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Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

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PhD Thesis
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Printed by:	GraphicCo (June 2017)
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Preface

The work presented in this PhD thesis was conducted from July 2013 to May 2017 at the Department of Environmental Engineering of the Technical University of Denmark (DTU) under the supervision of Professor Thomas Fruergaard Astrup and co-supervision of Professor Thomas Højlund Christensen. The PhD project was funded by the IRMAR Project and by the Danish Environmental Protection Agency (Miljøstyrelsen).

The PhD thesis is organized in two parts: the first part puts into context the findings of the PhD in an introductive review; the second part consists of the four scientific journal papers listed below. These will be referred to in the text by their paper number written with the Roman numerals **I-VI**.

I Bisinella, V., Christensen, T.H., Astrup, T.F. (2017). Future scenario modelling within Life Cycle Assessment: A systematic review. Submitted.

II Bisinella, V., Conradsen, K., Christensen, T.H., Astrup, T.F. (2016). A global approach for sparse representation of uncertainty in Life Cycle Assessments of waste management systems. *International Journal of Life Cycle Assessment*, 21(3), 378-394.

III Bisinella, V., Götze, R., Conradsen, K., Damgaard, A., Christensen, T.H., Astrup, T.F. (2017). Importance of waste composition for Life Cycle Assessment of waste management solutions. Submitted.

IV Bisinella, V., Conradsen, K., Christensen, T.H., Astrup, T.F. (2017). Integrated uncertainty and scenario analysis for Life Cycle Assessments of future waste management systems. Manuscript.

In this online version of the thesis, Papers **I-IV** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from DTU Environment, Technical University of Denmark, Bygningstorvet, Building 115, 2800 Kgs. Lyngby, Denmark, info@env.dtu.dk.

In addition, the following publications, not included in this thesis, were also concluded during this PhD study, as well as a range of conference papers:

- Bisinella, V., Brogaard, L.K.S., T.H., Astrup, T.F. (2016). Material Flow Analysis of the Danish solid waste management system. Report for internal use at the Danish Environmental Protection Agency.

- Bisinella, V., Brogaard, L.K.S., T.H., Astrup, T.F. (2016). Life Cycle Assessment of waste management scenarios for Copenhagen municipality in 2025. Confidential report for internal use at the Copenhagen municipality.

Acknowledgements

First and foremost, I would like to thank my supervisor *Thomas Fruergaard Astrup* for choosing me for this wonderful and challenging topic. What an adventure! I am extremely thankful for how he has trusted my ideas and encouraged me in the toughest days, while patiently waiting for me to overcome my limits and reach for new, farther goals.

I would like to thank my co-supervisor *Thomas Højlund Christensen* for his always precious advice and for motivating and inspiring me to be creative, smart and wander off the beaten track. I would also like to thank him for introducing me to *Knut Conradsen*, who I consider my unofficial co-supervisor. I would like to thank Knut for always finding time for discussing my ideas and for patiently teaching me how to write them down, never without some dark, unsweetened coffee.

It was an honour for me to sit and work at *DTU Environment*. I remember thinking about this Institute as an environmental engineering heaven when I was studying back in Padova. It was, indeed, true. Every day in these past four years I was inspired by each single one of my co-workers, especially my fellow PhD students, who I thank very much. I would especially like to thank my office mate *Alberto* for having been such an amazing travel companion in this adventure. Special thanks also go to *Anders*, *Line*, *Davide*, *Trine*, *Veronica*, *Ramona*, and *Roberto* for the fruitful collaborations and the enriching discussions, and to *Vincent* and *Tonio* for their contagious laughter and never ending support. DTU Environment has been a true family for me in difficult times, and I will never forget the help and support I received, especially from the truly exceptional *Charlotte Lind*, *Stig Kenneth Plougmand* and *Anne Harsting*.

I would like to acknowledge also my truly inspiring neighbours and friends *Anette* and *Jens* for supporting me and for making me part of their wonderfully creative “Parisian” circle.

I am very grateful for all the wonderful friends I have met here in Copenhagen, with whom I share this wonderful experience, especially *Carlita*, all the crazy *Blue House* people, *Raimon*, *Rafik* and many, many others.

I am immensely grateful to my family, for having allowed me the space to challenge myself with this PhD journey and grow, while endlessly supporting me with their unconditional trust and love. Last but not least, I would like to thank *Raffaele* for having been my personal guru through the thick and thin, and a daily part of my family here.

This thesis is dedicated to my beloved late grandfather *Aldo Simonetto*, who bravely let me play with his MS-DOS since I was very, very little and who has always been my role model.

Summary

Life Cycle Assessment (LCA) is an acknowledged tool for quantifying the sustainability of waste management solutions. However, the use of LCA for decision-making is hindered by the strong dependency of the LCA results on the assumptions regarding the future conditions in which the waste management solutions will operate. Future scenario methods from the management engineering field may provide valid approaches for formulating consistent assumptions on future conditions for the waste management system modelled with LCA. However, the standardized LCA procedure currently does not offer much guidance on how to model future scenarios in LCA.

This thesis highlights critical findings aiming at strengthening the role of LCA in decision support and strategic planning for waste management. In particular, the thesis thoroughly investigated the future scenario methods, the existing guidance on modelling of future scenarios in LCA, all peer-reviewed articles in the literature combining future scenarios and LCA, across sectors, and the specific modelling mechanisms occurring in LCA when assessing future scenarios. For each of these aspects, the thesis investigated the specific needs of the waste management field. The quantitative modelling implications were tested within real-scale LCA models focusing on the management of residual waste in Denmark. In a wide range of scenarios, this thesis addressed the influence on the LCA model results of realistic technology and waste composition uncertainties, as well as the effects of implementing future energy scenarios and design-stage technologies.

The thesis underlines that future scenarios can be used to formulate consistent assumptions for waste management systems. However, in order to obtain well-founded quantitative results with LCA, the implementation of future scenarios should comply with the following conditions:

- Future scenarios should include important aspects identified within the case-specific LCA model.
- Important aspects can be identified from a preliminary LCA, but should always be evaluated again after implementing the future scenarios in LCA.

Identification of important aspects (such as parameters of the modelled technologies, waste composition, and framework conditions) ultimately governing the LCA results of the future scenarios should be regarded as a funda-

mental part of the future scenario process and be communicated to the final receivers of the LCA. The main outcome of this thesis is a systematic framework that can be used to assess future scenarios in LCAs of waste management systems. The framework combines approaches developed during the PhD study in order to systematically address the modelling implications of combining future scenarios and LCAs of waste management systems.

The study developed a systematic definition of importance of LCA model parameters based on their input uncertainty and their sensitivity on results with a Global Sensitivity Analysis (GSA) approach. Within LCAs of waste management systems, the GSA approach allowed quantifying the importance of the waste composition versus the more commonly tested technology parameters. Less than 10 waste composition parameters as well as 5-6 technology parameters, out of a total of 750 waste and technology parameters in the LCA model, were found important for the results across all tested impact categories. These findings were used to improve existing step-wise approaches for quantification of uncertainty in LCA. Moreover, this PhD study provided a novel method to quantitatively determine the most robust waste management solution across several future scenarios combining results of uncertainty analysis and scenario analysis into a simple and conveyable score.

The systematic framework for future scenarios in LCA should start from a preliminary LCA carried out on the case-specific system and identifying the important aspects with the GSA approach. The future scenarios can be formulated with whichever future scenario technique in preference, including the important aspects identified in the preliminary LCA. Then, the future scenarios can be implemented in further LCAs. A subsequent determination of important parameters with GSA is fundamental for identifying the aspects of the model ultimately governing the future scenario results and any necessary revisions in the future scenarios or model data. Finally, sustainability on the long-term can be strengthened by the combined use of uncertainty and scenario analysis. This means that the LCA results can be communicated as probabilities of each individual waste solution being environmentally better compared to the others, together with a clear indication of which aspects and parameters critically affect the performance of the solution.

The proposed systematic framework can be adapted to LCAs carried out in all fields and can also be used to quantitatively carry out systematic scenario analyses on the assumptions of present-day LCAs.

Dansk sammenfatning

Livscyklusvurdering (LCA) er et anerkendt værktøj til kvantificering af den miljømæssige bæredygtighed af løsninger på affaldsområdet. Anvendelsen af LCA som beslutningsstøtteværktøj er dog udfordret af, at LCA-resultaterne i høj grad afhænger af antagelser om de fremtidige rammebetingelser, som affaldsteknologierne vil operere inden for. Ingeniørmæssige metoder til analyse af fremtidsscenarier giver mulighed for konsistent at formulere antagelser omkring fremtidsscenarier, også for affaldssystemet. Imidlertid er der i de standardiserede LCA procedurer ikke meget vejledning i, hvordan disse fremtidsscenarier skal integreres i LCA.

Denne afhandling tilvejebringer et kritisk grundlag for styrkelse af LCA's rolle som beslutningsstøtteværktøj ved strategisk planlægning af affaldshåndtering. I afhandlingen lægges især vægt på en grundig analyse af metoder i relation til fremtidsscenarier, en gennemgang af eksisterende retningslinjer til modellering af fremtidsscenarier, en vurdering af videnskabelige artikler om fremtidsscenarier i LCA, samt analyse af de modelmæssige aspekter ved inddragelse af fremtidsscenarier i LCA. Dette blev undersøgt med specifik fokus på affaldshåndtering. Implikationer for LCA-modellering blev kvantitativt undersøgt for realistiske scenarier for håndtering af husholdningsaffald i Danmark. Betydningen af realistiske usikkerhedsestimater for teknologier og affaldssammensætning blev testet i en række scenarier, herunder effekterne af at inddrage fremtidige energiscenarier og teknologier under udvikling.

Afhandlingen understreger, at fremtidsscenarier er nyttige til at formulere konsistente antagelser for affaldssystemer. Imidlertid bør følgende betingelser være opfyldt for implementeringen af fremtidsscenarier i LCA:

- Fremtidsscenarierne skal inddrage de betydende aspekter af de konkrete scenarier og den specifikke LCA-model.
- De betydende aspekter kan identificeres ud fra en indledende LCA, men bør altid vurderes igen efter implementeringen af fremtidsscenarierne.

Identificering af de betydende aspekter som i sidste ende afgør LCA-resultaterne (fx teknologiparametre, affaldssammensætning og rammebetingelser), bør anses som en fundamental del af arbejdet med fremtidsscenarier og kommunikationen til beslutningstagerne. Det primære resultat af denne afhandling er en metodemæssig ramme til analyse af fremtidsscenarier i LCA af affaldssystemer. En række forskellige metoder udviklet igennem PhD stu-

diet er kombineret for at tilvejebringe en samlet og systematisk procedure for integration af fremtidsscenarier med LCA af affaldssystemer.

Først og fremmest er udviklet en systematisk definition af betydende parametre i LCA-modeller baseret på parametrenes usikkerhed og følsomhed for de samlede resultater, "Global Sensitivity Analysis" (GSA). GSA-metoden muliggjorde en kvantificering af betydningen af affaldssammensætningen sammenlignet med betydningen af usikkerheder for typiske teknologiparametre. Ud af i alt 750 undersøgte affalds- og teknologiparametre blev færre end 10 parametre for affaldssammensætningen og 5-6 teknologiparametre fundet betydende for de endelige LCA-resultater på tværs af alle undersøgte påvirkningskategorier. Resultaterne blev anvendt som basis for at forbedre eksisterende metoder til kvantificering af usikkerheder i LCA. Herudover blev tilvejebragt en ny og kvantitativ metode til identifikation af den mest "robuste" løsning til affaldshåndtering på tværs af flere fremtidsscenarier; resultatet af usikkerheds- og scenarieanalyse blev kombineret til en samlet score, som er nem at kommunikere.

Systematisk analyse af fremtidsscenarier i LCA bør til at starte med anvende GSA-metoden på en indledende version af LCA modellen for identificering af de betydende aspekter. Fremtidsscenarierne kan videre formuleres ved anvendelse af de ønskede teknikker og modeller, så længe fremtidsscenarierne inkluderer de identificerede betydende aspekter. Herefter implementeres fremtidsscenarierne i LCA-modellen. GSA-metoden bør herefter gentages også for fremtidsscenarierne for at sikre, at alle betydende aspekter er tilstrækkeligt undersøgt og nødvendige ændringer af scenarierne og data er gennemført. Vurderingen af den langsigtede bæredygtighed kan herved styrkes ved kombinationen af usikkerheds- og scenarieanalyse. Dette betyder, at LCA-resultaterne kan fastlægges som sandsynligheder for hvorvidt en specifik affaldsløsning er miljømæssig favorabel sammenlignet med alternative løsninger. Samtidig klarlægges de aspekter og parametre med størst indflydelse på miljøpåvirkningerne fra den pågældende affaldsløsning.

Den metodemæssige ramme udviklet i denne PhD kan tilpasses LCA inden for andre fagområder, og kan på tilsvarende vis anvendes på analyser af rammebetingelser uden et fremtidssigte.

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Abbreviations

CIBA	Cross-Impact Balance Analysis
FSA	Formative Scenario Analysis
GSA	Global Sensitivity Analysis
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MFA	Material Flow Analysis
NSR	Normalized Sensitivity Ratio
PE	Persons Equivalents
SC	Sensitivity Coefficient
SR	Sensitivity Ratio
V	Variance

Impact assessment categories

CC	Climate change
ET	Freshwater ecotoxicity
FE	Freshwater eutrophication
HTc	Human toxicity, cancer effects
HTnc	Human toxicity, non-cancer effects
IR	Ionizing radiation
ME	Marine eutrophication
OD	Ozone depletion
PM	Particulate matter
POF	Photochemical ozone formation
RD	Resource depletion
RDfos	Resource depletion, fossil
TA	Terrestrial acidification
TE	Terrestrial eutrophication

1 Introduction

1.1 Background and motivation

Waste management plays a fundamental role for the sustainability of our society. The aim of waste management is to recover materials and energy from residues of all sectors, and to handle and dispose what cannot be recovered with the least possible burdens to the environment. Designing and planning efficient waste management systems is thus strategically important for optimizing the use of resources while preserving the environment for future generations.

Life Cycle Assessment (LCA) is a standardized methodology (ISO, 2006a) used to assess the environmental performace of products and systems. Within waste management, LCA is used to assess how waste management systems can be best planned from the design phase. LCA allows comparing alternative solutions in order to find the best combination of waste collection, treatment and disposal that maximizes recovery and minimizes environmental impacts for the specific case for which the waste management system is designed. LCA takes into account the potential environmental impacts associated to the resources necessary to handle the waste, but also the potential emissions that may occur during treatment. When material and energy resources are recovered, the waste management system is credited with the avoided potential emissions that would have been necessary to produce these resources.

However, LCA becomes more challenging when it aims to assess waste management systems on a long time horizon. The long-term perspective is necessary because usually waste management systems are only potential solutions at the design phase, are not fully implemented until only years after they are planned, and last for decades after they are constructed (*e.g.* Brogaard et al., 2013). A good LCA should thus assess whether a waste management system still represents the best solution even in the potentially different future conditions in which it may operate.

So far, different future conditions have been considered as uncertainties in the LCA model. In particular, the future context in which the waste management system may operate has been tested with scenario analysis (Clavreul et al., 2012), *i.e.* assessing the variations brought to the LCA results by changing assumptions such as the energy system (Tonini et al., 2013), the waste composition (Christensen et al., 2009), or the type of goods recycled (Brogaard et al., 2014). The assumptions on recovered energy and materials have often shown to be crucial for the LCA results and for the identification of the best waste management solution (Fruergaard and Astrup, 2011), ultimately limiting the role of LCA for strategic planning. Moreover, the scenario analysis on choices and assumptions has so far been kept separate from the assessment of the uncertainty related to the LCA model parameters (Clavreul et al., 2012), further complicating the interpretation of results.

Since the 1960s, management engineering has been employing *future scenarios* (or foresight, future scenario analysis, and similar) in order to study future developments in many fields. Future scenario methods are centred on the identification of *important* scenario aspects and provide creative yet systematic ways to formulate *alternative visions* for the future (*i.a.*, Wiek et al., 2006). Future scenarios have been successfully used to interpret the dynamics influencing the studied systems and offered systematic ways to address possible future situations (Ringland and Schwartz, 1998). In waste management, future scenarios have facilitated the use of stakeholders' knowledge on uncertain future developments affecting the waste management system (Meylan et al., 2013; Saner et al., 2011; Spoerri et al., 2009). Future scenarios thus may offer the possibility to consistently model the future contexts in which waste management systems may operate and reduce the uncertainty of the LCA model results. The potential for combining future scenarios and LCA has been addressed by many experts in the LCA and the foresight field (Frischknecht et al., 2009; Fukushima and Hirao, 2002; Hellweg et al., 2005; Höjer et al., 2008a; Spielmann et al., 2005). However, the LCA standard procedure currently does not offer much specific guidance on how to carry out long-term assessments, and so far modelling implications derived by combining the two methods for waste management systems have never been thoroughly assessed.

1.2 Research objectives

This doctoral work aims at strengthening the role of LCA for decision making and strategic planning within the waste management field. In particular, the objectives of this PhD thesis were to:

- Review and analyse future scenario theory and methods as well as existing formal guidance for the use of future scenarios in LCA.
- Systematically review existing literature focusing on the combined use of future scenarios and LCA, across all study fields and especially within waste management.

- Identify critical modelling implications when combining future scenarios with LCA and LCA of waste management systems. In particular:
    - Develop a systematic approach for the quantitative definition of *important* LCA model aspects based on Global Sensitivity Analysis (GSA).
    - Assess the *importance* of technology parameters as well as waste composition within LCAs of waste management systems.
    - Develop a quantitative approach for assessing *alternative visions* in LCA models by combining uncertainty and scenario analysis.
- Combine the developed approaches in a framework for systematically investigating future scenarios within LCA of waste management systems.

The thesis is structured in the following six sections:

- Section 2 describes the LCA and future scenario methods, with a special focus on their use in waste management, and presents a review of the attempted frameworks for the combination of the two methods in the literature (Paper **I**).
- Section 3 presents the results of a systematic review conducted on the combined use of LCA and future scenarios in peer-reviewed studies in the literature, across all sectors, and provides recommendations for official guidance on combining future scenarios and LCA (Paper **I**).
- Section 4 presents a GSA approach for evaluating the *importance* of LCA model parameters (Paper **II**), which is also specifically applied to LCAs of waste management systems to evaluate the importance of technology and waste composition parameters (Paper **III**).
- Section 5 presents a quantitative approach for combining scenario and uncertainty analysis in LCAs of future waste management systems (Paper **IV**) and provides a recommended framework for LCAs of future waste management systems unifying the knowledge of the previous sections.
- Section 6 provides conclusions and final recommendations.
- Section 7 provides future work perspectives.

2 LCA and future scenarios: Principles, use in waste management and current guidance

The work carried out for this thesis was performed at the intersection between three areas: LCA, future scenarios and waste management. The aim of this section is (i) to illustrate the main characteristics of the LCA and future scenario methods, with a special focus on their use in waste management and (ii) to provide a chronological overview of official guidance attempts for combining LCA and future scenarios. Knowledge of the general LCA and future scenario models' procedure and structure, together with the specific needs of the waste management sector, is fundamental for understanding which aspects were comprised in the attempted frameworks so far and which others have been investigated in Papers **I-IV**.

2.1 LCA

2.1.1 General principles

As mentioned in the Introduction, LCA is a standardized method for quantifying the environmental performance of products and systems. The goal of LCA is to assess the environmental impacts associated to the life cycles of products, which consist of resource extraction, production, use and end-of-life. LCA has been regulated by ISO (2006a; 2006b) and further recognized guidelines have been provided by the ILCD Handbook (European Commission 2010a; European Commission 2010b).

LCA is an iterative process composed by four phases: goal and scope definition, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA) and interpretation (ISO, 2006a). Goal and scope define the essential features of the LCA study: the system boundary, the level of detail, the intended application, time and geographical scopes, as well as the function (product or service) to which the environmental impacts are associated (also known as "functional unit"). The LCI is an inventory of input and output data (such as chemicals, energy) necessary to accomplish the function defined in the goal and scope. In the LCIA phase, environmental impacts for different environmental categories (*e.g.* climate change, toxicity, etc.) are calculated based on the LCI data and the results are discussed with respect to the initial goal. Good LCA practice should also involve discussion of data quality, *e.g.*

representativeness towards the initial goal and scope, as well as sensitivity and uncertainty analyses (ISO, 2006b).

The ILCD Handbook describes the LCA model also using the subdivision between technosphere and ecosphere (European Commission 2010a). The ecosphere represents the environment where the environmental impacts potentially occur in the LCIA phase. The technosphere comprises all substance transformation processes required to fulfil the goal of the study (the product system described by the LCI data) that eventually affect the ecosphere. The technosphere is further subdivided in foreground and background system. The foreground system includes case-specific processes and technologies, while the background system includes general processes and technologies (European Commission 2010a).

The LCI data modelling approach for the background system differs if the goal of the practitioner is to account for potential environmental impacts or to assess the environmental consequences of potential changes brought by the functional unit of the foreground product system (ISO, 2006b). In the first case the LCI data modelling approach is attributional; in the second case it is consequential (*i.a.*, Weidema et al., 2004; Ekvall et al., 2005).

Although not officially defined in the standardized procedure and the ILCD Handbook, the use of the term "*scenario*" in LCA is very common. Scenario is used to indicate a product or system alternative compared to another and can usually comprise the data describing the alternatives in the foreground system, but also the context in which the alternatives are assessed: background system and ecosphere.

2.1.2 LCA of waste management systems

In Europe, the use of LCA for assessing the impacts related to waste management systems and for supporting waste management planning is encouraged by the EU Waste Framework Directive (EU Directive 2008/98/EC). LCAs of waste management systems (also known as "waste-LCAs") are transversal to the product systems and focus on the end-of-life phase. An exhaustive overview of waste-LCAs studies was provided by Laurent et al. (2014a; 2014b).

Modelling waste management systems in LCA requires particular attention for a number of aspects. First of all, the functional unit of waste-LCAs focuses on managing waste. Waste is composed by heterogeneous materials, whose characteristics are influenced by local conditions and waste collection schemes. The composition of waste materials affects the environmental emissions associated with waste treatment, recycling and disposal, as well as the recovery of materials and energy, as evidenced in Bisinella et al. (2017c) (submitted; Paper **III**). Numerous chemical substances present in the waste thus need to be traced throughout the phases of the waste management system. Moreover, emissions from the final waste disposal may occur over a long time, requiring specific modelling.

Therefore, waste-LCAs are substantially different from typical product and manufacturing oriented LCAs. To appropriately address waste technologies, dedicated and advanced LCA models are required, such as the EASETECH model (Clavreul et al., 2014). EASETECH allows modelling waste as a mix of fractions (*e.g.* plastic, paper, etc.) and tracking their physico-chemical properties (*e.g.* energy content, fossil carbon, etc.) throughout the modelled technologies. Each process in EASETECH models an actual waste treatment technology. The processes take into account consumption and production of LCIs based on the properties of the functional unit, but also direct waste emissions and emissions connected to the specific technology type that may occur during treatment.

Waste-LCAs are thus often large and complex models, where results are subject to uncertainty for inherent data variability, unrepresentative datasets and modelling assumptions (Clavreul et al., 2012). In the literature this uncertainty is generally subdivided between (i) variability of the model input values, or parameters (parametrical uncertainty), but also (ii) the assumptions regarding the context in which the model takes place (epistemic uncertainty; Spielmann et al., 2005) and (iii) the uncertainties regarding the underlying LCA model assumptions and calculations (Huijbregts et al., 2003; Lloyd and Ries, 2007; Spielmann et al., 2005).

Parametrical uncertainty in waste-LCAs was thoroughly addressed by Clavreul et al. (2012), who proposed a step-wise assessment of contribution, sensitivity and uncertainty associated to the model parameters. In order to facilitate this, EASETECH allows the user to manually edit each data entry, which can be associated to one value, a list of values or a probability distribution (normal, uniform, lognormal or triangular). The uncertainty assigned can be propagated with a Monte Carlo simulation tool to calculate the output uncertainty of the LCA results.

So far, the assessment of epistemic and model uncertainties has been carried out separately from parametrical uncertainty by means of *scenario analysis*, a sensitivity analysis on the assumptions taken. Clavreul et al. (2012) describe scenario analysis as an individual test of each assumption taken in order to assess the effect of the changes on the model results. The same process is referred to in the ILCD Handbook as “assumption scenarios” (European Commission 2010a).

Although waste-LCAs are based on thousands of input parameters, energy and material recovery efficiencies from waste have often resulted in sensitive model input parameters, especially when LCAs were carried out with a consequential approach (*i.a.*, Eriksson et al., 2007; Turconi et al., 2011; Fruergaard & Astrup, 2011). In these cases, scenario analysis performed on the LCI dataset representing the substituted energy and material evidenced that the choice of such datasets was decisive for identifying the waste management solution with the best environmental performance. Results of waste-LCA studies may therefore be intrinsically bound to the very specific assumptions for the framework conditions in which the assessment is set and may ultimately serve as a less useful input for decision-making or strategic planning.

2.2 Future scenarios

2.2.1 General principles

Future scenarios, also known as *future* or *foresight studies* (also scenarios, future scenario analysis, or similar), are well-established management engineering methods used to systematically explore future situations. Future scenarios have been developed and used since the 1960s for numerous applications from global to local scales, including military and corporate strategy, political transition, and community-based natural resources management (Bohensky et al., 2011). Nowadays future scenarios are experiencing a renewed popularity for strategic decision making and change management, with special attention to global environmental challenges (Varum and Melo, 2010). Commonly known future scenarios are those used within global climate and energy reports (International Energy Agency, 2016; IPCC, 2007).

Future scenarios should not be intended as forecasts or predictions of the future (Harries, 2003; Meristö, 1989). Instead, the paradigm of future scenarios is based on the belief that it is not possible to describe the future as a single image, but rather several plausible *alternative visions* are needed to describe the range of possible futures (IPCC, 2000; Siddiqui and Marnay, 2006; Wiek et al., 2006). Scenarios are intended to highlight central elements of a possible future and to draw attention to the *important aspects* that will drive future developments (Kosow and Gaßner, 2008; Schnaars, 1987; Wiek et al., 2006). As an example, important aspects for the waste management sector are framework conditions such as policies and regulation, subsides, involvement of society, but also more specific technical aspects such as waste management technologies, waste composition, etc.

For this reason, understanding these central *important aspects* and causal connections in the studied system and the description of the development from the present to the future are considered an integral and fundamental part of the future scenarios (Bood and Postma, 1997; Meristö, 1989; Rasmussen, 2011). Scenarios are also commonly used and known as "scenario analysis", *i.e.* an alternative to sensitivity analysis in order to test case-specific assumptions and choices in models (epistemic uncertainty; Clavreul et al., 2012). Within the foresight practice, a future scenario is thus defined as an internally consistent description of a future situation, including the path of development leading to that situation (Kosow and Gaßner, 2008).

There are numerous approaches in the literature in order to formulate future scenarios. However, the scenario building process unfolds in a similar way across different approaches and is usually characterized by five phases carried out iteratively, see Figure 1 (Godet, 2000; Jarke, 1999; Kosow and Gaßner, 2008; Rasmussen, 2011; Rosenbaum et al., 2012). These phases are:

1) Goal and scope definition. The goal definition is fundamental for the categorizing of the future scenario type according to the question that the scenario wishes to answer. Börjeson et al. (2006) identified three main typologies:
    - Predictive scenarios (probable, what will happen?)
    - Explorative scenarios (possible, what can happen?)
    - Normative scenarios (preferable, how can a specific target be reached?).
2) Identification of case-specific important aspects for the future scenario. The scenario is developed assigning future values to the identified important aspects.
3) Combination of the future values into consistent scenario sets. There are numerous approaches that can be used both to identify and to characterize the future states of the central important aspects of the future scenarios.

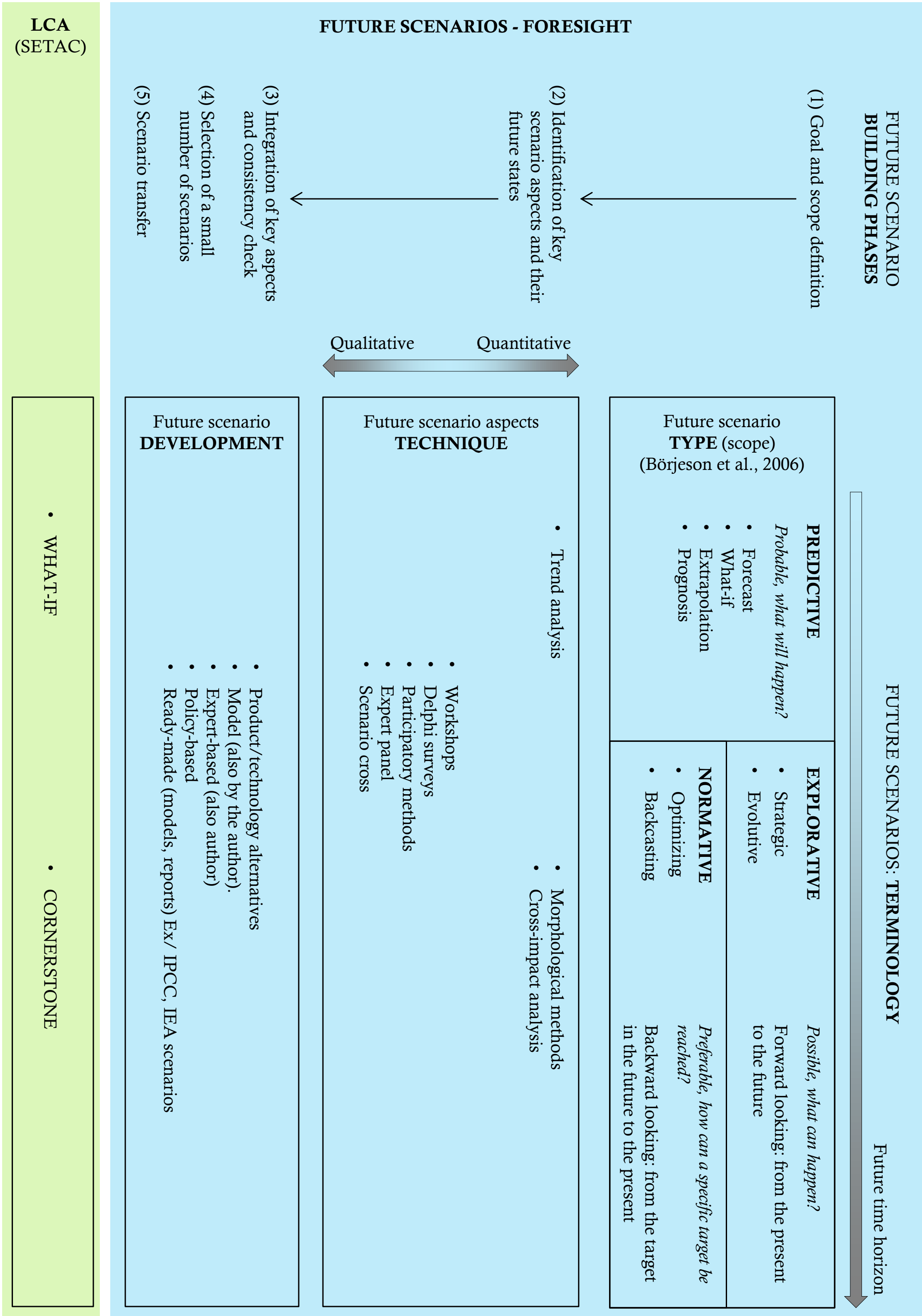


Figure 1. Keywords and terminology of foresight and LCA (from Paper **I**). The terminology is subdivided between future scenarios and LCA. Future scenario building phases and associated terminology subdivided according to the future time horizon. Based on Börjeson et al. (2006), Weidema et al. (2004), Pesonen et al. (2000), Rasmussen (2011), Kosow & Gaßner (2008), Ringland & Schwartz (1998), Godet (2000).

These approaches can be qualitative, quantitative or a combination of methods (Harries, 2003; Swart et al., 2004). Examples and keywords are provided in Figure 1. Additional techniques are then used to integrate the information on the future states and developing the scenarios.

4) Definition of a limited number of consistent scenarios. Many authors suggest limiting the number of scenarios to an ideal number of three or four (Meristö, 1989; Schnaars, 1987; Wollenberg et al., 2000).
5) Contextualization of the scenarios to the specific case (also known as "scenario transfer", Rosenbaum et al., 2012) and visual representation (known as "visualization").

The visual representation of the future scenarios may use different characteristic "shapes". Noteworthy examples are the scenario funnel (Kosow and Gaßner, 2008; Weidema et al., 2004) and the scenario cross. For the scenario cross, two aspects or properties are selected as axes, and four scenarios are identified within the quadrants (Rasmussen, 2011). The most famous scenario cross is the growth-share matrix; examples of axes are importance and uncertainty of the scenario aspects (Ringland and Schwartz, 1998).

The function of the process of constructing the future scenarios usually goes beyond simply generating the results. The process of formulating the future scenarios increases the knowledge of the analysed system. Communicability and transparency across disciplines is also increased, by integrating qualitative and quantitative knowledge and inputs from different study fields. For this reason, future scenarios can be useful for decision-support and policy making (Godet, 2000; Rasmussen, 2011; Wiek et al., 2006).

2.2.2 Future scenarios applied to waste management and LCA

Future scenarios have been used within few waste management studies for integrating qualitative and quantitative knowledge of various sources and disciplines. In Switzerland, expert-based quantitative scenario techniques such as Formative Scenario Analysis (FSA) (Scholz and Tietje, 2002) and Cross-Impact Balance Analysis (CIBA) (Weimer-Jehle, 2006) were used in order to merge literature and stakeholders' knowledge on uncertain future developments affecting the waste management system. The FSA approach was applied to recycling of construction and demolition waste (Spoerri et al., 2009), CIBA approach was applied to scenarios for waste glass packaging disposal (Meylan et al., 2013) and both approaches were combined for waste incineration (Saner et al., 2011). The studies provided a contextualized vision of the waste management system based on the interaction of societal, policy and economic factors and ultimately generated a number of consistent scenarios.

Therefore, future scenarios seem promising methods to support the assumptions on the framework conditions in which waste-LCAs are set by creating consistent *a priori* scenarios on the important aspects affecting the waste management system. Meylan et al. (2014) later applied the formulated scenarios for glass packaging within an LCA model, which was included in the literature review provided in Bisinella et al. (2017a) (submitted; Paper **I**). However, in the case of the Swedish project TOSUWAMA (Towards Sustainable Waste Management; Finnveden et al., 2013; Söderman et al., 2016), which tested the effect of future waste policies using a combination of a general equilibrium model, an economic optimisation model and LCA, the future scenarios hardly affected the LCA results. Münster et al. (2013) suggested that future scenarios that are ultimately tested within LCA should include aspects that are usually central for the results, especially scenarios for the energy system when the LCA is based on consequential modelling.

2.3 Existing framework suggestions for future scenario modelling within LCA

The large benefits derived by systematically combining future scenarios and LCA have been highlighted by a number of LCA and foresight experts (Frischknecht et al., 2009; Fukushima and Hirao, 2002; Hellweg et al., 2005; Höjer et al., 2008; Spielmann et al., 2005). Future scenarios can potentially affect many elements of the LCA and waste-LCA model structure.

The first formal framework attempt for using future scenarios within LCA was carried out by a Working Group on "Scenario Development in LCA" established by SETAC-Europe in 1998. The Working Group was expected to provide results in a series of phases: a general framework, a data modelling framework for LCI and LCIA, and a final review on case studies. The general framework was provided by Pesonen et al. (2000). The publication aimed at defining the relevant concepts for scenario development in LCA studies. A future scenario in LCA was defined as a "description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future and (when relevant) also including the presentation of the development from the present to the future". The publication introduced the concepts of "prospective LCA", "what-if" and "cornerstone" scenarios (Figure 1). Prospective LCA investigated product systems which do not exist yet today, describing new products or decisions on, *e.g.*, long term strategies. A what-if scenario was characterized by short or medium time horizon and can be used to assess small scale systems well-known to the author of the study. Conversely, cornerstone scenarios involved long term horizons and large scale systems that can be used as frames for what-if scenarios.

The LCI and LCIA modelling framework was provided by Weidema et al. (2004). According to the authors, prospective LCA aims at describing the consequences of changes, rather than being necessarily linked to a future point in time. Therefore, the authors proposed a consequential LCI data modelling approach. Moreover, the publication suggested choosing between what-if and cornerstone scenario types within the goal and scope definition phase of the LCA. What-if and cornerstone scenarios can both act on technosphere and ecosphere (and "valuesphere", if impacts are normalized or weighted). Without case-specific cornerstone scenarios, the authors proposed using default scenarios based on socio-cultural archetypes (individualist, egalitarian and hierarchical) for the LCIA phase (ecosphere and valuesphere). Finally, the publication highlighted the confusion related to the concept of scenarios within LCA studies. Scenarios are used to denote technological alternatives, but also to denote the frame in which the technological alternatives are compared. The framework of the Working Group was partly followed by Fukushima & Hirao (2002), Hellweg et al. (2005) and Spielmann et al. (2005). Fukushima & Hirao (2002) and Spielmann et al. (2005) developed cornerstone scenarios in which technological what-if scenarios were tested. Hellweg et al. (2005) used cornerstone scenarios affecting both technosphere and ecosphere. The literature review on case studies combining future scenarios and LCA originally foreseen by SETAC was ultimately never carried out.

The findings of the Working Group were expected to result in a framework or a guideline possibly expanding the ISO 14040 series. However, in the 2006 revision of the standard series, the use of future scenarios within LCA was still not systematically addressed. Moreover, a precise definition of scenario was not provided. The 14040 standard did however consider the use of future scenarios, stating that "LCA does not predict absolute or precise environmental impacts due to the fact that some environmental impacts are clearly future impacts" (ISO, 2006a). In contrast to Weidema et al. (2004), the standard did not assign a specific LCI modelling approach for future scenarios. According to the ISO standard, temporal and technological representativeness should be assessed irrespective of the LCI data modelling.

The following ILCD Handbook (European Commission 2010a) did not provide additional guidance on future scenarios. The publication mentions limitations in reaching the required overall accuracy, precision and completeness for studies set further away in the future or characterized by new technologies. Again, time was not a criterion for choosing between LCI data modelling types, since all types could potentially model a future system. However, the publication provided a measure of time frames: short term (1-5 years), mid-term (5-10 years) and long term (more than 10 years). Differently than Weidema et al. (2004) and ISO (2006a), attributional and consequential approaches are distinguished by whether they support decisions instead of whether they are change- or consequence-oriented. An attributional approach was advised for micro level decision support with short and mid-term time horizons; a consequential approach was advised for macro level decision support with mid and long time frames.

In 2012, a workshop organized by the European Commission addressed the methodological loophole on future-oriented LCAs (De Camillis et al., 2013). The organizers aimed at identifying the most suitable LCI data modelling approach to assess future scenarios for policies and long term strategies contexts, due to the often different results brought by attributional and consequential modelling. The participants did not reach an agreement. Instead, very case-specific modelling approaches and the combined used with other external models (*e.g.*, global macro-economic models) were discussed in detail. Such distinct combinations are often assigned with specific names (*e.g.*, MLCA of Dandres et al., 2012; DLCA of Frischknecht & Stucki, 2010, etc.). The participants agreed on the necessity to ensure consistency when using multiple modelling tools and on the scenario type definitions of Börjeson et al. (2006).

3 Future scenarios within LCA

This section provides the findings of a systematic review of journal articles that have combined LCA and future scenarios. The review process focused on understanding the general foresight and LCA knowledge of such studies, the modelling implications of combining future scenarios and LCA, and whether specific sectors showed particular modelling preferences or practices that could be successfully applied to waste management. The findings allowed providing recommendations on terminology and on the combined use of future scenarios and LCA. Details are provided in Bisinella et al. (2017) (submitted; Paper **I**).

3.1 Status of the combined use of future scenarios and LCA

The literature review identified a total of 262 peer reviewed journal articles across 38 different countries, 86 journal titles and 8 main research topics. Figure 2 shows the year of publication of the articles selected for the review with topic detail. The review evidenced that the combined use of future scenarios and LCA is currently expanding.

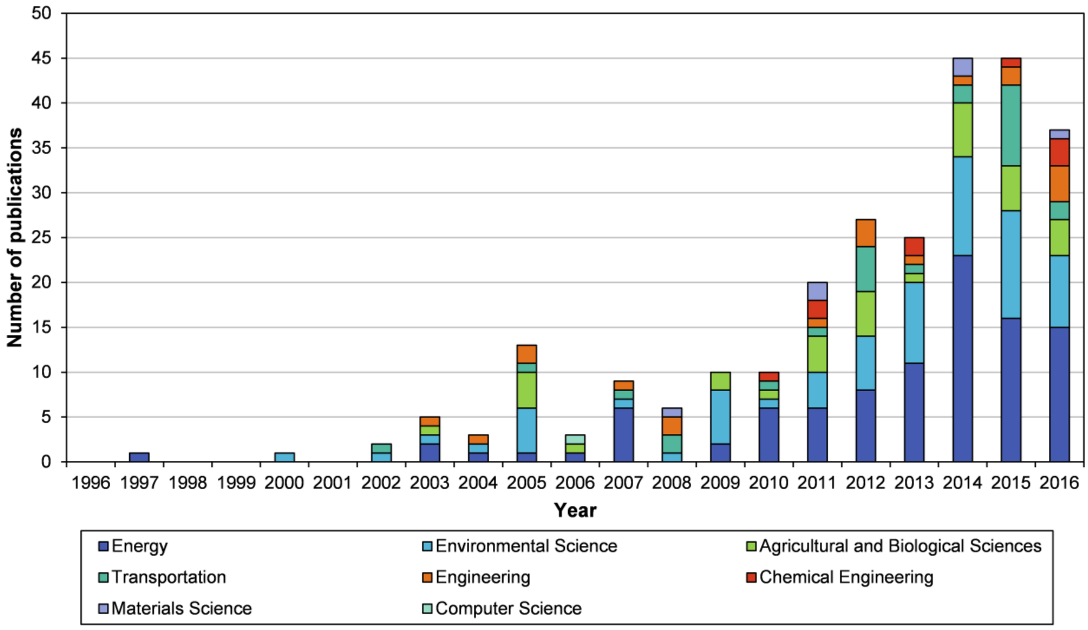


Figure 2. Occurrence of publications combining LCA and future scenarios in the years, subdivided by topic detail. "Engineering" comprises mainly civil and structural engineering (from Paper **I**).

Half of the articles compliant with the scope were published between 2013 and 2016, especially with focus on energy (renewable energy, sustainability and the environment), environmental sciences (waste management), agriculture and biological sciences, and transportation. Figure 2 suggests that future scenarios combined with LCA are being widely used in the literature and that they will plausibly continue to be largely utilized in the upcoming years. However, the combination of the two methods is currently hindered by a number of aspects related to the absence of a commonly agreed framework.

First and foremost, the lack of guidance for combining the two methods resulted in an inevitable formulation of a wide range of diverse approaches. The approaches were characterized by different sequential use of future scenarios and LCA and by the use of case-specific additional models at different phases of the study. For 67 % of the retrieved articles, the scenarios were *a priori* and directly tested in the LCA model. In 10 % of the studies the LCA was performed before the future scenarios and in 23 % of the studies the LCA was performed before and after the future scenarios. In 40 % of the studies, the LCA and future scenarios were linked only indirectly by application of additional models. The additional models ranged, among others, from Material Flow Analysis (MFA) and external databases to optimization and foresight-specific models. 23 % of the different combinations of future scenarios, LCA and additional models analysed in Paper **I** were proposed as methodological frameworks. However, the combinations were most often tailored to specific case studies and topics, rather than referencing to already existing framework attempts or generally applicable methodologies.

Secondly, due to the absence of a commonly agreed framework, minimum quality requirements for the studies were not defined. As a result, half of the retrieved publications did not fulfil the basic ISO requirements for LCA and only one fourth of the studies showed knowledge of the foresight theory. As far as LCA was concerned, a substantial share of articles assessed only a limited number of impact categories (European Commission 2010b) and lacked a well-defined goal, scope and functional unit. The choice of LCI data modelling approach was seldom stated, hindering transparency and communicability of the studies. The majority of the articles did not assess data quality, sensitivity and uncertainty, or, in general, compliance of the model with the scope of the study. This was especially detrimental for consistency and transparency when additional models or external databases were employed.

The future scenarios were mostly predictive, defined by technological alternatives and, unexpectedly, frequently without a clearly specified time horizon. Most often the studies defined *a priori* important scenario aspects, *e.g.* as features of technological alternatives. In the fewer cases with higher knowledge of foresight, the scenarios were mostly explorative and normative and based on experts' opinions and models. In these cases the temporal scope of the studies ranged between mid (10-30) and long (30-50) time horizons, which were interestingly different and longer than those indicated in the ILCD Handbook (European Commission 2010a). This indicates that the actual unregulated practice of combining future scenarios and LCA is extending much farther in the future than originally expected.

The lack of an official framework also did not allow the definition of shared terminology and keywords for the studies, which further contributed to the variability of the approaches in the literature. The most important example is the use of the term *scenario*, which is employed both in the LCA and foresight fields, but lacking a clear definition for the cases in which the two methods are combined. Further confusion arises from the fact that additional scenarios can be employed in both fields as scenario analysis in order to test epistemic uncertainty. For these reasons, the literature review carried out in Paper **I** investigated the number of scenarios tested within the LCA models, but also whether the number of future scenarios was conceptualized differently and if the studies employed scenario analysis as sensitivity analysis. In 66% of the studies retrieved for Paper **I**, the number of LCA scenarios corresponded to the number of future scenarios. However, in the remaining cases where LCA and future scenarios were conceptualized differently, future scenarios were generally a lower number of wider future scenario contexts ("cornerstone", "framework" scenarios on background conditions formulated outside the LCA model, *e.g.* IPCC climate scenarios) in which LCA scenarios were tested. The final number of assessed scenarios was generally higher than the number of LCA scenarios, since LCA's technological alternatives could be potentially tested within each of the "framework" future scenarios, and the epistemic choices made for both LCA and framework scenarios could be further tested with additional scenarios.

The numerous diverse approaches, general low LCA and foresight quality, and confused use of terminology were observed within all the retrieved topics. It was not possible to identify a sector where the combination of future scenarios and LCA was consistently characterized by unique modelling features that could be generalized and used within other sectors. Good practice examples were present for all the identified topics and coincided with the studies with equally good knowledge of LCA and future scenarios.

In general, the wide variety of possible modelling options has allowed high flexibility and a broad use across research fields, reflecting the intrinsic creativity of the future scenario process. However, the lack of a systematic procedure and clarity, low quality LCAs and the confused use of future scenario terminology may affect the communicability, transparency and general value of these studies for decision-support and policy making.

3.2 Archetypes

Irrespective of the sectors and the specific additional models used, the numerous approaches for combining future scenarios and LCA could be summarized by three main archetypes depending on the relative positions between future scenarios and LCA. The Input archetype (I) comprises cases in which the LCA was carried out before the future scenario. The Output archetype (O) comprises the cases where future scenarios were formulated *a priori* and then applied within LCA. The Hybrid archetype (H) is a combination of the two previous cases and comprises studies that carried out the LCA before as well as after the future scenarios. The archetypes can also be subdivided in sub-types, numbered according to the use of additional models and their position with respect to LCA and future scenarios (details provided in Paper **I**). Figure 3 summarizes the main archetypes and their subtypes.

The subdivision of the articles according to archetypes greatly simplified the wide range of existing approaches and allowed identifying common features between archetypes. The output archetypes O1 (future scenarios directly applied in LCA) and O3 (future scenario applied in LCA, but with use of an additional model between the future scenario and the LCA) were the most abundant, reflecting the most straightforward combination of *a priori* future scenarios directly tested in LCA. However, the substantial presence of H1 archetypes (17 %) indicates that the combination of the future scenario and LCA methods should not be only limited to the O types. The highest LCA quality was observed for O types, while the highest knowledge of foresight was observed for I and H types, as well as for more complex sub-types in general. When future scenarios were formulated *a priori* (O types), the number of future scenarios most often corresponded to the number of LCA scenarios. A similar number of LCA and future scenarios was observed also for the second LCA in the H archetypes.

ARCHETYPES			Number of publications per archetype
Main	Sub-type	STRUCTURE	
I - INPUT	I1	LCA → FUTURE SCENARIO	13
	I2	LCA → Additional model → FUTURE SCENARIO	5
	I3	LCA → FUTURE SCENARIO → Additional model	6
O - OUTPUT	O1	FUTURE SCENARIO → LCA	93
	O2	Additional model → FUTURE SCENARIO → LCA	10
	O3	FUTURE SCENARIO → Additional model → LCA	56
	O4	FUTURE SCENARIO → LCA → Additional model	5
	O5	Additional model → FUTURE SCENARIO → Additional model → LCA	1
H - HYBRID	H1	LCA → FUTURE SCENARIO → LCA	41
	H2	LCA → Additional model → FUTURE SCENARIO → LCA	8
	H3	LCA → FUTURE SCENARIO → Additional model → LCA	9

Figure 3. Archetypes for the combination of future scenarios, LCA and additional models. The three main archetypes (I, Input, O, Output and H, Hybrid) are subdivided in their sub-types according to the position of the additional model. The number of publications retrieved by the review per archetype is reported, based on 247 case studies (modified from Paper **I**).

The highest differences between number of scenarios were observed for the I type, where the number of future scenarios could be lower or higher, depending whether the future scenario had an optimizing or an explorative focus, respectively. The H types showed the highest occurrence of *important* scenario aspects identified from the results of the first LCA, but only rarely with sensitivity (2 %) and uncertainty (3 %) analyses.

3.3 Future scenarios within waste management LCAs

Waste management and disposal articles were 33, corresponding to the 13 % of the retrieved studies. Waste management substantially contributed to articles combining future scenarios and LCA from 2013 to 2016, indicating the growing interest in assessing the long-term sustainability within this sector.

The quality of the LCA studies was higher than generally observed across sectors. Only half of the studies referred to the ISO standard for LCA, but the goal, scope and functional unit were well defined in 77 % of the publications. However, the apparent knowledge of future scenarios was remarkably lower. Only 6 articles showed knowledge of foresight and only half of the articles stated the time horizon of the study.

Between the archetypes, O1, O3 and H1 were the most abundant, with O1 and H1 types showing the highest knowledge of LCA and O3 showing the highest knowledge of foresight (Figure 4). For all archetypes, the scenario types were mostly predictive and explorative. O3 archetypes mainly differed from the other studies by the use of additional models in order to develop the future scenarios tested in the LCA. Important scenario aspects were selected *a priori* from the LCA model for all the O archetype studies. The studies comprised in the H1 archetypes identified important scenario aspects from the preliminary LCA, in all cases based on a sensitivity analysis and never with uncertainty analysis.

Six publications proposed the method utilized for the study as a possible new framework for assessing the long-term sustainability of waste management solutions. Levis et al. (2013; 2014) and Münster et al. (2013) suggested modelling the waste management system with a dynamic, optimization perspective and comprising economy and capacity effects on the explored waste management scenarios. Moreover, Münster et al. (2013) and Moora & Lahtvee (2009) especially focused on modelling the energy system, as the background aspect usually influencing the outcomes of waste-LCAs, especially if carried out with a consequential approach. Meylan et al. (2014) took into account economic factors as well, but based the study on consistent future scenarios based on stakeholders' knowledge and CIBA. Lastly, Villares et al. (2016) applied future scenarios to a design-stage process.

All the proposed methods correspond to O1 and O3 archetypes. In these studies the future scenarios were investigated externally from the LCA model, which was only the very last step of the modelling sequence in all cases. The effect of the implementation of the future scenarios on the LCA model was assessed by means of scenario analysis on the future scenario assumptions and evaluating the variations in the LCA results. Therefore, even if the future scenarios created may be consistent and elaborate, direct application of the formulated scenarios in LCA does not constitute a systematic improvement with respect to how epistemic uncertainty has been addressed in LCA so far. Results may still be intrinsically bound to the assumptions, serving limited guidance to decision-making and scenario planning.

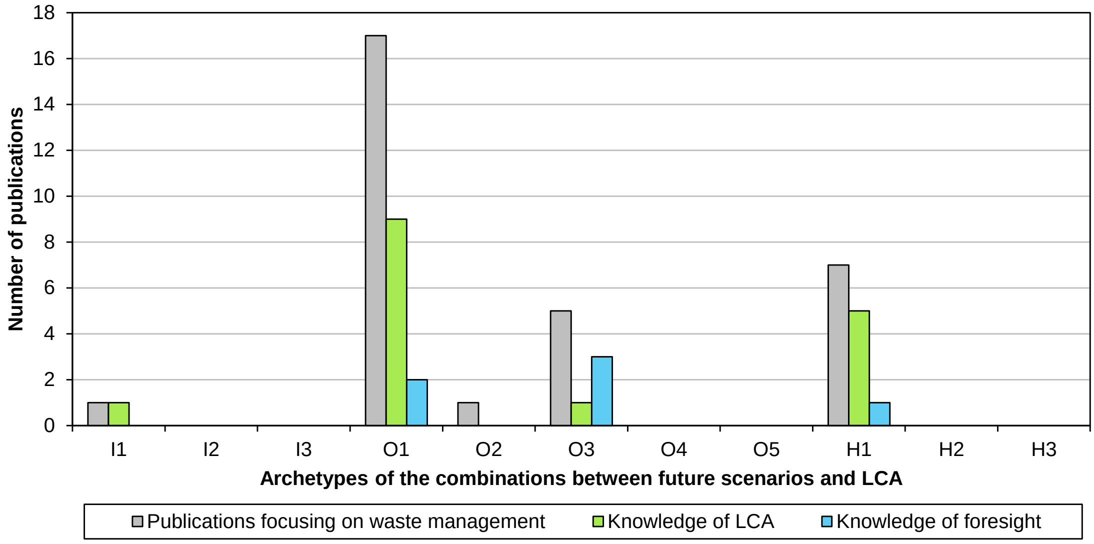


Figure 4. Occurrence of publications focusing on waste management and containing a case study (31 publications) in the archetypal combinations between future scenarios and LCA. The Figure indicates the apparent knowledge of LCA and foresight of the publications comprised in each archetype. Please refer to Figure 3 for details on the archetypes.

3.4 Recommendations for the combined use of future scenarios and LCA

Official guidance on the joint use of future scenarios and LCA is essential for reliably assessing the sustainability of long-term solutions and for unambiguously interpreting the results of such studies.

First and foremost, official guidance should contain a clear definition of *scenario*. A general scenario can be defined as "a set of aspects describing a specific situation at a specified time". When time has explicitly a future horizon, the scenario becomes a *future scenario*. Within LCA, a scenario is described by input values and associated LCI process data, as well as LCIA circumstances. As explained in the Introduction, LCI data can be distinguished between case-specific foreground system and average background system data (European Commission 2010a). Therefore, irrespective of the time frame, a clear definition of scenarios in LCA should thus specify the aspects included.

The use of "*technology scenarios*" is recommended for scenarios affecting the foreground system and "*framework scenarios*" for scenarios affecting aspects of the background system context and the LCIA phase (impact assessment, normalization, weighting). Both recommended scenario definitions resemble the concepts of "what-if" and "cornerstone" scenarios introduced by SETAC (Pesonen et al., 2000; Weidema et al., 2004). However, the use of "what-if" term can potentially be confused with probable, "what-if" scenario types (Börjeson et al., 2006), which are also bound to a specific foresight goal and short time frames. Moreover, "what-if" and "cornerstone" scenarios were never explicitly associated to LCI and LCIA aspects and were bound to specific time horizons and scenario scales, while the recommended definitions are adaptable to any time horizon and scale of the scenarios. Table 1 provides an illustrative subdivision of the recommended terminology.

A clear definition for scenarios in LCA facilitates the formulation of future scenarios and their communicability. As an example, researchers can specify that the future time horizon affects the technology scenarios only, while the framework scenario is considered unchanged (*e.g.* future scenarios on technological alternatives, with a short time horizon). On the other hand, researchers may want to test how alternative technology scenarios perform in different future framework conditions, as in the case about future waste management scenarios for the municipality of Copenhagen assessed in Bisinella et al. (2017b) (manuscript; Paper **IV**).

Table 1. Recommended terminology for scenarios in comparison with the LCI and LCIA subdivision and terminology employed by the SETAC Working Group on scenario development in LCA.

Recommended terminology	**LCI and LCIA subdivision** (European Commission 2010a)		**SETAC** (Weidema et al., 2004; Pesonen et al., 2000)	
Technology scenarios	LCI	Foreground system	Technosphere	What-if Scenarios
Framework scenarios		Background system		?
	LCIA	Impact assessment	Ecosphere	
		Normalization	Valuesphere	Cornerstone scenarios
		Weighting		

Official guidance should maintain the current freedom for choices regarding the LCA modelling, the future scenario formulation, the use of additional models, and for the sequence in which they are combined. Indeed, according to the foresight theory, creativity is a fundamental aspect for the quality and usefulness of the outcomes of such studies. However, creative approaches should not overlook basic quality requirements, especially for the standardized procedure of LCA when the study aims at supporting decisions.

A formal guidance could thus provide a framework for mandatory quality requirements as a structured checklist in which researchers could report their case-specific elective modelling choices. A clear declaration of choices and criteria, such as the ones used in the literature review carried out in Paper **I**, would aid transparency and communicability of the studies. This framework would also be particularly useful for illustrating the variety of future scenario choices to LCA experts, while summarizing the minimum LCA quality requirements to foresight experts.

An example of the recommended procedure is provided in Figure 5. The recommended procedure should be carried out as a check-list in the goal and scope phase of the study and verified iteratively. Tick boxes represent mandatory aspects. The choices corresponding to each mandatory aspect are elective. Goal and scope should preferably be in accordance between LCA and future scenarios in order to identify the most suitable future scenario type for the goal of the study. Moreover, a clear definition of the temporal scope is necessary for unambiguously setting the time horizon of the study. Then, the researcher should decide the archetype sequence between the intended LCA and future scenarios. If additional models are used, the researcher should clearly define where there in the archetype these additional models interact with the LCA or future scenario.

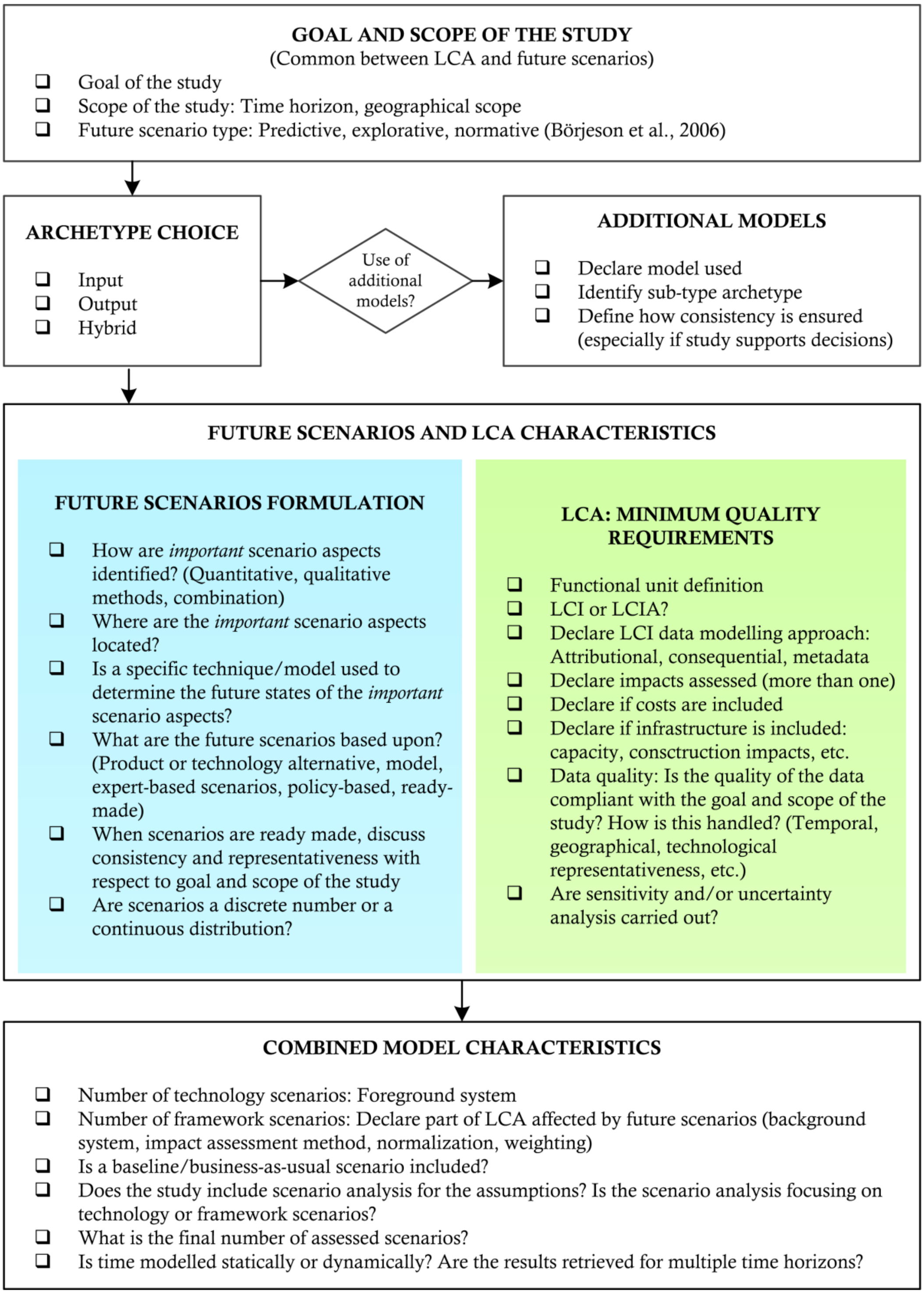


Figure 5. Example of recommended procedure for the combined use of future scenarios and LCA.

The characteristics of future scenarios and LCA should then be specified. Minimum quality requirements necessary for clarity and understanding of the studies for foresight and LCA experts were identified. Finally, researchers should describe the characteristics of the model combining future scenarios and LCA aspects, in particular the number of technology and framework scenarios, the presence of additional scenarios for scenario analysis, the aspects of LCA affected, time modelling choices, and so on.

Finally, LCA experts could not agree on the best LCI data modelling approach when assessing future scenarios (De Camillis et al., 2013). Both attributional and consequential approaches are affected by the subjective assumptions taken by the researcher, which should always be specified in order to guarantee transparency and reliability. However, with respect to modelling future scenarios and LCA, it is recommended to adopt the consequential modelling approach, where consequential is intended as *change-oriented* (Ekvall et al., 2016). The intent of assessing consequences complies with the primary future scenario function to *rehearse change* (Ringland and Schwartz, 1998). The LCI data modelling approach should thus take into account the consequences of the future scenarios rehearsed within LCA, as also expressed by many authors (Ekvall et al., 2005; Finnveden et al., 2009; Weidema et al., 2004), rather than being dependent on the scale of the analysis. This concept was already expressed in the “Prospective LCA” introduced by Weidema et al. (2004) and Pesonen et al. (2000), but in the articles retrieved for the literature review “prospective” was associated to both attributional and consequential approaches with short time frames, probably due to the resemblance to the “predictive” scenarios term, suggesting the need to pay particular attention to the terminology within future official guidelines.

4 Important scenario aspects in LCA

Good foresight practice suggests that understanding central *important* elements, aspects and causal connections in the studied system is an integral and fundamental part of the future scenario process (Bood and Postma, 1997; Meristö, 1989; Rasmussen, 2011). The determination of important aspects of the system being studied becomes fundamental when future scenarios are based on a preliminary LCA, as in the I and H archetypes identified in Paper **I**.

This section summarizes the findings obtained by a through exploration of the concept of *importance and important aspects* in LCA and waste-LCA models. A novel, systematic and reproducible analytical method for identification of important scenario aspects in LCA was provided by Bisinella et al. (2016) (Paper **II**). Then, the importance associated with waste composition parameters characterized by low sensitivity and high uncertainty was investigated using the analytical method developed in Paper **II**. Details are provided in (Bisinella et al., 2017c) (submitted; Paper **III**). The findings are summarized in a novel step-wise approach for the determination of important scenario aspects within LCAs of waste management systems.

4.1 Analytical calculation of importance in LCA based on Global Sensitivity Analysis

As introduced in section 2.1, LCA often presents complex and case-specific characteristics and the determination of important aspects and the mechanisms influencing the results should be identified within each case-specific model. Since LCA is a model, these “aspects” are (i) the input parameters (parametrical uncertainty), but also (ii) the assumptions (epistemic uncertainty) and (iii) the model uncertainties (Huijbregts et al., 2003; Lloyd and Ries, 2007; Spielmann et al., 2005). Aspects (ii) and (iii) are choices that are usually investigated with scenario analysis and will be examined in section 5. Parametrical uncertainty, on the other hand, offers the possibility to determine the importance of the model input parameters quantitatively with uncertainty analysis.

Thus, in our context, *importance* is a global concept, defined by the influence of the interaction of sensitivity and uncertainty of the parameters in a model (Heijungs, 1996; Saltelli et al., 2006). The final uncertainty of the model result takes into account both aspects. While sensitivity accounts for the weight of a parameter in a case-specific model configuration, the input uncertainty related to a parameter does not depend on the system, but on the parameters' nature and characteristics. A schematized relationship between input uncertainty and sensitivity in a model is shown for fictitious parameters in Figure 6. The axes represent the sensitivity and input uncertainty associated to each parameter and the dots represent the sensitivity and output uncertainty scores for each fictitious parameter. If no input uncertainty is assigned to the model parameters, it is not possible to calculate any output uncertainty, but only to calculate the sensitivity associated to the parameters. If the same input uncertainty is assigned to all parameters, the output uncertainties will mirror the results of the sensitivity analysis. Parameters may have high sensitivity but low input uncertainty, or vice versa. For this reason, a systematic quantification of importance should take into account both aspects. Interestingly, importance and uncertainty of scenario aspects were often suggested as scenario axes in the formulation of the scenario cross in numerous future studies (Ringland and Schwartz, 1998).

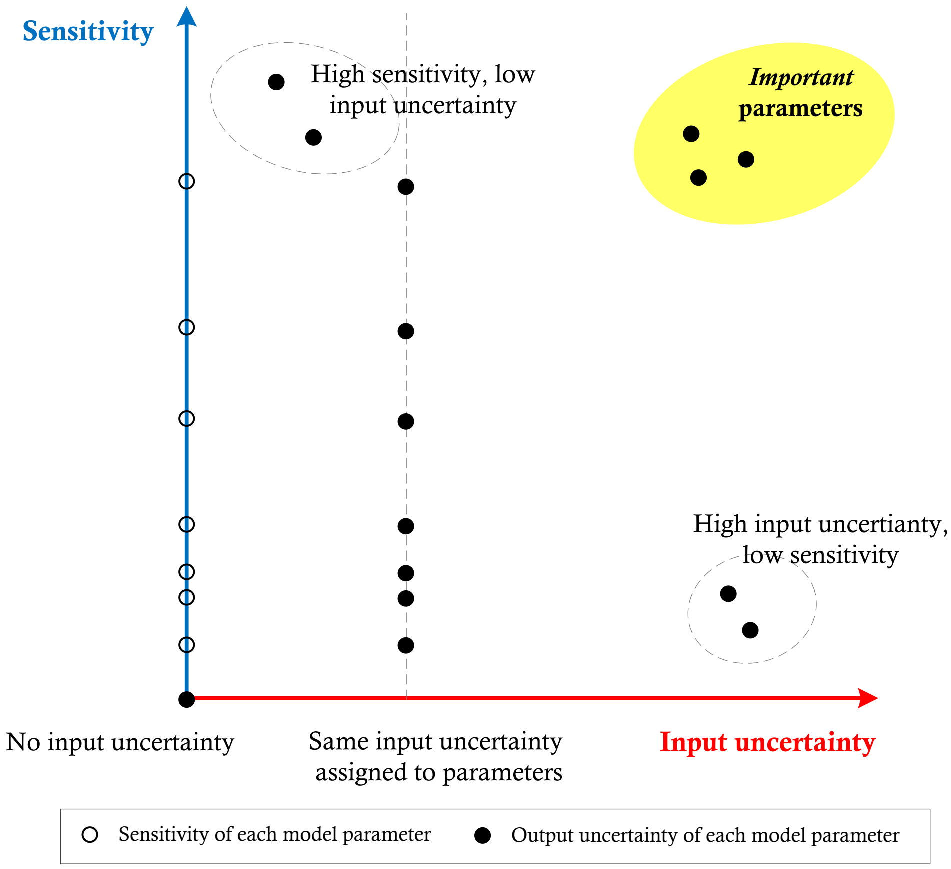


Figure 6. Schematized interaction between sensitivity of model parameters and their input uncertainty.

LCA modellers should always master the causal connections and relationships between the model inputs and outcomes in order to deliver credible and transparent results, especially when aiming at supporting decisions. In the particular case of future scenarios combined with LCA, understanding the mechanisms governing uncertainty propagation in LCA is essential for interpreting the quantitative results obtained. Uncertainty is inherent to future studies (Weidema et al., 2004) and, within the LCA model, future scenarios are often represented by a modified subset of selected model inputs.

Heijungs & Kleijn (2001) and Clavreul et al. (2012) suggested approaches for quantifying uncertainty in LCA results based on step-wise assessment of contribution, sensitivity, uncertainty and discernibility analyses. Nevertheless, Paper **I** showed that sensitivity and uncertainty analyses were rarely carried out, and that important scenario aspects were most often selected *a priori*. These observations comply with previous reviews of LCA studies (Laurent et al., 2014b; Lloyd and Ries, 2007). Uncertainty analysis was rarely carried out due to its perceived complexity and more easily identifiable sensitive parameters were ultimately identified as important scenario aspects.

This logic is even more problematic when *a priori* important aspects are chosen based on usually sensitive aspects in other LCA studies, or uncertainty is propagated only for sensitive parameters, not allowing the quantification of the full influence of input parameters with low sensitivity and high uncertainty. *A priori* and unjustified exclusion of individual parameters does not offer a valid approach to uncertainty propagation.

The analytical method presented in Paper **II** provides an *importance* measure based on understanding the fundamental connections between sensitivity and uncertainty of the model parameters in a Global Sensitivity Analysis (GSA) approach. The method was tested within a waste-LCA model on three real-scale scenarios for the management of residual household waste in Denmark. The study was carried out with the EASETECH model and impacts were assessed for 14 ILCD recommended impact categories (European Commission, 2010b). The study counted 80 input parameters for each assessed scenario, mainly related to the modelled technologies (*e.g.* energy recovery and source segregation efficiencies, process-specific emissions, transport distances, etc.) and few waste properties.

The proposed method calculates the uncertainty of the LCA results associated to each model input parameter based on a simplified formulation that utilizes the sensitivity and the input uncertainty of the model parameters. The sensitivity is represented by the sensitivity coefficient (*SC*; Clavreul et al., 2012), which measures the weight of the parameters in the specific model structure and should thus be calculated contextually. The input uncertainty is a variance (*V*) representing the probability distribution associated to the natural variability or the assigned uncertainty of the parameters. The variance can represent different distribution types and uncertainty ranges.

Representing a general LCA mathematically as:

$$Y^j = f(X_1, ..., X_n) \quad (1)$$

where Y is the result of the LCA for the impact assessment category *j* as a function of *n* parameters X_i. Then, the analytical uncertainty associated to each of the model parameters can be approximated as:

$$V(Y)_i^j \approx \left(SC_i^j\right)^2 \cdot V_{input}(X_i) \quad (2)$$

where *SC* is the sensitivity associated to the parameter X_i in the j^{th} impact category, and V_{input} is the input uncertainty associated to the parameter X_i. The total uncertainty of the LCA results for the impact category *j* can be approximated by the sum of the individual variances, which are assumed to be independent:

$$V(Y)^j \approx \sum_{i=1}^{n} \left[V(Y)_i^j\right] \quad (3)$$

The results of the proposed analytical method comply with uncertainty propagation results obtained with Monte Carlo sampling for each of the model parameters, as well as for the total uncertainty results. However, the proposed method offers considerably shorter computational times and a transparent understanding of the uncertainty propagation mechanisms in LCA. Modellers are compelled to carry out a thorough sensitivity analysis, can easily connect the single parameters to their uncertainty and evaluate the uncertainty results as a consequence of the contribution of the individual parameters to the total uncertainty.

Indeed, the contribution of each parameter to the total uncertainty is given the ratio of Equation (2) and Equation (3). By progressively ranking the contributions of each parameter, it is possible to identify *important* parameters, defined as the parameters representing most of the uncertainty within an impact category. Figure 7 shows that for the illustrated scenario most of the uncertainty is controlled by 5-6 parameters within each impact category, by 10 parameters across impact categories.

Paper **II** showed that only a sparse number of parameters is sufficient to represent most of the uncertainty in an LCA scenario. This is due to shared important parameters across impact categories. The identification of these critical parameters should thus be carried out in context with the system modelled and considering multiple impact categories. Moreover, the identification of the most important parameters allows prioritizing the efforts to improve quality of data and connected processes in a systematic and consistent way.

Equation (3) provides a fast approximation of the uncertainty around the LCA results and allows identifying potentially overlapping results in LCA studies comparing the performance of multiple scenarios. So far, the performance of such scenarios was compared with a discernibility analysis based on results of Monte Carlo sampling comprising all the parameters in the scenarios.

Paper **II** demonstrated that the parameters identified with the GSA approach are sufficient to obtain the same discernibility analysis results, but in a faster and more efficient manner. This represents a considerable "shortcut" with respect to the past time-demanding simulations.

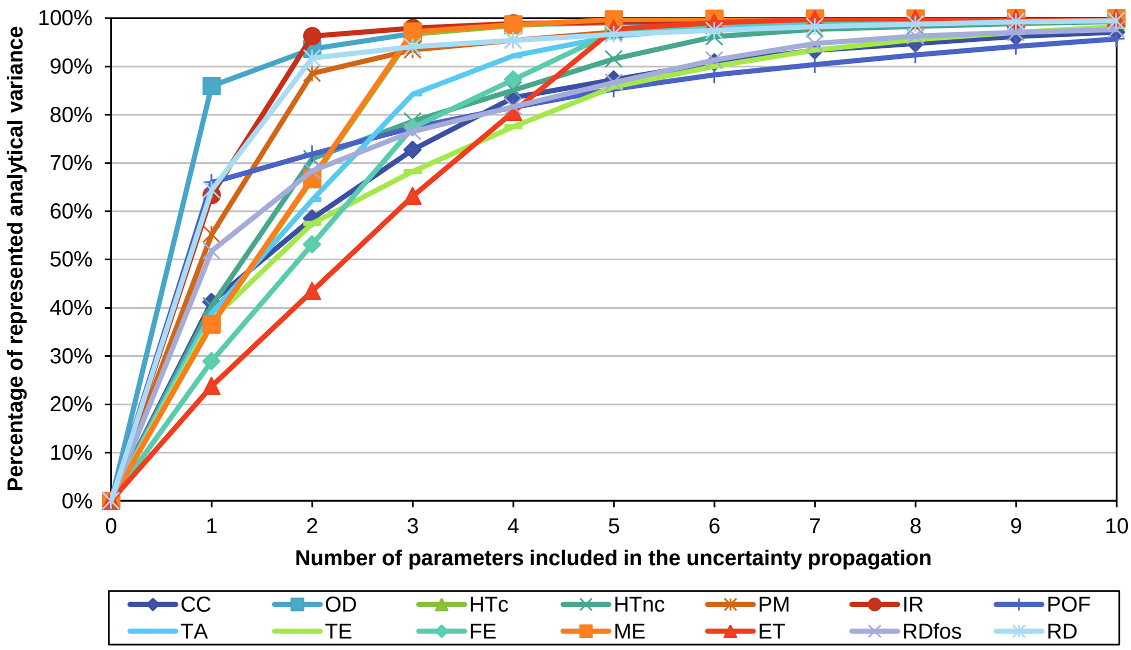


Figure 7. Percentage of the total analytical variance reached with a variable number of parameters included in the uncertainty propagation for one of the scenarios developed for Paper **II**. The lines represent the impact categories, please refer to Abbreviations.

4.2 Importance of the waste composition in LCA

A specific focus is required for LCAs of waste management systems, which can connect the environmental performance of the scenarios to the characteristics of the waste composition when using dedicated LCA tools as the EASETECH model (Clavreul et al., 2014). Past studies showed that the waste composition usually presented low sensitivity and that variations in the composition did not change the ranking of the performance of the scenarios assessed (Christensen et al., 2009; Passarini et al., 2012; Slagstad and Brattebø, 2013). On the other hand, numerous studies recorded higher effects and sensitivity for parameters connected to the energy background system (framework scenario), which result as commonly perceived *a priori* important scenario aspects (Münster & Meibom 2010; Mathiesen et al. 2009; Münster et al. 2013). However, due to the unavailability of international standard methodologies for characterizing the waste, the uncertainty associated to the waste composition data can actually be considerably high (Götze et al., 2016). This uncertainty can potentially be even higher when LCA studies have to rely on secondary data in the literature.

Paper **III** utilized the approach developed in Paper **II** for assessing the importance of waste composition data. The approach was utilized in the three real-scale waste-LCA scenarios for treatment of residual household waste in Denmark developed for Paper **II**. Paper **III** included realistic uncertainties for technology parameters, such as electricity and heat recoveries, source segregation efficiencies, process-specific emissions, etc. The uncertainty for physico-chemical properties of the waste materials was based on the literature review of Götze et al. (2016). Overall, the study presented a much higher number of input parameters than those utilized to test the GSA approach in Paper **II**: 405 individual waste properties and 345 technology parameters. The uncertainties retrieved from Götze et al. (2016) were particularly large and skewed.

Waste composition data contributed significantly to the LCA results and the uncertainty associated with these results. The GSA approach showed that the output uncertainty was mainly characterized by the waste physico-chemical properties and that uncertainty could be sparsely represented also when waste composition uncertainty was included (Figure 8). In particular, less than 10 physico-chemical properties dominated the uncertainty of the LCA results across impact categories. Including the uncertainties of the waste composition showed how these properties can influence results to the degree that the uncertainty around the results can span from benefits to burdens. Moreover, in some cases, the distributions of the results of different scenarios were overlapping and required a discernibility analysis for identifying the scenario with the best performance. In this context, the contribution of the parameters to the total uncertainty can be used to identify the physico-chemical properties that determine the best scenario.

As in Paper **II**, the results were tested against and found compliant to the results of the Monte Carlo sampling. However, the large and skewed uncertainties of the physico-chemical properties caused very high deviations from the average results, visible both from the analytical and sampled uncertainty. For these cases, a Monte Carlo simulation was required in order to establish the position of the average result within the often non-symmetrical output uncertainty distributions.

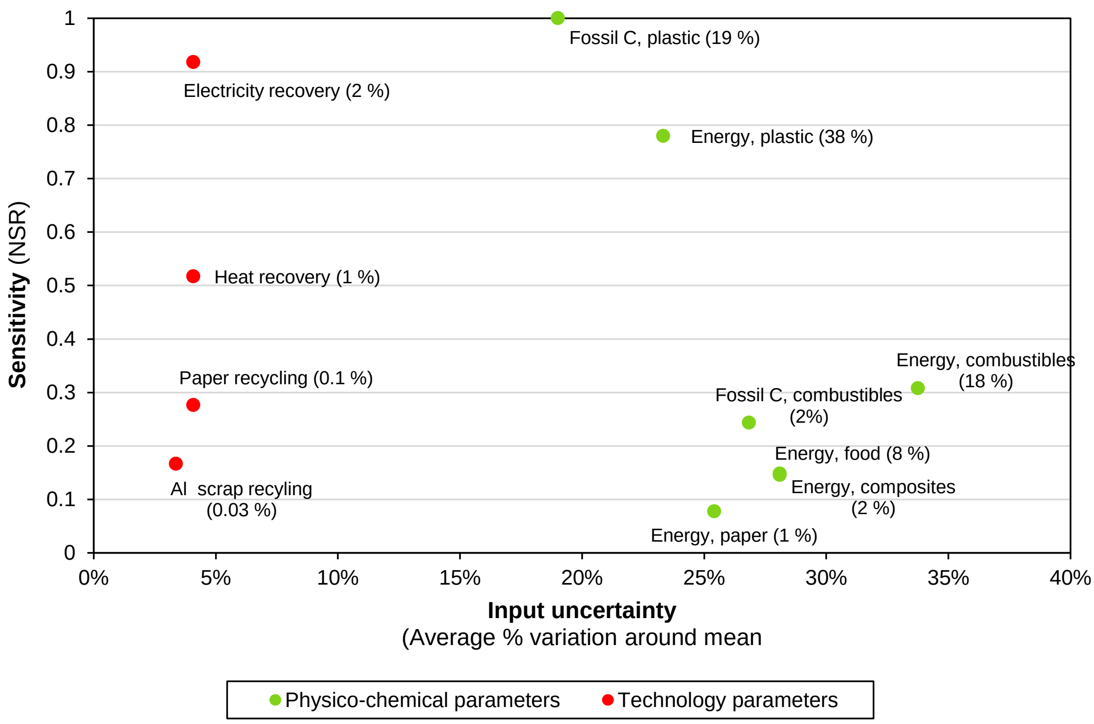


Figure 8. Input uncertainty (average % variation around the mean parameter value), sensitivity (Normalized Sensitivity Ratio, see Paper **III**) and output uncertainty (in parentheses) of a selection of important parameters (representing 99 % of the output uncertainty in one of the scenarios in Paper **III** for the climate change (CC) impact category). Examples of technology parameters in the Figure are electricity and heat recovery efficiencies, paper and aluminium recycling efficiencies. The illustrated physico-chemical parameters are energy content of the waste (plastic, paper, food, composite and combustible waste), and fossil carbon content of plastic and combustible waste.

Paper **III** showed that the coefficient of variation (CV) calculated from the analytical uncertainty can be utilized for indicating when average impact values should be obtained from a Monte Carlo simulation. These results highlight the importance of evaluating the shape of the distribution for parameters with large input uncertainties.

The low sensitivity of the waste composition is probably the reason why realistic variations of the waste fraction amounts (*e.g.* paper, glass, plastic, etc.) within a given waste composition (*e.g.* Danish municipal solid waste) do not influence the ranking of the scenarios in the literature. This effect was also tested in Paper **III**. However, even if the ranking was not affected, the LCA results differed in magnitude, indicating that case specific waste composition data are needed for appropriate environmental assessments of waste solutions. Also, the results clearly indicate that, sensitivity analysis alone cannot be used for identifying important scenario aspects if waste composition data is included. Uncertainty propagation based only on the most sensitive parameters can only quantify a fraction of the actual uncertainty of the LCA results. As an example, in the case of the scenario and impact category in Figure 8, the highly sensitive parameters illustrated (electricity recovery efficiency, fossil carbon contained in plastic waste, energy content of plastic waste) contribute to 59 % of the uncertainty.

Due to the high sensitivity of energy recovery parameters, the inherent choices of the energy processes representing the framework scenario could potentially change the magnitude of the average results. However, the energy recovery parameters are usually characterized by low technical uncertainty and did not contribute significantly to the output uncertainty in Paper **III** (Figure 8). On the other hand, the energy content of the waste, on which the energy recovery is based, often turned out to be among the most important scenario aspects. The results highlight that for LCAs of waste management systems, scenario analysis for the framework conditions cannot disregard the potential effect of the waste composition and that the two assessments should preferably be carried out jointly.

In the case of scenario analysis however, not all contributions to the LCA results would change. A simple contribution analysis carried out for Paper **III** systematically identified that direct waste emissions during treatment would be invariant with respect to framework scenario changes. The choice of representative waste composition data and understanding the mechanisms through which it influences the results are thus fundamental especially for carrying out LCAs of future waste management scenarios.

The investigation of the full effects of the waste composition in Paper **III** could not be carried out for all aspects of the waste composition. The waste amounts and the dry matter content are currently represented as a hierarchy of relative information, or "closed data". With the available modelling tools, both analytical and sampling methods can only provide an approximation of the true uncertainty associated with these parameters. The approximate results of the GSA indicate that fractional parameters may be important for the output uncertainty, despite the limited input uncertainty of these parameters.

4.3 Stepwise quantification of importance in LCAs of waste management systems

Based on the results of Paper **II** and Paper **III**, a modification of existing step-wise approaches for quantification of uncertainty in waste-LCAs is suggested. The approach is presented in Figure 9. The method proposed in Paper **II** integrates existing step-wise approaches for uncertainty analysis by introducing a global uncertainty analysis before uncertainty propagation. The novel approach applies to LCA in general, but also offers specific insights for LCAs of waste management solutions.

The well-established first steps suggested by Clavreul et al. (2012) and Heijungs & Kleijn (2001) are still essential. The contribution analysis (Step 0) constitutes the very first screening of the modelled system and is fundamental to identify the features affecting most of the results. For waste-LCAs in particular, the contribution analysis identifies the direct emissions associated to the waste composition that would be invariant with changes involving the framework conditions. The contribution analysis also identifies features of the system linked to waste composition properties.

Sensitivity analysis (Step 1) is also fundamental in order to understand the weight of the input parameters in the system due to the case-specific system configuration. The sensitivity analysis step allows the calculation of sensitivity coefficient (SC), sensitivity ratios (SR, please refer to Paper **II**) and normalized sensitivity ratios (NSR, please refer to Paper **III**), which are fundamental for applying the GSA method presented in Paper **II**.

The GSA method (Step 2, Equations 1-3) requires multiplying the input uncertainty of the parameters with the SCs calculated in Step 1. The method provides an approximation of the uncertainty on the results and allows ranking the parameters according to their contribution to these uncertainties. This step allows systematic identification of the most important scenario aspects, for which data quality should be prioritized, as well as identifying which other parameters can be kept in their initial range without affecting the uncertainty results. This step can considerably reduce efforts regarding the waste composition data. Within comparative LCAs, the estimated total uncertainty can be used to assess how much the results may vary around their mean value. For example, this uncertainty can be plotted as a min-max error bar on the mean scenario result.

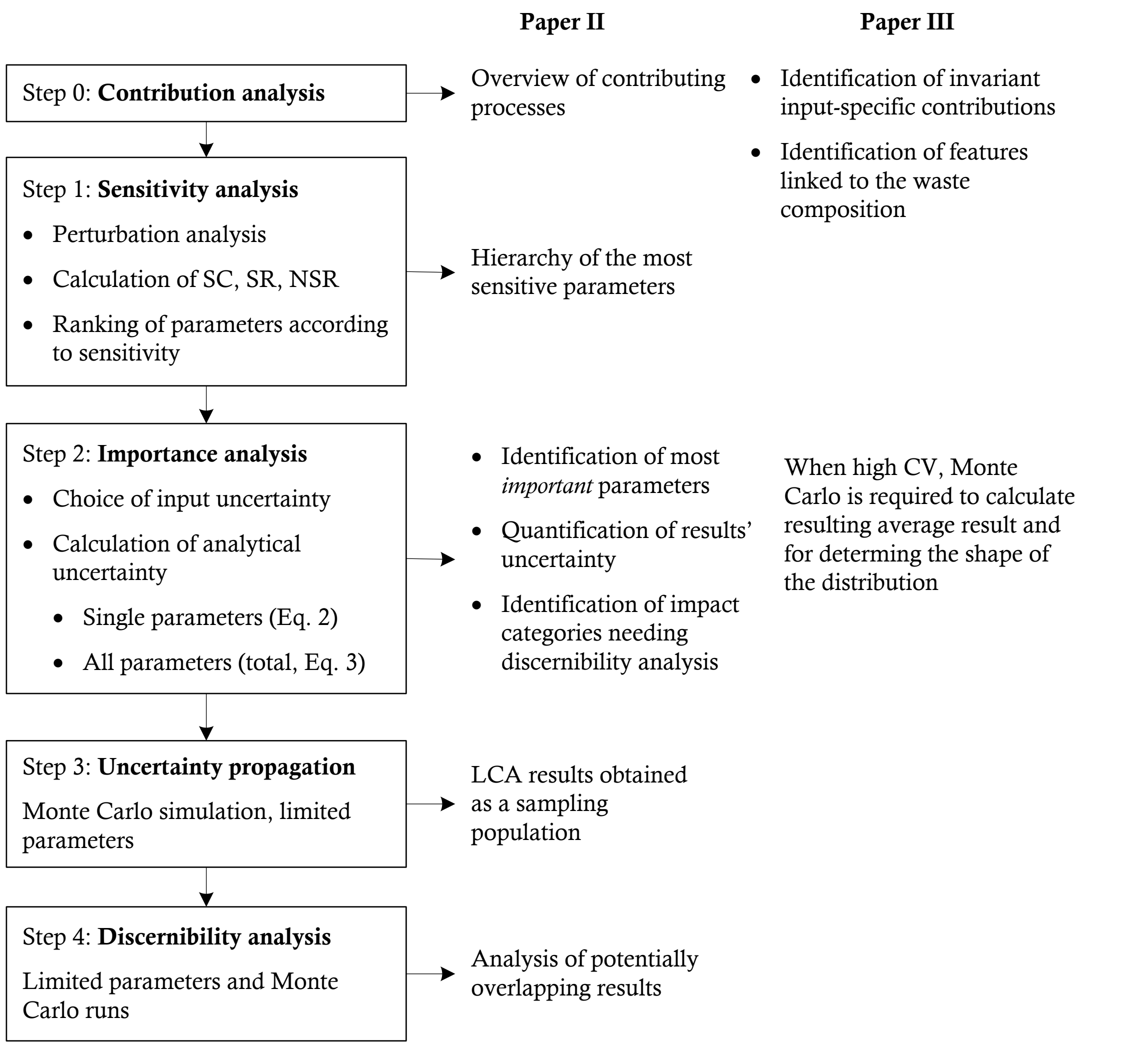


Figure 9. Step-wise approach for quantitative global importance and uncertainty analysis revised according to the findings in Paper **II** and Paper **III**.

Comparing the results expressed as min-max intervals, some scenarios may present overlapping results. In these cases a Monte Carlo simulation and a discernibility analysis are necessary to determine which waste management solution provides the best performance. Calculating the coefficient of variation (CV) allows identifying results with a high potential deviation around their mean result value and that may require a Monte Carlo simulation for a more precise determination of the mean result, as well as the shape of the distribution. This is essential especially in cases with high input uncertainties obtained from highly skewed distributions, *e.g.* waste physico-chemical properties.

The Monte Carlo simulation (Step 3) can be limited to the sparse parameter set that represent the uncertainty, both for the determination of the shape of the distribution of the results and for the discernibility analysis (Step 4), and thus considerably reducing computational efforts.

5 Quantitative framework for alternative visions in LCA

The future scenario paradigm is based on the concept that the future should be described by several *alternative visions*, rather than with a single precise image (IPCC, 2000; Siddiqui and Marnay, 2006; Wiek et al., 2006). As previously introduced in section 2.1, in LCA alternative framework scenarios and modelling choices have so far been tested with scenario analysis, and that such choices of framework conditions have often been a decisive factor in the ranking between technology scenarios for waste management solutions (*e.g.* Fruergaard & Astrup, 2011; Eriksson et al., 2007) (please refer to section 3.4 for definitions of framework and technology scenarios). The communicability and the usefulness of scenario analysis results have also been hindered by the fact that so far scenario analysis has been carried out separately from parameter uncertainty, dividing the interpretation of the results in two separate channels. On the contrary, parametrical uncertainty analysis should not be overlooked when analysing multiple future scenarios: the decision-maker should be fully aware of the uncertainties in each scenario for making comparisons between them (Weidema et al., 2004).

Section 5.1 presents a novel method for combining scenario and uncertainty analysis in LCA. This method aims at solving the everlasting dichotomy between uncertainty and scenario analysis in a manner simply conveyable to users. Details are provided in Bisinella et al. (2017b) (manuscript; Paper **IV**). Section 5.2 unifies the learnings of the previous sections in a comprehensive framework for carrying out systematic LCAs of future waste management solutions.

5.1 Combined scenario and uncertainty analysis for identifying the most robust solution

The method for combining scenario and uncertainty analysis in LCA is illustrated in Figure 10. The method is based on the results of the Monte Carlo simulation and consists of averaging the results of a discernibility analysis (Step 4) carried out between technology scenarios. The discernibility analysis obtains pairwise probabilities of one technology providing a better performance than another (Step 4a). By averaging the pairwise results of the discernibility analysis within a framework scenario, an “average probability measure” is obtained. This measure may be used to assess to which degree each technology scenario provides the best environmental performance (Step 4b). Averaging the probabilities across the framework scenarios (Step 4c) allows identifying the most *robust* scenario (Step 4d), defined as the technology scenario obtaining the highest average probability measure of representing the best solution across framework scenarios. The method thus allows to quantitatively determining the most *robust* technology scenarios across many framework scenarios.

a) Step 4a - Discernibility Analysis results

Pair-wise probability of scenarios in the rows to perform better than scenarios in the columns

4a.1

Climate change - Framework Scenario 1					
Scenario	**1**	**2A**	**2B**	**3**	***Average (row)***
1	-	100%	97%	100%	*99%*
2A	0%	-	38%	43%	*27%*
2B	4%	62%	-	58%	*41%*
3	0%	58%	42%	-	*33%*

4a.2

Climate change - Framework Scenario 2					
Scenario	**1**	**2A**	**2B**	**3**	***Average (row)***
1	-	46%	47%	98%	*64%*
2A	54%	-	51%	92%	*66%*
2B	53%	49%	-	84%	*62%*
3	2%	8%	16%	-	*9%*

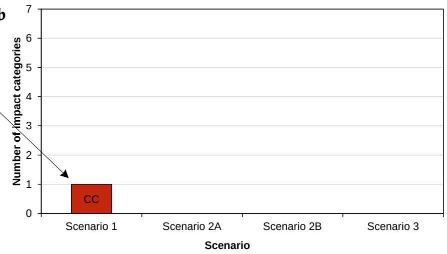
4a.3

Climate change - Framework Scenario 3					
Scenario	**1**	**2A**	**2B**	**3**	***Average (row)***
1	-	0%	0%	30%	*10%*
2A	100%	-	85%	100%	*95%*
2B	100%	15%	-	100%	*72%*
3	70%	0%	0%	-	*23%*

4a.4

Climate change - Framework Scenario 4					
Scenario	**1**	**2A**	**2B**	**3**	***Average (row)***
1	-	0%	0%	21%	*7%*
2A	100%	-	94%	100%	*98%*
2B	100%	6%	-	100%	*69%*
3	79%	0%	0%	-	*26%*

b) Step 4b - Average within a framework scenario



c) Step 4c - Average across framework scenarios

4c

Climate change - Across framework scenarios					
Scenario	**1**	**2A**	**2B**	**3**	***Average (row)***
1	-	37%	36%	62%	*45%*
2A	63%	-	67%	84%	*71%*
2B	64%	33%	-	86%	*61%*
3	38%	16%	14%	-	*23%*

d) Step 4d – Identification of the most robust technology, CC

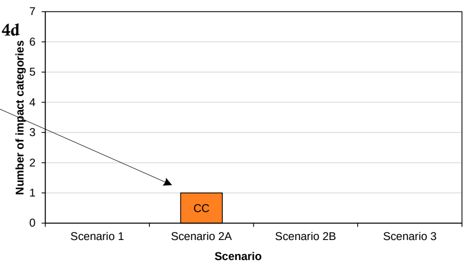


Figure 10. Quantification of robustness applied to the climate change (CC) impact category. Matrices 4a.1 – 4a.4 show the discernibility analysis results (Step 4a) between technology scenarios for each framework scenario. Figure 4b illustrates the average result for CC within framework scenario 1 (Step 4b). Matrix 4c shows the average results across energy frameworks (Step 4c) and Figure 4d illustrates the most robust solution for CC (Step 4d) (from Paper **IV**).

The impact categories, as well as the framework scenarios, are considered equally important and the method should be carried out within each impact category. The proposed method is applicable to comparative LCAs with the purpose of identifying the technology scenario with the best environmental performance within one framework scenario as well as across different frameworks scenarios.

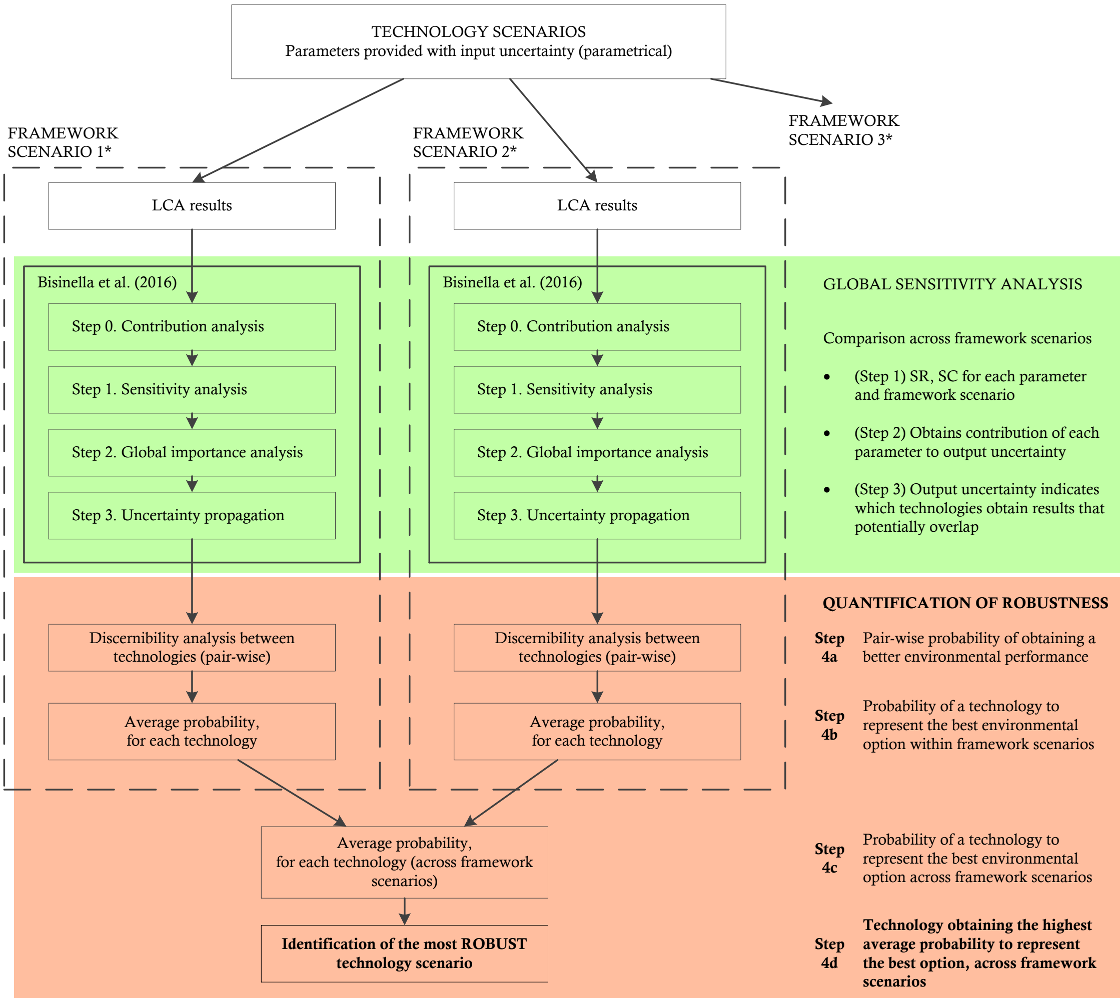


Figure 11. Generic methodology for quantification of robustness of technology scenario across framework scenarios, extending the current step-wise uncertainty assessment procedure (Paper **II**). The methodology allows any number of technology and framework scenarios. Both scenario types can be set in the present or in the future. The methodology is based on understanding of model mechanisms through global sensitivity analysis and on calculation of probabilities based on Monte Carlo simulation results (from Paper **IV**).

The case study utilized for Paper **IV** illustrated a typical case requiring the use of the proposed method. The changes in the framework scenario were based on possible future energy background systems. The case study portrayed a real-scale comparative assessment between future waste management scenarios for treatment of residual waste in the city of Copenhagen and included realistic uncertainties for technology parameters. Paper **IV** simulates the aspects most often tested in the literature based on sensitivity analyses or *a priori* choices (*e.g.*, Münster et al., 2013). The LCA results for the technology alternatives in the different framework scenarios did not allow identifying a clearly better waste management solution. The analytical uncertainty calculated according to the GSA approach was overlapping for many technology scenarios in different framework scenarios. A Monte Carlo simulation and a discernibility analysis were ultimately necessary for assessing the performance of the technology scenarios.

The proposed method for quantification of robustness indicated which waste management option had the "highest averaged probability measure" of obtaining the best environmental performance and provided an unambiguous final ranking. The method did not provide one best technology scenario before all others since all impact categories were considered equally important. Figure 12 illustrates an example of final results of the proposed method for the case study assessed in Paper **IV**.

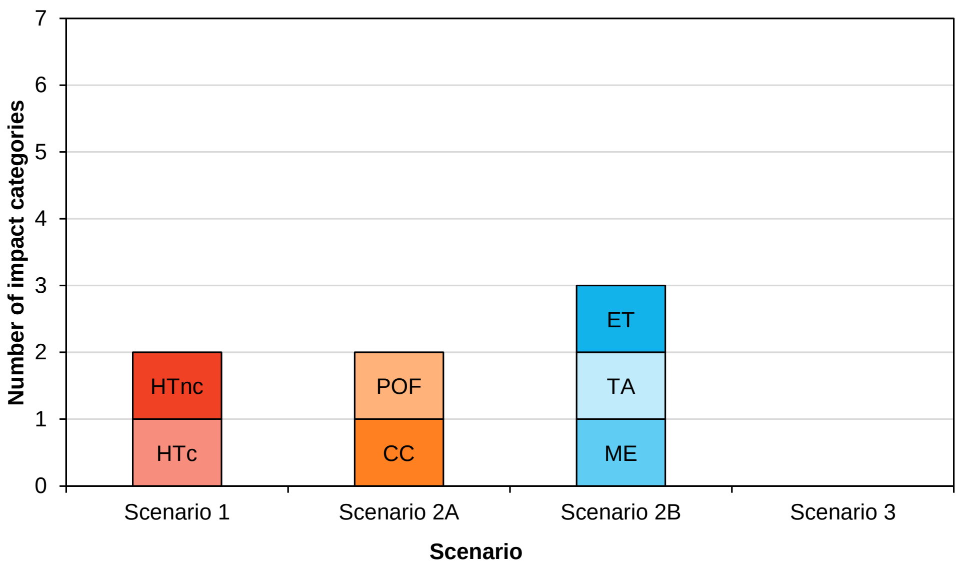


Figure 12. Results of the quantification of robustness method across framework scenarios for the case study assessed in Paper **IV**. The Figure shows the impact categories for which the technology scenarios on the *x* axis have the highest probability to obtain the best results (from Paper **IV**).

Each scenario was assigned with the impact category where its technology provides the most robust result. The method allows the final receivers of the LCA to decide which impact category to prioritize. In this respect, the results of the discernibility analysis also quantify the extent to which other impact categories are potentially penalized (Figure 13). The method allows the introduction of further uncertainty sources, such as waste composition and data quality and, if needed, weighting between future framework conditions.

By applying the GSA approach to each technology scenario and framework scenario analysed, it was possible to quantify the effect of the scenario analysis on the sensitivity coefficients. A change of framework scenario indeed caused a shift in the weight of the model parameters due to the change of the model configuration. The highest differences in sensitivity were recorded not only for parameters connected to the energy data inventories, but also for parameters that became more sensitive due to the framework scenario change. As an example, Table 2 shows that, in the case study assessed in Paper **IV**, when the energy savings became less beneficial, energy and heat parameters contributed progressively less in the uncertainty contribution analysis and other factors emerged. Moreover, the framework scenario changes focused on the energy system mostly affected the climate change (CC) impact category and only marginally affected the other impact categories.

Step 4c - Average across framework scenarios

Step 4d – Identification of the most robust technology

Pair-wise probability of scenarios in the rows to perform better than scenarios in the columns

Climate change - Across framework scenarios					
Scenario	**1**	**2A**	**2B**	**3**	***Average (row)***
1	-	37%	36%	62%	*45%*
2A	63%	-	67%	84%	*71%*
2B	64%	33%	-	86%	*61%*
3	38%	16%	14%	-	*23%*

Scenario 2A is the most robust solution for climate change (CC)

Pair-wise probability of Scenario 2A to provide a worse performance than the scenarios in the rows

Marine eutrophication - Across framework scenarios					
Scenario	**1**	**2A**	**2B**	**3**	***Average (row)***
1	-	99%	4%	100%	*68%*
2A	1%	-	0%	66%	*23%*
2B	96%	100%	-	100%	*99%*
3	0%	34%	0%	-	*11%*

Figure 13. In this example from Paper **IV**, Scenario 2A results the most robust technology scenario across framework scenarios for climate change (CC). If hypothetical stakeholders decided to prioritize CC, the discernibility analysis across framework scenarios also provides the extent to which other impact categories are penalized with respect to other technologies. Here this is shown for the marine eutrophication (ME) impact category.

Table 2. Normalized results, analytical uncertainty results and contribution to variance (CTV) for each technology and framework scenario for the CC impact category. The results are relative to 1 tonne of waste. The CTV is reported as percent contribution of the parameters to the analytical uncertainty of each scenario. The parameters reported are those required to reach the 95 % of the analytical uncertainty for each technology and framework scenario. INC1: incineration, new technology; INC2: incineration, existing facility; AD: anaerobic digestion (from Paper **IV**).

	Framework scenario 1 Coal, natural gas		Framework scenario 2 Coal, biomass	
	Scenario parameter	*CTV (%)*	Scenario parameter	CTV (%)
Scenario 1				
Results CC (PE/tonne)	-5.53E-02		-4.50E-02	
Analytical uncertainty $(PE/tonne)^2$	1.58E-06		1.16E-06	
	Electricity recovery, INC 1	*41%*	Electricity recovery, INC 1	*56%*
	Electricity recovery, INC 2	*19%*	Electricity recovery, INC 2	*26%*
	Share incinerated waste, INC1/INC2	*17%*	Aluminium recovery (scraps)	*7%*
	Heat recovery, INC 1	*10%*	Electricity consumption, INC 1	*4%*
	Aluminium recovery (scraps)	*5%*		
Scenario 2A				
Results CC (PE/tonne)	-3.60E-02		-3.68E-02	
Analytical uncertainty $(PE/tonne)^2$	7.37E-05		7.03E-05	
	Water addition, AD	*92%*	Water addition, AD	*92%*
	Percentage methane upgraded	*3%*	Percentage methane upgraded	*3%*
Scenario 2B				
Results (PE/tonne)	2.18E-02		-6.21E-03	
Analytical uncertainty $(PE/tonne)^2$	3.64E-04		3.13E-04	
	Water addition, AD	*99%*	Water addition, AD	*99%*
Scenario 3				
Results CC (PE/tonne)	4.10E-02		1.95E-03	
Analytical uncertainty $(PE/tonne)^2$	1.86E-05		1.78E-05	
	Water addition, AD	*86%*	Water addition, AD	*88%*
	Electricity recovery, INC 2	*5%*	Electricity recovery, INC 2	*5%*
	Electricity recovery, INC 1	*3%*	Electricity recovery, INC 1	*3%*

Table 2. *(continued)* Normalized results, analytical uncertainty results and contribution to variance (CTV) for each technology and framework scenario for the CC impact category. The results are relative to 1 tonne of waste. The CTV is reported as percent contribution of the parameters to the analytical uncertainty of each scenario. The parameters reported are those required to reach the 95 % of the analytical uncertainty for each technology and framework scenario. INC1: incineration, new technology; INC2: incineration, existing facility; AD: anaerobic digestion (from Paper **IV**).

	Framework scenario 3 Wind, natural gas		**Framework scenario 4 Wind, biomass**	
	Scenario parameter	CTV (%)	Scenario parameter	CTV (%)
Scenario 1				
Results CC (PE/tonne)	-4.75E-02		-4.70E-02	
Analytical uncertainty $(PE/tonne)^2$	4.56E-07		6.24E-07	
	Heat recovery, INC 1	*36%*	Share incinerated waste, INC1/INC2	*82%*
	Share incinerated waste, INC1/INC2	*33%*	Aluminium recovery from scraps	*14%*
	Aluminium recovery from scraps	*19%*		
	Heat recovery efficiency, INC 2	*6%*		
Scenario 2A				
Results CC (PE/tonne)	-3.69E-02		-2.99E-02	
Analytical uncertainty $(PE/tonne)^2$	7.37E-05		7.03E-05	
	Water addition, AD	*92%*	Water addition, AD	*92%*
	Percentage methane upgraded	*3%*	Percentage methane upgraded	*4%*
Scenario 2B				
Results (PE/tonne)	-9.26E-04		1.88E-02	
Analytical uncertainty $(PE/tonne)^2$	1.07E-04		8.18E-05	
	Water addition, AD	*95%*	Water addition, AD	*92%*
			Percentage methane upgraded	*3%*
Scenario 3				
Results CC (PE/tonne)	9.64E-03		3.59E-02	
Analytical uncertainty $(PE/tonne)^2$	4.33E-06		4.32E-06	
	Water addition, AD	*74%*	Water addition, AD	*70%*
	Percentage methane upgraded	*6%*	Share incinerated waste, INC1/INC2	*12%*
	Yield, AD	*4%*	Percentage methane upgraded	*6%*
	Share incinerated waste, INC1/INC2	*4%*	Yield, AD	*4%*
	Heat recovery, INC 1	*3%*	Aluminium recovery (scraps)	*2%*
	Heat recovery, INC 2	*2%*	Source segregated food waste	*2%*
	Aluminium recovery (scraps)	*2%*		

The results indicate that focusing on framework scenarios determined *a priori* without systematically assessing the model mechanisms might cause unforeseen changes in the model parameters governing the results. The data quality of the ultimately important parameters might not have been elaborated as much as the framework scenarios tested (*e.g.*, Münster et al., 2013). In particular, with progressively "cleaner" energy technologies LCAs of waste management systems are likely to be more affected by the direct waste emissions shown in Paper **III** than by the reduced savings from energy substitution. Moreover, applying a priori framework scenario changes might not affect all impact categories equally.

In this context, the GSA approach offers a systematic way to understand changes in model dynamics caused by the scenario analysis process. Moreover, if applied within preliminary LCAs, as in the I and H archetypes, the GSA can be a valid screening tool for verifying which model aspects have been affected by the implementation of the future scenarios. Ideally, future scenarios should test the case-specific characteristics of the technologies assessed. Implementation of future scenarios in LCA should not overlook the mechanisms that govern the results. Indeed, knowledge and understanding of the mechanisms induced by the introduction of the future scenario should be an integral part of the foresight practice within LCA. *Important scenario aspects* are also those governing the results in the end, and especially their potential future values.

5.2 Systematic framework for robust LCAs of future waste management systems

In the light of the learnings provided by Paper **I-IV** it is possible to define general recommendations in order to systematically carry out LCAs of future waste management systems. The recommended procedure is illustrated in Figure 14.

The procedure should start with the definition of goal and scope of the study in accordance to the structured checklist provided in Figure 4. Between the archetypes identified in Paper **I**, it is recommended to use the H type, since it offers the possibility to base the selection of *important* scenario aspects from a preliminary LCA. The preliminary LCA should assess one or more baseline technology scenarios within a baseline framework scenario, including uncertainty on waste composition data. In order to identify the most important aspects, it is sufficient to carry out Steps 0-2 of the approach presented in Figure 8. In particular, the contribution analysis should identify the waste-specific direct emissions and connections between processes and waste properties (*e.g.* in the case of energy content). Guidance on how to provide for input uncertainty can be found in the Supplementary Material of Paper **II**.

Depending on the goal and scope of the study, future scenarios can be formulated according to the preferred scenario building method (Figure 1), but taking into account the results of the importance analysis. Paper **IV** has shown how understanding actually important factors for the modelled systems may be more effective than just applying future scenarios *a priori*. The future scenario step should specify which aspects of the LCA are affected by the future scenario, *i.e.* technology scenarios, framework scenarios (any aspect between background system and LCIA context), or both.

After carrying out as many LCAs as required by the number of future scenarios generated, it is recommended to carry out the GSA approach again (Steps 0-2). The results would allow systematically identifying the important scenario aspects governing the results in the future scenario assessed. This step is particularly important for understanding the sensitivity mechanisms induced by the introduction of the future scenario. As previously discussed for Paper **IV**, understanding of these mechanisms should be considered an integral part of the foresight practice within LCA. If the quality of the data of the important scenario aspects ultimately governing the results is not sufficiently representative for the scope of the study, it is advised to improve the quality of the data and re-iterating the LCA on the future scenarios. Moreover, if the future scenarios do not effectively test all the aspects intended in the goal and scope, the future scenarios should be revised as well.

Finally, if results of the analytical uncertainty propagation are overlapping, exhibit high CVs, it is necessary to understand the shape of the output distributions or to identify the most robust solution, Step 3 (Monte Carlo simulation) and 4a-4d in Figure 8 (discernibility analysis and quantification of robustness) should be carried out.

The recommended approach is as well applicable outside the waste management system. Moreover, if the future time frame is substituted with any time frame, the procedure offers a systematic framework for assessing technological scenarios in LCA by means of combined parametrical uncertainty and scenario analysis, both for epistemic and modelling uncertainties.

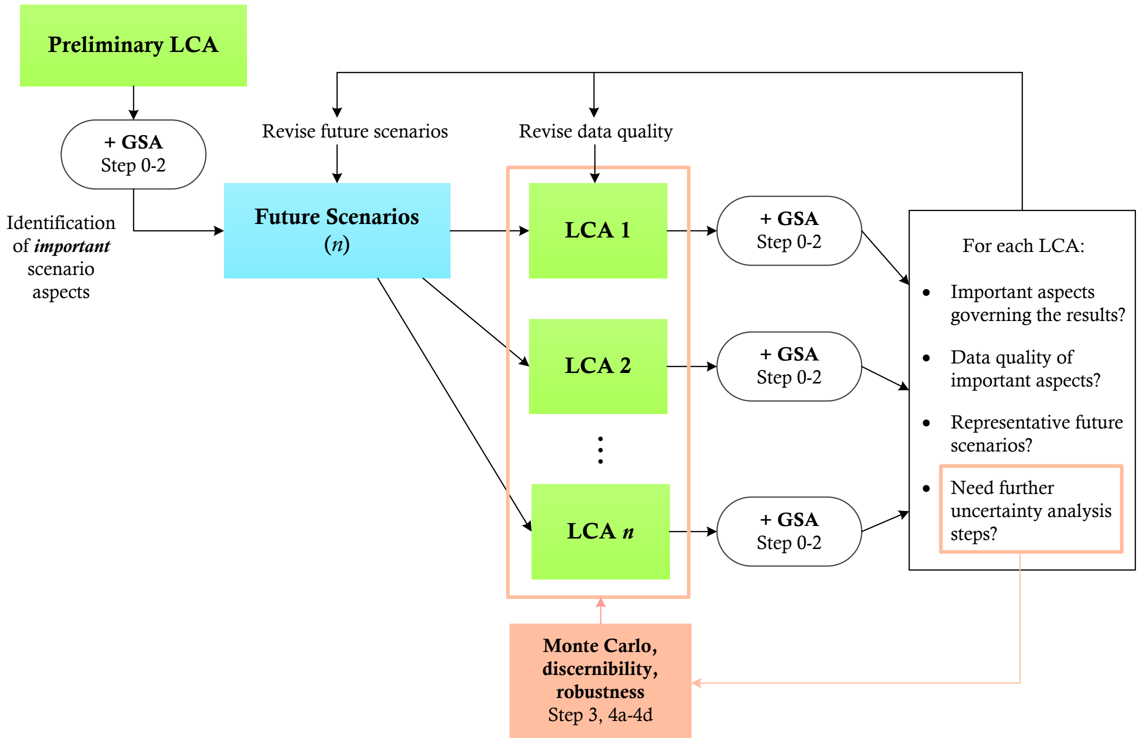


Figure 14. Recommended systematic framework for robust assessment of LCAs of future waste management systems.

6 Conclusions

This thesis compiled and analysed existing future scenario theory, terminology and methods. This comprehensive overview highlighted the main features that should characterize future scenarios in compliance with the foresight principles. Within waste management, foresight provided understanding of the general system dynamics, but independently from the LCA model mechanisms.

Formal attempts of SETAC, ISO and ILCD to frame future scenarios within LCA were thoroughly analysed, with particular attention to the modelling approaches and LCA phases involved. The LCA standard methodology foresees that LCAs may address future scenarios, but without providing specific guidelines.

In order to investigate this methodological loophole, a systematic literature review was carried out on all peer-reviewed journal articles combining LCA and future scenarios, across sectors. The review highlighted the need of formal guidance in order to regulate the existing approaches, especially in terms of quality standards and terminology. The review identified three main archetypes for combining future scenarios and LCA (Input, Output and Hybrid) and provided recommendations for formal guidance based on mandatory quality aspects and elective choices, for both the LCA and foresight fields. Within waste management, future scenarios have most often been modelled *a priori* and only subsequently tested in an LCA model. This approach resembles common evaluation of scenario assumptions through scenario analysis.

The concepts of *importance* and important scenario aspects within LCA were explored thoroughly. Importance in LCA is defined by the influence of the interaction of sensitivity and uncertainty of the model parameters. Sensitivity portrays the weight of a parameter in the model, which affects the result. However, input uncertainty is needed to provide a connection to the realistic variability of parameters outside the LCA artificial model. Therefore, sensitivity analysis alone or *a priori* choice of important aspects is not a complete assessment of the LCA model mechanisms. In order to facilitate the identification of important parameters, an analytical GSA approach was developed to further simplify existing uncertainty analysis approaches in waste-LCAs. The approach showed that a sparse subset of important parameters is sufficient for representing most of the variability of the results and for carrying out discernibility analyses.

The GSA approach was also used in order to assess the effects of the waste composition uncertainty on the LCA results. The high input uncertainty of the waste composition data resulted in large and skewed output uncertainties that spanned from benefits to burdens. Waste composition parameters resulted among the most important scenario aspects in all impact categories, indicating the necessity to include waste composition and its uncertainty when carrying out waste-LCAs.

The use of *alternative visions* by means of scenario analysis to describe future waste management systems in LCA was tested with a novel quantitative approach developed to unambiguously identify *robust* future waste management systems in LCA. The method involved utilizing uncertainty propagation results to identify the solution with the highest average probability measure of obtaining the best results. The GSA approach applied to the future scenarios quantitatively identified the effects of the scenario analysis in the sensitivity of the model parameters and showed how the change of framework conditions influenced the subset of important parameters ultimately governing the results.

Based on the learnings, recommendations for systematic quantification of the long-term sustainability of future waste management systems were provided. Various future scenario methods can be used to identify potential aspects and dynamics affecting the waste management system and to model interactions between waste management and these external factors. However, if the ultimate goal is to provide quantitative information on the long-term sustainability of waste management solutions with LCA, the modelling mechanisms existing in the LCA model should not be disregarded. Yet, these should always be assessed within each case-specific model and never *a priori*. Researchers are advised to utilize the Hybrid archetype and to perform the GSA approach after the preliminary LCA as well as after the LCAs based on the future scenarios. GSA allows identifying important aspects governing the results of the future LCAs and verifying needs to revise data quality and future scenarios. Finally, if required, further uncertainty analysis and robustness can be assessed. This PhD work ultimately highlighted that, when LCA is involved in long-term sustainability assessment of waste management systems, identification of the *important* aspects governing not only the preliminary LCA, but also the "future-LCA" results is essential. Identification of important aspects ultimately governing the results from the future scenarios should be regarded as a fundamental part of the foresight process and a responsibility of the modeller towards the final receivers of the LCA.

7 Future perspectives

Based on the work carried out in this PhD thesis, need for further research has been identified, in particular:

- Using the framework recommended in section 5.2 for an LCA on future scenarios that includes realistic technology uncertainties as well as waste composition and its uncertainty. In particular, carrying out a preliminary LCA would allow tailoring the future scenarios to the important aspects evidenced by the GSA approach, on top of the aspects usually suggested by stakeholders.
- Identifying general range values for framework conditions affecting the waste management systems, *e.g.*, "default energy scenarios". This would allow focusing on future scenarios for the waste management system characteristics, rather than on scenarios for external factors that ultimately do not affect the results. As an example, identifying climate change ranges for future energy technologies that only slightly affect the LCA climate change results would allow focusing on future scenarios for the waste composition, which majorly affects the climate change results in "cleaner" energy framework conditions.
- Data quality and parametrical uncertainty are intrinsically bound. Integration of data quality within the GSA analytical approach would allow adding technological, temporal and spatial representativeness to the technical uncertainty so far addressed. Data quality indicators may be correlated with the uncertainty of technologies at the design stage and with the uncertainty of assessments carried at longer time horizons.
- The work carried out for Paper **III** showed that the full importance of waste fractions and water content could not be estimated due to the closed structure of the waste composition dataset. Further research should focus on tailored uncertainty propagation methods, for example using compositional data analysis (Aitchison, 1986), or on modelling based on a different functional unit. Subsequently, these procedures should be implemented in EASETECH.
- The extensive work carried out on case studies showed that some parts of the LCA modelled system were not affected by the scenario changes, thus maintaining invariant SCs and SRs. Knowledge of such model mechanisms allows to further simplify analytical uncertainty assessment, which could be smartly re-calculated only for the variant parts.

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9 Papers

The following papers are included in the thesis:

- **I** Bisinella, V., Christensen, T.H., Astrup, T.F. (2017). Future scenario modelling within Life Cycle Assessment: A systematic review. Submitted.

- **II** Bisinella, V., Conradsen, K., Christensen, T.H., Astrup, T.F. (2016). A global approach for sparse representation of uncertainty in Life Cycle Assessments of waste management systems. *International Journal of Life Cycle Assessment*, 21(3), 378-394. DOI: 10.1007/s11367-015-1014-4

- **III** Bisinella, V., Götze, R., Conradsen, K., Damgaard, A., Christensen, T.H., Astrup, T.F. (2017). Importance of waste composition for Life Cycle Assessment of waste management solutions. Submitted.

- **IV** Bisinella, V., Conradsen, K., Christensen, T.H., Astrup, T.F. (2017). Integrated uncertainty and scenario analysis for Life Cycle Assessments of future waste management systems. Manuscript.

In this online version of the thesis, Papers **I-IV** are not included but can be obtained from electronic article databases *e.g.* via www.orbit.dtu.dk or on request from:

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