 1 Combination of sources of uncertainty and methods to address them

PMS		Parameter uncertainty								Model uncertainty							Scenario uncertainty				
Aleatoric		x	x	x		x		x													
Epistemic			x		x		x		x	x	x	x	x	x	x	x	x	x	x	x	x
Source / Methods		Data quality: Multiple sources	Data quality: Data collection errors	Data quality: Data estimations errors	Data quality: Linguistic uncertainty	Data quality: Inherent randomness	Lack of data: No data	Lack of data: Data gaps	Lack of data: Unrepresentative data	Model structure errors	Approximations in computer coding	Simplification by averaging	Simplification by reducing observations	Simplification by reducing variables	Simplification of the functional form	Extrapolation errors	Choice of cost allocation	Choice of cost definition	Choice of methodology	Choice of system boundaries	Choice of weighting
Deterministic	Exclusion of parameters													x		x			x	x	o
	Point estimate		x	x		o		o	o												
	Rules of thumb / best guest		x	x		o	x	x	o			x								x	o
	Sensitivity analysis	o	o	x		o	x	x	x			o	o	x	o		o		x	x	x
	Scenario analysis	o		o		o		o	x			o	o	x	o		o		o	x	o
Probabilistic	Design of experiment		x	x									x						o		
	Importance sampling		x	x		o			o				x								
	Latin hypercube sampling		x	o		o		x	o				x	o							
	Monte Carlo Simulation	o	x	x		o	x	x	x				x	x	x					o	o
	Random sampling		x	x		o							x			x					
	Subset simulation							o					x								
Possibilistic	Bayesian expert opinion	o	x	o	o	o	x	x	o	o		x		x		x	o	o	o	o	x
	Bayesian Markov Chain		x	x			x	o													
	Bayesian Latent Markov Decision Process		x	o			o	o	o												
	Fuzzy sets	x			x		x	x	o											x	
	Evolutionary and Genetic Algorithm							x		x										x	
Simple methods	Analogy to prior literature	x	x	o	o	o	x	x	x	o	o	x	o	x	x	o	o	o	x	o	o
	Check by comparing with deterministic model									x		x		o					x		
	Check by multiple cases								o		x								x		

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	Check by tests within the model			x						o	x	o	o	o	x	o					
	Increasing data transparency	x	x	o	o	x		o	x		x	o					x	x	o	x	o
	Measuring and field data	o	o				x	o	x	x											
	Standardization (standard specification)	x			x				x								x	o	x	o	o
	Standardization (software, databases)	x	o	o	o			x	o									x	x		

x: methods to address uncertainty identified in literature
o: methods to address uncertainty suggested by the authors

For the choice of method, no obvious pattern is visible in Table 1 at first glance. In Table 1, it seems that deterministic methods predominate the category of scenario uncertainty and probabilistic methods the one of parameter uncertainty. Possibilistic methods are applied infrequently. The last class, so-called other methods, are applied in all areas and describe less statistical but rather procedure-based techniques, e.g. using data based on analogy to prior literature.

As mentioned before, the main problem for LCC is unavailability of data and related uncertainty of input parameters. Most applied methods in this area are Sensitivity Analysis (Herbold 2000; Sterner 2000; Singh and Tiong 2005), rules of thumb or best guesses (Rabl 1985; Hinow and Mevissen 2011; Liu et al. 2014), Bayesian Expert Opinion (Apostolakis 1990; Budnitz et al. 1997; Kayrbekova et al. 2011), and analogy to prior literature (Hong and Hastak 2007; Mavrotas et al. 2010; Hinow and Mevissen 2011). Data quality, in particular data estimation errors, is mainly addressed by two methods, namely Monte Carlo Simulation (Ergonul 2005; Jung et al. 2009; Firouzi and Rahai 2012; Saassouh and Lounis 2012) and Sensitivity Analysis (Walls and Smith 1998; Zayed et al. 2002; Choe et al. 2008).

Scenario uncertainty, such as the choice of input parameter and system boundaries, is mainly addressed by improved documentary transparency (Reich 2005; Upadhyay et al. 2012; Moore and Morrissey 2014) and two original deterministic approaches: Sensitivity Analysis (Budnitz et al. 1997; Swarr et al. 2011; Liu et al. 2014) and Scenario Analysis (Tähkämö et al. 2012; Li et al. 2014; Robert and Gosselin 2014). Contrarily, the choice of methodology is dominated by other methods, i.e. standardization (Andrade and Teixeira 2012; Mata et al. 2014; Noori et al. 2014), check by comparing with a deterministic model (Zhu et al. 2012; Aissani et al. 2014), the exclusion of parameters (Han et al. 2014), check by multiple cases (Hong et al. 2007), or analogy to prior literature (Battke et al. 2013).

To give an example, multiple data sources can be addressed by means of Monte Carlo Simulations (MCS). In that case, using min, max, and median values for triangular shaped probability distribution functions derived from a literature search within MCS may illustrate the effect on the overall result as a kind of Sensitivity Analysis (e.g. Nachtmann and Needy 2003). Surely, MCS does not directly help in the choice between sources, but it does indicate their implications. Similarly, Sensitivity Analysis, possibly in combination with rules of thumb concerning the size, may address data collection errors by estimating measurement errors for each input parameter showing impacts on the overall result. A comprehensive overview of sources and related applied methods is presented in a table within Appendix A. That table shall provide guidance to readers looking to identify existing (better) practice (see Section 3.4).

The selection of the methods according to a specific source or type of uncertainty is important as every method has its advantages and disadvantages. It should be kept in mind that quality of data is a “relative concept” (Silvestre et al. 2015), meaning for a given national context a data set may count as appropriate, whereas it is not in another national context. Common to all deterministic methods are the following critical points. First, deterministic approaches can only be used when all data is known with certainty (Kishk 2004). If there is

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variability associated with input parameters, deterministic approaches are not able to cope with this kind of uncertainty (Walls and Smith 1998). Second, many important phenomena cannot be modeled by deterministic approaches, e.g. actual ground motion parameter in seismic risk assessments (Apostolakis 1990; Budnitz et al. 1997). For these phenomena, more sophisticated models are necessary. Third, deterministic methods are limited in their application to real world scenarios as they cannot display continuous scales. Deterministic models are only able to predict two states for each variable or performance measure, i.e. failure or non-failure (Saassouh and Lounis 2012). Consequently, deterministic models cannot ensure a long service life because they fall short in selecting the appropriate design, maintenance, and rehabilitation strategies (Saassouh and Lounis 2012). Consequently, tailored methods are important to address uncertainty and often more sophisticated methods lead to better results.

There is some criticism regarding probabilistic methods, too. First, in most cases the forms of the distributions are based on estimates that do not directly stem from historical data and, therefore, their accuracy is questionable (Lindholm and Suomala 2007; Li and Madanu 2009). Half a century ago, Weiler (1965) already concluded that many errors in the outputs of simulation models could be traced back to assigning incorrect values to the parameters of a distribution, and indeed the selection of an appropriate distribution. There are tests to verify the chosen distribution: Chi-square, Kolmogorov-Smirnov, Anderson-Darling (Boussabaine and Kirkham 2004). Luckily, some software packages enable the correct choice of distribution from a given data set by integrating these tests. Second, lack of a strong statistical background of some LCC practitioners leads to the inappropriate application of probabilistic methods (Apostolakis 1990). Thus, not only the wrong distribution but also the wrong application of these methods leads to misinterpretation. Similarly, for a decent application, experts must understand how their judgments will be used (Budnitz et al. 1997). A similar disadvantage is the missing differentiation between short-term and long-term consequences (Wen and Kang 2001). Hence, the researcher has to be able to interpret results adequately in order to avoid a wrong application of the results. Third, most non-parametric methods see a drawback in the choice of the bandwidth (smoothing parameter). A wrong choice of this parameter will either under- or over-smooth the representation of the true distribution (Asiedu and Besant 2000).

The seemingly easier applicability of deterministic and probabilistic methods is the main disadvantage of possibilistic methods, as they need a high level of expertise for adequate application. A lot of time and highly skilled employees are required, which hampers frequent application in real-life projects. As mentioned before, practitioners trust their instincts based on their own experience more than on data-based analysis. The use of possibilistic methods demands even more effort and they are thus hardly ever applied in practice.

3.2 Identified patterns in applying methods to address uncertainties

Reviewing the current status quo in Section 3.1, different patterns of usage and scholarly discussions for the identified sources as well as addressing methods of uncertainty were observed. This includes sources and methods hardly or not studied at all within the context of LCC for infrastructure (see Table 1).

As shown previously in Section 3 (see Table 1), the most popular sources of uncertainty are related to data quality and availability. As indicated by an assigned ‘x’, linguistic uncertainty, as an exception, is seldom studied. Sensitivity Analysis and MCS are possible methods to handle them. On the other hand, methods for probabilistic modeling like Design of Experiment (Patra et al. 2009) and Subset Simulation (Walls and Smith 1998) are infrequently discussed and applied. Among methods related to Bayesian statistics and possibilistic modeling, these gaps seem even larger: the Bayesian Latent Markov Decision Process has only rarely been applied in previous research (e.g. Mishalani and Gong 2009). Reconsidering the complexity of those methods as described in Part I of our series, these low application levels are not surprising. Yet, the task of detecting why certain methods are applied or others are not in specific circumstances and articles is demanding.

Table 1 offers additional insights. Whereas ‘x’ symbolizes that research is conducted, ‘o’ marks combinations of sources and methods that could be feasible but have not been analyzed yet. For example, scenario analysis is a method able to showcase many more sources than as currently applied. In case of multiple data sources, scenarios as a means of sensitivity analysis could calculate different LCC outcomes based on each data source. It seems clear that scenarios are not able to explain a choice for a single data source. However, it provides an indication of magnitude (of changes in the overall LCC result) when choosing a certain data source over an alternative one. Therefore, it may help each LCC analyst to screen for key drivers which suggest they are worth additional data collection routines or data estimation methods in order to make a more profound choice. Here, the meaning of the first row, ‘Exclusion of parameters’, should be clarified. For example, Stamford et al. (2014) exclude Carbon Capture Storage for coal, because that technology was not commercially available, hereby referred to as ‘no data’. Considering current practice in LCC, LCA, and LCSA, exclusion of parameters is widespread and surely necessary to build any model (of real life systems). By ‘Exclusion of parameters’, the authors understand a deliberate, arbitrary decision based e.g. on lack of data. Dixit et al. (2010) exemplifies that boundaries were set in “past embodied energy analyses […] whenever it became difficult to acquire the necessary reliable and consistent information”. The relatively empty row signals that, though often applied, it is not an appropriate method to propagate uncertainty within LCC or LCA. In case of excluding parameters, the bare minimum requirement is to document (‘Increasing data transparency’) and qualitatively discuss its potential consequences for each LCC or LCA estimation.

How can the current limited interest in some of the presented methods be resolved? Some methods may prove to be impractical or do not address uncertainties as expected. Or, as just illustrated for ‘Exclusion of parameters’, a method is not recommended practice. Other barriers include lack of knowledge about methods and their limitations. This review shall help to overcome that obstacle by presenting existing applications to the scholarly community. Showcasing sources and addressing methods, their origin, and applied examples may help to reduce reservations regarding them. Transparently showcasing research gaps may motivate scholars to reconsider LCC approaches or start new research on methods.

As introduced in Section 1, research in the field of uncertainty related to LCC for infrastructure is of great importance when mirroring its share in negative externalities (Menikpura et al. 2012; Ostermeyer et al. 2013; 2014). LCC is seen as a decisive factor to include economics, but also the cost of externalities of products and services (Simões et al. 2013). Most authors within the study pool are motivated by the idea that more sophisticated methods to address uncertainty may “significantly change, hopefully enhance, results derived by using the conventional deterministic method” (Zhu et al. 2012). That review shares this understanding that an increasing sophistication is very useful (Zhu et al. 2012) for LCC as compared to purely deterministic models.

Another pushing factor is the integration of methods within software packages (Bolger 1996). A good example is MCS. Software like Oracle Crystall Ball (Kishk 2004), Palisade @RISK (Nachtmann and Needy 2003; Lindholm and Suomala 2007; Zhu et al. 2012), PRé Consultants’ SimaPro, and US-NREL’s HOMER (Anwari et al. 2012; Kumar and Bhimasingu 2015) all include MCS more or less with a mouse click, although it does not release each analyst from being familiar with each method’s limitations or from interpreting results of MCS in an appropriate manner. Still, a persisting and intrinsic problem is hard to counteract: more sophisticated methods

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may add extra time in computer power, time to analyze, funding needs for working hours, and additional dialogue between LCC practitioners, (engineering) experts, and lack of understanding by those who receive LCC results. Computer time can be reduced by applying data compression techniques such as Latin Hypercube sampling instead of standardized MCS. Lack of understanding can only be addressed by patience and thorough communication of problem sets, applied methods, and achieved outcome.

Moreover, scholars may learn from each other across disciplines. That means methods applied to a different field of application could be transferred to infrastructure with minor adaptations. Or, as is presented within the next Section 3.3, one can study uncertainty modeling for similar life cycle based concepts like LCA and LCSA.

3.3 Learning from applied methods within LCSA and LCA

In order to close existing research gaps, this section aims to draw parallels from scholarly fields. LCA and LCSA are then a logical choice to scrutinize, as LCC is discussed as a third pillar within LCSA (Klöpffer 2008; Schau et al. 2011; Zamagni 2012). In this review, the vivid scholarly discussion over what other type of hybrid LCA-LCC serves as the best way to support sustainability assessments is neither continued nor is of interest (Heijungs et al. 2013). The authors of this review follow Klöpffer and Ciroth (2011) who refuted arguments by Jørgensen et al. (2010) that, in turn, had not advocated LCC as necessary within LCSA.

Schmidt (2003) claims that LCC entails larger uncertainties than LCA, especially in early stages of development. Nevertheless, LCA applications to the same products often end in very different results (Williams et al. 2009), too. LCA has a seemingly more intense discussion about data quality und uncertainty propagation within its scholarly community as compared to LCC. Björklund (2002a) presented the first comprehensive survey "of methods and approaches for data quality management, sensitivity analysis, and uncertainty analysis published" for LCA. Although focusing on uncertainty located in the inventory phase, she systemizes sources of uncertainties in a formerly unseen manner while criticizing the current practice of point estimates as overestimating reliability. She roots critique that LCA researchers fail to handle data quality issues and lack a systematic approach to uncertainty analyses back to as early as 1992.

In 1996, authors within the International Journal of Life Cycle Assessment discussed approaches to address uncertainty of generic (e.g. Heijungs 1996; Kennedy et al. 1996) or sector specific nature (e.g. Chevalier and Téno 1996). Eventually, Huijbregts et al. (2001) published a framework to assess data uncertainty within life cycle inventories. Similarly, Data Quality Indicators (DQI), as suggested by Weidema and Wesnæs (1996), which center on input parameters, namely data inaccuracy and lack of representative data, are deep-rooted within the LCA community. Research on DQI and pedigree matrix is ongoing (Henriksson et al. 2014; de Saxcé et al. 2014; Muller et al. 2014). Scenario uncertainty is discussed along with the many choices of LCA analysts e.g. functional unit, system boundaries, etc. (Ciuffo et al. 2012; Clavreul et al. 2012). Björklund (2002a) stated that "choices are unavoidable" and there is "not one single correct choice".

As a response to ongoing research, many cautionary statements were included in the ISO 14040 series (Ross et al. 2002; ISO 14040:2006; ISO 14044:2006) and a handbook for data quality was published (ILCD Handbook, EU-COM JRC IES 2015). Corominas et al. (2013) argue to improve overall LCA reliability by strictly following the ISO methodological standards. Unfortunately, that guidance may be overlooked by LCA analysts for reasons of budget, time, and resource constraints. As Münch and Günther (2013) show, for allocation procedures related to LCAs for bioenergy systems, the ISO standard is often neglected and rarely do LCA practitioners document their decisions in a transparent manner. The scholarly community focusing on LCSA is also questioning how to accommodate or manage uncertainty, as the latter is seen as inherent (Zamagni 2012).

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In summary, the scholarly community for LCA and LCSA is at the forefront of framing methods to address parameter and scenario uncertainty. Model uncertainty seems to play a minor role within the discussion. Or, as Ciuffo et al. (2012) suggest, it is "common practice to consider the model uncertainty alongside the parametric inputs." When looking at the screened pool of LCA and LCSA studies related to infrastructure (see Appendix B for a complete list), one can draw parallels in the following manner: sources should be similar, if not equal, on the analytical level. The PMS categorization is equally applicable. Then, methods of handling these uncertainties shall be comparable and can be adapted to LCC problems. Therefore, Table 1 as displayed in Section 3.1 is extended by replacing identified white spots (marked with "o") with 'Δ' where applications for LCA exist. Within the LCA community, 'uncertainty analysis' usually refers to mapping the uncertainty in the inputs into the uncertainty measures in the outputs. In that sense, uncertainty is understood in a narrower sense as compared to this review.

Table 2 Extended combination of sources and methods by LCA and LCSA

PMS		Parameter uncertainty								Model uncertainty							Scenario uncertainty				
Aleatoric		x	x	x		x		x													
Epistemic			x		x		x		x	x	x	x	x	x	x	x	x	x	x	x	x
Methods	Source	Data quality: Multiple sources	Data quality: Data collection errors	Data quality: Data estimations errors	Data quality: Linguistic uncertainty	Data quality: Inherent randomness	Lack of data: No data	Lack of data: Data gaps	Lack of data: Unrepresentative data	Model structure errors	Approximations in computer coding	Simplification by averaging	Simplification by reducing observations	Simplification by reducing variables	Simplification of the functional form	Extrapolation errors	Choice of cost allocation	Choice of cost definition	Choice of methodology	Choice of system boundaries	Choice of weighting
Deterministic	Exclusion of parameters													x		x			x	x	o
	Point estimate		x	x		o		o	o												
	Rules of thumb / best guest		x	x		o	x	x	o			x								x	o
	Sensitivity analysis	Δ	o	x		Δ	x	x	x			o	o	x	Δ		Δ		x	x	x
	Scenario analysis	Δ		o		Δ		o	x			o	o	x	Δ		Δ		o	x	Δ
Probabilistic	Design of experiment		x	x									x						o		
	Importance sampling		x	x		o			o				x								
	Latin hypercube sampling		x	o		o		x	o				x	o							
	Monte Carlo Simulation	o	x	x		Δ	x	x	x				x	x	x					Δ	Δ
	Random sampling		x	x		o							x			x					
	Subset simulation							o					x								
Possibilistic	Bayesian expert opinion	Δ	x	o	o	o	x	x	Δ	o		x		x		x	Δ	o	Δ	Δ	x
	Bayesian Markov Chain		x	x			x	o													
	Bayesian Latent Markov Decision Process		x	o			o	o	o												
	Fuzzy sets	x			x		x	x	o											x	
	Evolutionary and Genetic Algorithm							x		x										x	
Simple methods	Analogy to prior literature	x	x	Δ	Δ	o	x	x	x	o	o	x	o	x	x	o	Δ	o	X	Δ	Δ
	Check by comparing with deterministic model									x		x		o					X		
	Check by multiple cases								o		x								X		
	Check by tests within the model			x						o	x	Δ	o	Δ	x	o					
	Increasing data transparency	x	x	Δ	o	x		o	x		x	o					x	x	O	x	o
	Measuring and field data	Δ	Δ				x	o	x	x											
	Standardization (standard specification)	x			x				x								x	o	X	o	o

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	Standardization (software, databases)	x	Δ	o	Δ			x	Δ									x	X		

x: methods to address uncertainty identified in literature for LCC
o: methods to address uncertainty suggested by the authors
Δ: methods to address uncertainty identified in literature for LCA/LCSA

Not surprisingly, the comparison with LCA and LCSA mostly fills gaps within parameter (13) and scenario uncertainty (11), whereas applications for model uncertainty is only improved within 4 articles. That underlines the initially expected focus on the former two types of uncertainty. Examples now follow assorted along the columns of parameter uncertainty (each column representing one source).

Dixit et al. (2010) argue that lack of standardization or ambiguity in literature makes estimation difficult in case of multiple data sources. Ergo, 'Δ' are set in the respective rows. Silvestre et al. (2015) suggest in the case of mixed data the characterization of each data source by means of DQI in order to transparently show possible deviations from the scope of the study. As DQI is hereby categorized as Bayesian expert opinion, this class receives a 'Δ'. Buyle et al. (2013) points to DQI as a means to handling data collection errors as well as the Ecoinvent database. Corominas et al. (2013) differentiate between foreground and background Life Cycle Inventory (LCI) data. The former should be measured directly or collected by comprehensive vendor-supplied information; the latter derives from databases. The same authors also demand appropriate final mass balances for all analyzed compounds within the class of data estimation errors. Heijungs and Huijbregts (2004) criticize a missing common understanding of terms like 'significant' or 'large', referred here as linguistic uncertainty. They suggest standardization, software, and multiple cases to reduce that non-standardized terminology, referred to here as 'other method'. Li et al. (2013) recommend applying MCS to illustrate inherent variability. "Future techniques", a term relating to Scenario Analysis as used in this paper, are suggested methods to encounter inherent variability as well (Georgiadou et al. 2012).

'No data' is often the consequence of confidentially within companies (Silvestre et al. 2015), which could only be handled by opening field data through contractual agreements. May and Brennan (2003) suggest applying rules of thumb in case of 'data gaps' to establish likely ranges, whereas data scarcity drives the application of possibilistic methods like Fuzzy Sets, DQI, or expert judgement in general (Nilsen and Aven 2003; Wang and Shen 2013; Corominas et al. 2013). Defined sources of uncertainty are sometimes recommended to handle other sources. Namely, Björklund (2002a) suggests using unrepresentative data in case of data gaps. Surely, DQIs are the method of choice to assess uncertainty related to unrepresentative data (Buyle et al. 2013). On the other hand, the confirmed method 'analogy to literature' is challenged by Laurent et al. (2014), arguing that roughly one third of their reviewed studies used inadequate literature data. Hence, that method may only be valid if combined with DQI or similar techniques. Generic databases may support practitioners in overcoming data gaps, while Muller et al. (2014) points to the necessary documentation of metadata along the dimensions time, location, technology etc. within each data set.

The IEC 60300-3-3 (2004) and Björklund (2002b) argue for the application of uncertainty importance analysis in order to explore all key issues. That process is twofold: a Sensitivity Analysis evaluates sources of uncertainty by determining its influence if varied. All sources are ranked according to its variance and influence upon the overall result. Their recommendations could add to the suggested guidance as presented in Section 3.4 (Figure 2). Namely, such importance ranking is recommended between identifying sources of uncertainty and the starting 'uncertainty analysis'. Another standardized procedure suggested by the ISO 14040 series (ISO 14040:3006; ISO 14044:2006) may be integrated: third party verification. Structured expert opinion is often

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presented as recommended practice in case of high uncertainties. Demanding expert feedback on LCC assumptions about data, model, and scenarios may offer a role model for what is denominated as communicating as well as monitoring and controlling results in Figure 2 in Section 3.4. External third party verification is time consuming and expensive, but considering internal expert feedback within the project team is an absolute prerequisite for an appropriate LCC.

Summarizing the historic development and identified practice on handling uncertainties within the scholarly community on LCA and LCSA, the authors strongly recommend fostering a dialogue between LCC, LCA, and LCSA practitioners and academics. That call is not new (Zamagni 2012; Hoogmartens et al. 2014), but the previous detailed gap analysis encourages scholars afresh. This section transparently shows how some current research gaps within LCC may be closed by LCA and LCSA.

3.4 Better practice of uncertainty analysis in LCC

This section summarizes our findings concerning existing practices of uncertainty analyses in LCC modeling. It also borrows from experiences within other life cycle based concepts like LCA and LCSA.

First, we suggest studying some of our screened articles as best practice. We recommend reading Engelhardt et al. (2014), Li et al. (2014), Zhu et al. (2012), Zakeri and Syri (2015) as well as Kim and Frangopol (2011). Naturally, there is not a single article that addresses all aspects of a better practice. Engelhardt et al. (2014) provide a valuable and thorough framework that helps to systemize the initial working steps of setting the context. Li et al. (2014) provide readers with an application of uncertainty analysis for wind power. The strength of their work is their clear and easy-to-follow working procedure. Zhu et al. (2012) compare a deterministic with a probabilistic model to assess ground source heat pumps. It is a good example of how to use MCS within a software like Palisade @RISK as a means to simulate cost data. Zakeri and Syri (2015) illustrate impacts of ignoring uncertainty for existing data about electrical energy storage systems in previous literature. Their results of that meta-analysis make a strong case for considering uncertainties. Lastly, Kim and Frangopol (2011) showcase Bayesian techniques related to inspection planning for highway bridges. They represent an example for applying an advanced possibilistic method. We additionally advocate screening the following studies related to LCA and LCSA in order to properly understand DQI as a meaningful method to assess data representativeness: Ciroth (2009) and Ciroth et al. (2013). An application of DQI is well-presented in Gavankar et al. (2015). Although the latter is not related to infrastructure, the articles paint a good picture of how DQI is put into practice.

Second, this review provides guidance for the readers' choice: Table 2 illustrated what sources and methods are applied to address uncertainties in LCC, LCA, and LCSA. Appendix A, which is sorted by the sources of uncertainty, then gives a thorough overview of all articles with their applied methods addressing uncertainty. Succeeding columns contain their addressing methods and the articles studying this combination. It allows the reader to identify articles applying a specific method that is of interest.

Third, uncertainties should eventually be transferred into business or project risks. Risk was initially defined as uncertain outcomes with good probability information (Park and Sharp-Bette 1990b) in Section 1. However, we associate the wider definition of uncertainty as used throughout this article with these project risks. That includes uncertainties with no probability information. As presented in previous sections, Bayesian techniques including Expert opinion offers a way to define expected probabilities in this case. In LCC modeling for infrastructure decisions, these uncertainties may convert into current (or future) requirements of the organization, following the standards ISO 31000 (2009) and IEC 62198 (2013). The ISO 31000 (2009) and IEC 62198 (2013) process of

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handling risks offers guidance on how to embed uncertainty analyses within business or project management practices. Whereas our review, so far, has covered areas that are named as risk assessment (including risk identification, risk analysis, and risk evaluation) and risk treatment within the standard, the ISO 31000 (2009) goes beyond that scope by introducing a framework about how to proceed with the results in a business context. Figure 2 illustrates a suggestion on how such integration in business management is feasible. It combines laid out analysis steps to identify sources of uncertainty with the ensuing matching of sources and methods. In the end, controlling and managing evaluated, accepted levels of uncertainties closes a feedback-loop to the initial steps of uncertainty analysis. It is of great importance that LCC modeling is accompanied with subsequent, iterative updates of data, and (sub-)modeling routines that pay respect to the cost commitment curve (Roy 2003). Clear communication of the results of uncertainty analyses is important in order to avoid misunderstandings, too (Heidmann and Milde 2013).

[Insert here Figure 2]

Fourth, by synthesizing our findings, including learning aspects from LCA and LCSA (see Section 3.3 and Simões et al. 2013), the LCC modeling requires information about the following: (1) intended goal and scope of the analysis; (2) definition of the product to be analyzed, including its structure, components, and function (including functional unit, and, ideally, a product tree or product breakdown structure); (3) the life cycle of the product and its components (system boundaries, perspective of analysis, level of externalities addressed, reference year); (4) a cost classification or cost breakdown structure including an allocation regime; (5) cost and related life cycle inventory data sources (technological, time, and geographical background as shown by DQI, currency units, discount rate); (6) model and scenario uncertainty analysis for (1) to (4); and (7) a data uncertainty analysis for (3) and (5). These working steps are included in Figure 2 (right-hand side) and may provide a checklist to practitioners. Working steps (1) to (4) refer to ‘setting the context’ in Figure 2. The processes ‘identifying sources of uncertainty’ and ‘uncertainty analysis’ are included in steps (5) to (7). The necessary follow-up by forming a business response towards identified and evaluated uncertainties is illustrated as step (8).

4 Conclusions

The results of an LCC are influenced by various uncertainties. These uncertainties rise with longer lifespans and higher complexity. Infrastructure projects are characterized by both aspects. The following research gaps were listed and discussed in the identified articles about uncertainty in LCC for infrastructure prior to our review series. They ranged from generic statements like “setting a framework to capture all or most important uncertainties” (Xu et al. 2012), to very specific requests, e.g. “an inflation index for a given pavement type could be extracted” (Gransberg and Diekmann 2004). Exemplary, Xu et al. (2012) demanded that uncertainty be estimated by probabilistic methods and propagating uncertainty with MCS. Further research on fuzzy set and possibilistic approaches for cases of unavailable data (Srivastava and Nema 2012; Xu et al. 2012; Zhang et al. 2014) is requested. Xu et al. (2012) asked for modeling approaches differentiating between epistemic and aleatoric uncertainty, too.

In summary, previous research lacks a holistic framework that categorizes uncertainties and methods to address them, nor does it provide guidance on which method has to be applied for a certain type of uncertainty. The aim

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of this series is to facilitate the handling of uncertainties in infrastructure LCC and shed light on the variety of methods to address them.

Part I of this series addressed two research gaps. First, it collected in a systematic and comprehensive way different types of uncertainty and methods to address them. Afterwards these uncertainties and methods were categorized and advantages and disadvantages were presented. The results help to level the playing field for readers not yet familiar with uncertainty in LCC. In addition, Part I sets the ground for evaluating suitability of methods within the context of LCC for infrastructure. The latter is conducted in Part II of the series, where the collected types of uncertainty were compared with applied methods. Further, we identified types of uncertainty that had been insufficiently addressed so far. In a third step, these types were covered by methods applied in other life cycle approaches. Finally, best practices for LCC practitioners were developed. Our results contribute to improving future applications of LCC as well as implementation of uncertainty analysis in management practice.

In Part I, 33 sources of uncertainty and 24 methods to address them were collected. Most applied methods are of deterministic character. They are easier to apply but not able to address all types of uncertainty. For probabilistic methods MCS is most often applied. Possibilistic methods are used only a few times as they are time consuming and require substantial effort and expertise; however, they create the best results. Suitability of sources and methods is guarded by these categorization schemes. We observed that data collection and estimation errors as well as the simplification by reduced observations are dominated by probabilistic methods. Further, methods to address inherent randomness are hardly mentioned in literature although there are several methods that fit very well to this kind of uncertainty.

In this context, we show that LCA and LCSA studies can teach LCC practitioners valuable lessons related to methods addressing parameter and scenario uncertainty. All in all, 28 previously unseen combinations of sources and methods to address uncertainty are discussed within pertinent research on LCA and LCSA. Learning potentials are largest for methods regarding data and scenario uncertainty. LCC analysts can learn the most for data representativeness (pedigree matrix) and Delphi scenario (planning). Third party verification, as demanded by the ISO 14040 series, encourages LCC analysts to include expert elicitation as a feedback routine not only on uncertain data, but also on modeling and system choices. Our findings encourage a vivid exchange of research and best practice between these three communities, namely LCC, LCA, and LCSA.

The results of this series provide guidance to practitioners in choosing the proper category; however, the individual method has to be selected case by case. The selection of the method depends on the type of uncertainty, the requirements to the methods, and the available time and expertise.

We aimed to provide even more insights, but during the study we experienced some drawbacks. First, we were not able to assign the identified sources to a certain life cycle stage. Instead, we analyzed the life cycle stages in which uncertainty analysis was performed. Second, we intended to assign the identified sources of subject hierarchy to the PMS categories. However, it turned out that the uncertainties in this category are parameter, model, and scenario uncertainty at the same time and, thus, a categorization was unrewarding. Third, we aimed to develop a step-by-step guidance for all types of uncertainties. During the research we noticed that too many variations and ramifications exist. As mentioned before, the selection of an appropriate method depends on the individual case and a comprehensive overview of these cases is not within the scope of a research article.

As presented above, the handling of uncertainties in infrastructure LCC improved with this series and became more structural. Additionally, best practices facilitate theoretical and practical application. Still, there remain

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several areas of further research. First, this article used broad suitability criteria of uncertainties and methods and, thus, the process could be refined and suitability tests intensified. Second, we started a first approach to integrate uncertainty analysis of LCC in risk assessment. The merging process is rather sophisticated and requires further efforts for satisfactory implementation. Third, dynamic changes of parameters within uncertainty analysis have large effects on the results. However, they are not fully understood and further research is necessary to develop appropriate methods. Finally, very little research regarding uncertainties in infrastructure modeling is conducted in the end-of-life phase. This led to underestimations in cost calculations as disposal or recycling costs were neglected.

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Appendix

[Insert here Appendix A]

Source of uncertainty	Method to address uncertainty	Deterministic	Probabilistic	Possibilistic	General	Applied in…
Data quality: Ambiguity / Multiple sources	Fuzzy sets			x		(Boussabaine and Kirkham 2004)
	Analogy to prior literature				x	(Andrade and Teixeira 2012)
Data quality: Data collection / Measurement errors	Increasing data / documentary transparency				x	(Sanyé-Mengual et al. 2015)
	Rules of thumb / best guess	x				(Rabl 1985)
	Importance sampling		x			(Budnitz et al. 1997)
	Monte Carlo Simulation		x			(Jung et al. 2009; Firouzi and Rahai 2012)
	Latin hypercube sampling		x			(Budnitz et al. 1997)
	Design of Experiment and Monte Carlo Simulation		x			(Patra et al. 2009)
	Random sampling		x			(Budnitz et al. 1997)
	Latent Markov Decision Process			x		(Madanat 1993; Mishalani and Gong 2009a; Mishalani and Gong 2009b)
	Increasing data / documentary transparency				x	(Battke et al. 2013; Aissani et al. 2014)
	Analogy to prior literature				x	(Mata et al. 2014)
Data quality: Data estimations errors and future imprecision	Rules of thumb / best guess	x				(Rabl 1985; Walls and Smith 1998)
	Sensitivity analysis	x				(Budnitz et al. 1997; Walls and Smith 1998; Sterner 2000; Zayed et al. 2002; Val 2007; Choe et al. 2008; Moore and Morrissey 2014)
	Monte Carlo Simulation		x			(Walls and Smith 1998; Ergonul 2005; Jung et al. 2009; Firouzi and Rahai 2012)
	Design of experiment		x			(Apostolakis 1990; Budnitz et al. 1997)
	Design of Experiment and Monte Carlo Simulation		x			(Patra et al. 2009)
	Random sampling		x			(Budnitz et al. 1997; Wen and Kang 2001a)
	Importance sampling		x			(Budnitz et al. 1997)
	Latin hypercube sampling		x			(Budnitz et al. 1997)
	Check by tests within the model				x	(Walls and Smith 1998)
Data quality: Lack of experience	Sensitivity analysis	x				(Sterner 2000)
	Latin hypercube sampling		x			(Budnitz et al. 1997)
	Importance sampling		x			(Budnitz et al. 1997)
	Random sampling		x			(Budnitz et al. 1997)
	Bayesian expert opinion			x		(Budnitz et al. 1997)
	Increasing data / documentary transparency				x	(Battke et al. 2013)
Data quality: Subjective judgement / Optimism bias	Sensitivity analysis	x				(Walls and Smith 1998; Zayed et al. 2002)
Data quality: Vagueness / Linguistic uncertainty	Standardization (Norm, standard, guideline or law)				x	(Mavrotas et al. 2010)
Data quality: Variability / inherent randomness	Increasing data / documentary transparency				x	(Battke et al. 2013)
Lack of data: Data gaps / lack of any data	Rules of thumb / best guess	x				(Rabl 1985; Herbold 2000; Hinow and Mevissen 2011; Liu et al. 2014)
	Sensitivity analysis	x				(Herbold 2000; Sterner 2000; Singh and Tiong 2005; Val 2007)
	Monte Carlo Simulation		x			(Firouzi and Rahai 2012)
	Latin hypercube sampling		x			(Butry 2009)
	Bayesian expert opinion			x		(Apostolakis 1990; Budnitz et al. 1997; Kayrbekova et al. 2011)
	Analogy to prior literature				x	(Hong and Hastak 2007; Mavrotas et al. 2010; Hinow and Mevissen 2011)
Lack of data: Unrepresentative data	Sensitivity analysis	x				(Russell 1981; Lindholm and Suomala 2007; Aissani et al. 2014; Moore and Morrissey 2014)

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Source of uncertainty	Method to address uncertainty	Deterministic	Probabilistic	Possibilistic	General	Applied in…
	Scenario analysis	x				(Russell 1981)
	Monte Carlo Simulation		x			(Lindholm and Suomala 2007; Minne and Crittenden 2015)
	Measuring and field data				x	(Zakeri and Syri 2015)
	Increasing data / documentary transparency				x	(Ciroth 2009)
	Standardization (Norm, standard, guideline or law)				x	(Mata et al. 2014)
	Analogy to prior literature				x	(Zakeri and Syri 2015)
Model errors and assumptions	Sensitivity analysis	x				(Sterner 2000; Singh and Tiong 2005; Choe et al. 2008; McDonald and Madanat 2012; Troldborg et al. 2014)
	Exclusion of parameters	x				(Yu et al. 2013)
	Monte Carlo Simulation		x			(Battke et al. 2013)
	Bayesian expert opinion			x		(Apostolakis 1990; Morcous and Lounis 2005)
	Increasing data / documentary transparency				x	(Aissani et al. 2014)
	Check by test within the model				x	(Kayrbekova et al. 2011)
Simplification by averaging	Rules of thumb / best guess	x				(Amoiralis et al. 2007)
	Bayesian expert opinion			x		(Apostolakis 1990)
	Check by comparing with reduced model				x	(Mavrotas et al. 2010)
	Analogy to prior literature				x	(Andrade and Teixeira 2012; Yu et al. 2013)
Simplification by reducing variables	Scenario analysis	x				(Minne and Crittenden 2015)
	Monte Carlo Simulation		x			(Chiu et al. 2013)
	Analogy to prior literature				x	(Andrade and Teixeira 2012; Mata et al. 2014)
Simplification of the functional form	Monte Carlo Simulation		x			(De León et al. 2013; Troldborg et al. 2014)
	Parametric method		x			(Mata et al. 2014)
	Analogy to prior literature				x	(Liu et al. 2014)
	Check by tests within the model				x	(Liu et al. 2014)
Choice of cost allocation	Increasing data / documentary transparency				x	(Reich 2005; Swarr et al. 2011)
	Standardization (Norm, standard, guideline or law)				x	(Swarr et al. 2011)
Choice of cost definition	Increasing data / documentary transparency				x	(Reich 2005; Swarr et al. 2011)
Choice of methodology	Exclusion of parameters	x				(Han et al. 2014)
	Sensitivity Analysis	x				(Sterner 2000)
	Standardization (Norm, standard, guideline or law)				x	(Hong et al. 2007; Andrade and Teixeira 2012; Anwari et al. 2012; Mata et al. 2014; Noori et al. 2014)
	Check by comparing with deterministic model				x	(Zhu et al. 2012; Aissani et al. 2014)
	Check by multiple cases				x	(Hong et al. 2007)
	Analogy to prior literature				x	(Battke et al. 2013)
Choice of input parameters and system boundaries	Sensitivity analysis	x				(Budnitz et al. 1997; Swarr et al. 2011; Liu et al. 2014)
	Rules of thumb / best guess	x				(Liu et al. 2014; Robert and Gosselin 2014)
	Scenario analysis	x				(Li et al. 2014; Robert and Gosselin 2014)TAH11:159
	Exclusion of parameters	x				(Reich 2005; Simões et al. 2013; Hong et al. 2014; Sanyé-Mengual et al. 2015)
	Increasing data / documentary transparency				x	(Reich 2005; Upadhyay et al. 2012; Moore and Morrissey 2014)
Choice of weighting	Sensitivity analysis	x				(Budnitz et al. 1997; Reich 2005)
	Bayesian expert opinion			x		(Jung et al. 2009)

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Source of uncertainty	**Method to address uncertainty**	**Deterministic**	**Probabilistic**	**Possibilistic**	**General**	**Applied in…**
Economical context – Demand	Scenario analysis	x				(Francis et al. 2011; Danaher 2012; Hong et al. 2014; Moore and Morrissey 2014)
	Exclusion of parameters	x				(Willuweit and O’Sullivan 2013; Sanyé-Mengual et al. 2015)
	Sensitivity analysis	x				(McDonald and Madanat 2012)
	Monte Carlo Simulation		x			(Li and Madanu 2009; Li and Sinha 2009; Settanni and Emblemsvåg 2010; Danaher 2012; Koltsaklis et al. 2014)
	Latent Markov Decision Process			x		(Madanat 1993; Mishalani and Gong 2009a; Mishalani and Gong 2009b)
	Standardization (Norm, standard, guideline or law)				x	(Anwari et al. 2012)
	Measuring and field data				x	(Willuweit and O’Sullivan 2013)3
Economical context – Inflation	Exclusion of parameters	x				(Tähkämö et al. 2012)
	Rules of thumb / best guess	x				(Walls and Smith 1998)
	Sensitivity analysis	x				(Walls and Smith 1998; Kang and Wen 2000; Wen and Kang 2001a; Wen and Kang 2001b; Zayed et al. 2002; Singh and Tiong 2005; Han and Park 2009; Lee et al. 2009; Allacker 2012; Kantola and Saari 2013; Li et al. 2014; Moore and Morrissey 2014; Zakeri and Syri 2015)
	Scenario analysis	x				(Rabl 1985; Lee et al. 2009; Francis et al. 2011; Okasha et al. 2012; Lai et al. 2013; Willuweit and O’Sullivan 2013; Han et al. 2014)
	Monte Carlo Simulation		x			(Walls and Smith 1998; Ehlen 1999; Herbold 2000; Ergonul 2005; Liu and Frangopol 2005; Hong et al. 2007; Lekov et al. 2010; Settanni and Emblemsvåg 2010; Andrade and Teixeira 2012; Eamon et al. 2012; Okasha et al. 2012; Zakeri and Syri 2015)
	Design of Experiment and Monte Carlo Simulation		x			(Patra et al. 2009)
	Subset simulation		x			(Willuweit and O’Sullivan 2013)
	Latin hypercube sampling		x			(Butry 2009)
	Bayesian expert opinion			x		(Greenberg et al. 2004; Patra et al. 2009)
	Bayesian expert opinion			x		(Butry 2009)
	Standardization (Norm, standard, guideline or law)				x	(Anwari et al. 2012; Tähkämö et al. 2012)
	Analogy to prior literature				x	(Allacker 2012; Menikpura et al. 2012; Aissani et al. 2014; Han et al. 2014; Hong et al. 2014; Moore and Morrissey 2014)
Economical context – Discount rate	Sensitivity analysis	x				(Walls and Smith 1998; Ehlen 1999; Herbold 2000; Kang and Wen 2000; Sterner 2000; Wen and Kang 2001a; Wirahadikusumah and Abraham 2003; Gransberg and Diekmann 2004; Ergonul 2005; Singh and Tiong 2005; Amoiralis et al. 2007; Hong et al. 2007; Francis et al. 2011; Allacker 2012; Kantola and Saari 2013; Li et al. 2014; Mata et al. 2014; Moore and Morrissey 2014; Zakeri and Syri 2015)
	Scenario analysis	x				(Walls and Smith 1998; Allacker 2012; Okasha et al. 2012; Moore and Morrissey 2014)
	Random sampling		x			(Wen and Kang 2001a; Okasha et al. 2012)
	Monte Carlo Simulation		x			(Walls and Smith 1998; Gransberg and Diekmann 2004; Ergonul 2005; Li and Madanu 2009; Li and Sinha 2009; Lekov et al. 2010; Danaher 2012; Zhang et al. 2014)

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Source of uncertainty	Method to address uncertainty	Deterministic	Probabilistic	Possibilistic	General	Applied in…
Economical context – Discount rate	Bayesian expert opinion			x		(Greenberg et al. 2004; Patra et al. 2009)
	Standardization (Norm, standard, guideline or law)				x	(Tähkämö et al. 2012; Yu et al. 2013; Minne and Crittenden 2015)
	Analogy to prior literature				x	(Reich 2005; Allacker 2012; Battke et al. 2013; Aissani et al. 2014)
Sociopolitical context – Regulation and taxation	Scenario Analysis	x				(Lee et al. 2009; Aissani et al. 2014; Shin and Singh 2014)
	Bayesian expert opinion			x		(Greenberg et al. 2004)
Technological context – Technological development	Scenario analysis	x				(Russell 1981; Willuweit and O'Sullivan 2013; Rathore and Roy 2014)
	Monte Carlo Simulation		x			(Ehlen 1999)
	Bayesian expert opinion			x		(Greenberg et al. 2004)
	Analogy to prior literature				x	(Battke et al. 2013; Hong et al. 2014)
	Standardization (Norm, standard, guideline or law)				x	(Moore and Morrissey 2014)
Natural context – Availability of resources	Sensitivity analysis	x				(Greenberg et al. 2004; Anwari et al. 2012; Li et al. 2014)
	Exclusion of parameters	x				(Rathore and Roy 2014)
	Point estimate	x				(Kavousi-Fard et al. 2014)
	Scenario analysis	x				(Russell 1981; Willuweit and O'Sullivan 2013; Rathore and Roy 2014)
	Design of Experiment and Monte Carlo Simulation		x			(Patra et al. 2009)
	Subset simulation		x			(Willuweit and O'Sullivan 2013)
	Monte Carlo Simulation		x			(Koltsaklis et al. 2014; Troldborg et al. 2014)
	Bayesian expert opinion			x		(Greenberg et al. 2004)
	Standardization (Norm, standard, guideline or law)				x	(Anwari et al. 2012)
	Analogy to prior literature				x	(Anwari et al. 2012; Troldborg et al. 2014)
Natural context – Environmental conditions	Exclusion of parameters	x				(Francis et al. 2011; Willuweit and O'Sullivan 2013)
	Sensitivity analysis	x				(Lee et al. 2009)
	Scenario analysis	x				(Wen and Kang 2001b; Francis et al. 2011; Danaher 2012; Simões et al. 2013; Shin and Singh 2014)
	Monte Carlo Simulation		x			(Kumar et al. 2009; Lekov et al. 2010; Danaher 2012; Chiu et al. 2013; De León et al. 2013; Fragiadakis et al. 2015; Zakeri and Syri 2015)
	Monte Carlo Simulation		x			(Kayrbekova et al. 2011)
	Latin hypercube sampling		x			(Butry 2009)
	Bayesian expert opinion			x		(Budnitz et al. 1997)
	Check by comparing with reduced model				x	(Shin and Singh 2014)
	Standardization (Norm, standard, guideline or law)				x	(De León et al. 2013; Shin and Singh 2014)
	Analogy to prior literature (data sets)				x	(Wen and Kang 2001b; Srivastava and Nema 2012; Willuweit and O'Sullivan 2013)
Organizational level – Funding and budget restrictions	Cannot directly be lowered by analytical methods, but has to be assessed before every project.					
Organizational level – Operating processes	Rules of thumb / best guess	x				(Walls and Smith 1998)
	Sensitivity analysis	x				(Ehlen 1999; Hansson and Bryngelsson 2009) (Walls and Smith 1998; Kang and Wen 2000; Zayed et al. 2002; Singh and Tiong 2005; Amoiralis et al. 2007; Val 2007; McDonald and Madanat 2012)
	Scenario Analysis	x				(Apostolakis 1990; Zhao et al. 2011)

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Source of uncertainty	Method to address uncertainty	Deterministic	Probabilistic	Possibilistic	General	Applied in…
Organizational level – Operating processes	Monte Carlo Simulation		x			(Ehlen 1999; Stewart et al. 2004; Ergonul 2005; Li and Madanu 2009)
	Design of Experiment and Monte Carlo Simulation		x			(Patra et al. 2009)
	Design of experiment		x			(Apostolakis 1990)
	Bayesian expert opinion			x		(Apostolakis 1990; Greenberg et al. 2004)
	Bayesian Markov Chain			x		(Jalayer et al. 2011)
Organizational level – Project and red-tape complexity	Exclusion of parameters	x				(Butry 2009; Zhao et al. 2011; Eamon et al. 2012; McDonald and Madanat 2012)
	Sensitivity Analysis	x				(Sterner 2000)
	Design of Experiment and Monte Carlo Simulation		x			(Patra et al. 2009)
	Fuzzy sets			x		(Boussabaine and Kirkham 2004)
Product level – Life time prediction	Rules of thumb / best guest	x				(Hong and Hastak 2007)
	Sensitivity analysis	x				(Walls and Smith 1998; Kang and Wen 2000; Sterner 2000; Wen and Kang 2001b; Singh and Tiong 2005; Han and Park 2009; McDonald and Madanat 2012; Ostermeyer et al. 2013; Moore and Morrissey 2014)
	Scenario Analysis	x				(Zayed et al. 2002; Li and Sinha 2009; Okasha et al. 2012)
	Random sampling		x			(Wen and Kang 2001a; Okasha et al. 2012)
	Monte Carlo Simulation		x			(Ntuen 1985; Ehlen 1999; Stewart et al. 2004; Ergonul 2005; Liu and Frangopol 2005; Hong et al. 2007; Jung et al. 2009; Li and Madanu 2009; Li and Sinha 2009; Lekov et al. 2010; Kayrbekova et al. 2011; Eamon et al. 2012; Firouzi and Rahai 2012)
	Bayesian Markov Chain			x		(Wirahadikusumah and Abraham 2003; van Noortwijk and Klatter 2004; Durango-Cohen and Tadepalli 2006; Jalayer et al. 2011)
	Bayesian expert opinion			x		(Patra et al. 2009)
	Latent Markov Decision Process			x		(Madanat 1993)
	Standardization (Norm, standard, guideline or law)				x	(Sanyé-Mengual et al. 2015)
	Analogy to prior literature				x	(Hong and Hastak 2007; Aissani et al. 2014)
Product level – Product performance and output	Scenario analysis	x				(Ostermeyer et al. 2013; Yu et al. 2013)
	Sensitivity analysis	x				(Upadhyay et al. 2012; Kantola and Saari 2013; Ostermeyer et al. 2013; Sanyé-Mengual et al. 2015)
	Bayesian expert opinion			x		(Ostermeyer et al. 2013)
	Fuzzy sets			x		(Zhang et al. 2014)
	Monte Carlo Simulation			x		(Zhu et al. 2012)
	Analogy to prior literature				x	(Aissani et al. 2014)
	Check by multiple cases				x	(Upadhyay et al. 2012)
	Standardization (Norm, standard, guideline or law)				x	(Yu et al. 2013; Kumar and Bhimasingu 2015)
Product level – Failure rates and product reliability	Sensitivity analysis	x				(Walls and Smith 1998; Wen and Kang 2001b; Val 2007; Han and Park 2009; Hinow and Mevissen 2011; McDonald and Madanat 2012; Aissani et al. 2014; Liu et al. 2014; Zakeri and Syri 2015)
	Scenario Analysis	x				(Rabl 1985; Wirahadikusumah and Abraham 2003; Allacker 2012)
	Rules of thumb / best guess	x				(Hinow and Mevissen 2011; Noori et al. 2014)

Source of uncertainty	Method to address uncertainty	Deterministic	Probabilistic	Possibilistic	General	Applied in…
Product level – Failure rates and product reliability	Design of Experiment and Monte Carlo Simulation		x			(Patra et al. 2009; Liu et al. 2014)
	Subset simulation		x			(Val and Stewart 2005; Choe et al. 2008; Aissani et al. 2014)
	Importance Sampling		x			(Chiu et al. 2013)
	Latin hypercube sampling		x			(Ntuen 1985; Mitropoulou et al. 2011)
	Monte Carlo Simulation		x			(Stewart et al. 2004; Ergonul 2005; Andrade and Teixeira 2012; Firouzi and Rahai 2012; Kim et al. 2012; De León et al. 2013; Noori et al. 2014)
	Bayesian Markov Chain			x		(Wirahadikusumah and Abraham 2003; van Noortwijk and Klatter 2004; Durango-Cohen and Tadepalli 2006; Jalayer et al. 2011; Andrade and Teixeira 2012; Kim et al. 2012)
	Genetic Algorithm			x		(Morcous and Lounis 2005; Hinow and Mevissen 2011)
	Bayesian expert opinion			x		(Morcous and Lounis 2005; Zhang et al. 2014)
	Latent Markov Decision Process			x		(Madanat 1993)
	Measuring and field data				x	(Hong and Hastak 2007; Shin and Singh 2014)
	Check by comparing with reduced model				x	(Terzi and Serin 2014)
	Analogy to prior literature				x	(Hong and Hastak 2007; Hinow and Mevissen 2011; Allacker 2012; Andrade and Teixeira 2012; Kim et al. 2012; Liu et al. 2014)
	Check by comparing with deterministic model				x	(Aissani et al. 2014)
	Check by tests within the model				x	(Liu et al. 2014)
	Measuring and field data				x	(Aissani et al. 2014)

[Insert here Appendix B]

No.	Abbr.	Author	Year	Title	Topic
	CIU12	Ciuffo, B. Miola, A. Punzo, V. Sala, S.	2012	Dealing with uncertainty in sustainability assessment. Report on the application of different sensitivity analysis techniques to fieldspecific simulation models	Energy infrastructure
	KUC14	Kucukvar, M. Noori, M. Egilmez, G. Tatari, O.	2014	Stochastic decision modeling for sustainable pavement designs	Transportation infrastructure
	MAN12	Manzardo, A. Ren, J. Mazzi, A. Scipioni, A.	2012	A grey-based group decision-making methodology for the selection of hydrogen technologies in life cycle sustainability perspective	Energy infrastructure
	PES13	Pesonen, H.-L. Horn, S.	2013	Evaluating the Sustainability SWOT as a streamlined tool for life cycle sustainability assessment	Generic
	SAL13b	Sala, S. Farioli, F. Zamagni, A.	2013	Life cycle sustainability assessment in the context of sustainability science progress (part 2)	Generic
	SAL13a	Sala, S. Farioli, F. Zamagni, A.	2013b	Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1	Generic
	STA14	Stamford, L. Azapagic, A.	2014	Life cycle sustainability assessment of UK electricity scenarios to 2070	Energy infrastructure
	ZAM12b	Zamagni, A.	2012	Life cycle sustainability assessment	Generic
	BEN08	Benetto, E. Dujet, C.	2008	Integrating fuzzy multicriteria analysis and uncertainty evaluation in life cycle assessment	Energy infrastructure

	Rousseaux, P.			
BJÖ02	Björklund, A.E.	2002	Survey of Approaches to Improve Reliability in LCA	Generic
BRE98	Bretz, R.	1998	SETAC LCA Workgroup: Data Availability and Data Quality	Generic
BUY13	Buyle, M. Braet, J. Audenaert, A.	2013	Life cycle assessment in the construction sector: A review	Construction materials
CIR13	Ciroth, A.	2013	Empirically based uncertainty factors for the pedigree matrix in ecoinvent	Generic
CLA12	Clavreul, J. Guyonnet, D. Christensen, T.H.	2012	Quantifying uncertainty in LCA-modelling of waste management systems	Waste treatment
COR13	Corominas, Ll. Foley, J. Guest, J.S. Hospido, A. Larsen, H.F. Morera, S. Shaw, A.	2013	Life cycle assessment applied to wastewater treatment: State of the art	Water infrastructure
COU97	Coulon, R. Camobreco, V. Teulon, H. Besnainou, J.	1997	Data Quality and Uncertainty in LCI	Generic
DIX10	Dixit, M.K. Fernández-Solís, J.L. Lavy, S. Culp, C.H.	2010	Identification of parameters for embodied energy measurement: A literature review	Buildings
DON04	Dones, R. Heck, T. Emmenegger, M.F. Jungbluth, N.	2004	Life Cycle Inventories for the Nuclear and Natural Gas Energy Systems, and Examples of Uncertainty Analysis	Energy infrastructure
FIN09	Finnveden, G. Hauschild, M.Z. Ekvall, T. Guinée, J. Heijungs, R. Hellweg, S. Köhler, A. Pennington, D. Suh, S.	2009	Recent developments in Life Cycle Assessment	Generic
GEO12	Georgiadou, M.C. Hacking, T. Guthrie, P.	2012	A conceptual framework for future-proofing the energy performance of buildings	Buildings
GRA15	Grant, A. Ries, R. Thompson, C.	2015	Quantitative approaches in life cycle assessment — part 2 — multivariate correlation and regression analysis	Buildings / Construction materials
GUI11	Guinée, J. Heijungs, R. Huppes, G. Zamagni, A. Masoni, P. Buonamici, R. Ekvall, T. Rydberg, T.	2011	Life cycle assessment: Past, present, and future	Generic
HEI96	Heijungs, R.	1996	Identification of key issues for further investigation in improving the reliability of life-cycle assessments	Generic
HEI04	Heijungs, R. Huijbregts, M.A.J.	2004	A Review of Approaches to Treat Uncertainty in LCA	Generic
HEI10	Heijungs, R.	2010	Sensitivity coefficients for matrix-based LCA	Generic
HEL03	Hellweg, S. Hofstetter, T.B. Hungerbühler, K.	2003	Discounting and the Environment	Generic
HEL14	Hellweg, S. Milà i Canals, Ll.	2014	Emerging approaches, challenges and opportunities in life cycle assessment	Generic
HOX14	Hoxha, E. Habert, G. Chevalier, J. Bazzana, M. Le Roy, R.	2014	Method to analyse the contribution of material's sensitivity in buildings' environmental impact	Buildings
HUI01	Huijbregts, M.A.J. Norris, G. Bretz, R. Ciroth, A. Maurice, B.	2001	Framework for Modelling Data Uncertainty in Life Cycle Inventories	Generic

	von Bahr, B. Weidema, B. de Beaufort, A.S.H.			
HUN09	Hung, M.-L. Ma, H.-W.	2008	Quantifying system uncertainty of life cycle assessment based on Monte Carlo simulation	Generic
LAU14	Laurent, A. Clavreul, J. Bernstad, A. Bakas, I. Niero, M. Gentil, E. Christensen, T.H. Hauschild, M.Z.	2014	Review of LCA studies of solid waste management systems – Part II: Methodological guidance for a better practice	Waste treatment
LAZ10	Lazarevic, D. Aoustin, E. Buclet, N. Brandt, N.	2010	Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective	Waste treatment
LEN06	Lenzen, M.	2006	Uncertainty in Impact and Externality Assessments	Generic
LI13	Li, Y. Chen, J. Feng, L.	2013	Dealing with Uncertainty: A Survey of Theories and Practices	Generic
LLO07	Lloyd, S.M. Ries, R.	2007	Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment	Generic
MAU00	Maurice, B. Frischknecht, R. Coelho-Schwirtz, V. Hungerbühler, K.	2000	Uncertainty analysis in life cycle inventory. Application to the production of electricity with French coal power plants	Energy infrastructure
MAY03	May, J.R.	2003	Application of Data Quality Assessment Methods to an LCA of Electricity Generation	Energy infrastructure
MUL14	Muller, S. Lesage, P. Ciroth, A. Mutel, C. Weidema, B.P. Samson, R.	2014	The application of the pedigree approach to the distributions foreseen in ecoinvent v3	Generic
REA08a	Reap, J. Roman, F. Duncan, S. Bras, B.	2008	A survey of unresolved problems in life cycle assessment. Part 1: goal and scope and inventory analysis	Generic
REA08b	Reap, J.	2008b	A survey of unresolved problems in life cycle assessment. Part 2: impact assessment and interpretation	Generic
ROS02	Ross, S. Evans, D. Webber, M.	2002	How LCA Studies Deal with Uncertainty	Generic
SAN11a	Santero, N.J. Masanet, E. Horvath, A.	2011	Life-cycle assessment of pavements. Part I: Critical review	Generic
SAN11b	Santero, N.J. Masanet, E. Horvath, A.	2011b	Life-cycle assessment of pavements Part II: Filling the research gaps	Generic
SIL15	Silvestre, J.D. Lasvaux, S. Hodková, J. de Brito, J. Pinheiro, M.D.	2015	NativeLCA - a systematic approach for the selection of environmental datasets as generic data: application to construction products in a national context	Construction materials
WAN13	Wang, E. Shen, Z.	2013	A hybrid Data Quality Indicator and statistical method for improving uncertainty analysis in LCA of complex system – application to the whole-building embodied energy analysis	Buildings
WIL09	Williams, E.D. Weber, C.L. Hawkins, T.R.	2009	Hybrid Framework for Managing Uncertainty in Life Cycle Inventories	Generic
YUA15	Yuan, C. Wang, E. Zhai, Q. Yang, F.	2015	Temporal discounting in life cycle assessment: A critical review and theoretical framework	Generic
ZAM12a	Zamagni, A. Masoni, P. Buttol, P. Raggi, A. Buonamici, R.	2012	Finding Life Cycle Assessment Research Direction with the Aid of Meta-Analysis	Generic

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Table captions

Table 1 Combination of sources of uncertainty and methods to address them

Table 2 Extended combination of sources and methods by LCA and LCSA

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Figure Captions

Fig. 1 Handling of uncertainties in LCC (Kishk 2004)

Fig. 2 Integrating uncertainty analysis into risk management (adapted from ISO 31000 (2009) and IEC 62198 (2013))