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PhD Thesis
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The synopsis part of this thesis is available as a pdf-file for download from the DTU research database ORBIT: http://www.orbit.dtu.dk

PREFACE

The work presented in this PhD thesis was conducted from January 2010 to June 2013 at the Department of Environmental Engineering of the Technical University of Denmark (DTU) under the supervision of Professor Thomas Højlund Christensen and co-supervision of Associate Professor Hubert Baumeister. The PhD project was funded by the 3R PhD school.

The PhD thesis is organised in two parts: the first part puts into context the findings of the PhD; the second part consists of the six scientific journal papers listed below. The papers are referred to by their roman numerals throughout the thesis (e.g.: Paper **I**).

   I.   Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H.: Review of LCA applications to solid waste management systems – Part I: Key learnings and perspectives. Submitted to Waste Management.

  II.   Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H.: Review of LCA applications to solid waste management systems – Part II: Methodological guidance for a better practice. Submitted to Waste Management.

 III.   Clavreul, J, Guyonnet, D., Christensen, T.H.: Quantifying uncertainty in LCA-modelling of waste management systems. Waste Management, 32, 2482-2495, 2012.

  IV.   Clavreul, J., Guyonnet, D., Tonini, D., Christensen, T.H.: Stochastic and epistemic uncertainty propagation. International Journal of Life Cycle Assessment, DOI 10.1007/s11367-013-0572-6. Published online April 2013.

   V.   Clavreul, J., Baumeister, H., Christensen, T.H., Damgaard, A.: EASETECH, an Environmental Assessment System for Environmental TECHnologies. Submitted to Environmental Modelling and Software.

  VI.   Yoshida, H., Clavreul, J., Christensen T.H., Scheutz, C.: Influence of data collection schemes on Life Cycle Assessment: the case of a municipal wastewater treatment plant. Manuscript.

In this online version of the thesis, the papers 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, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, reception@env.dtu.dk

ACKNOWLEDGEMENTS

ABSTRACT

Since the late 1990s, life cycle assessment (LCA) has been increasingly applied to waste management to quantify direct, indirect and avoided impacts from various treatment options. The construction of inventories for waste management systems differs from classical product-LCAs in that (1) these systems usually handle a heterogeneous mix of different waste fractions, (2) optimal treatments differ for these various fractions due to their chemical and physical properties and (3) emissions from final disposal places may occur over a very long time, depending on technology choice, and thus they have to be modelled rather than monitored as in classical LCA (e.g. landfilling or the application of processed waste on agricultural land). Therefore LCA-tools are needed which specifically address these issues and enable practitioners to model properly their systems.

In this thesis several pieces of work are presented. First a review was carried out on all LCA studies of waste management systems published before mid-2012. This provided a global overview of the technologies and waste fractions which have attracted focus within LCA while enabling an analysis of methodological tendencies, the use of tools and databases and the application of uncertainty analysis methods.

The major outcome of this thesis was the development of a new LCA model, called EASETECH, building on the experience with previous LCA-tools, in particular the EASEWASTE model. Before the actual implementation phase, a design phase involved a thorough analysis of requirements and the implementation of a conceptual model as a computational prototype, to ensure the feasibility of the model. During the development process, focus has been primarily placed on:

- Providing a toolbox of processes to model the different transfer functions found in waste treatment technologies. These material transfer functions specify how substances in input flows are transferred to output flows and environmental compartments and include for example processes for anaerobic digestion or landfill gas generation.

- Offering a flexible user interface where the user can connect freely all processes and combine them to build new treatment technologies and eventually scenarios.

- Keeping track of waste flows, throughout entire scenarios, as matrixes of fractions and chemical and physical properties.

- Displaying the time dimension of flows when needed, e.g. for gas and leachate emissions from landfill.

- Offering import functions which enable the use of newly released databases and life cycle impact assessment methods.

- Providing tools for uncertainty analysis.

Furthermore, as the review pointed out the lack of quantitative assessment of uncertainties in waste-LCA studies, a systematic approach was developed which includes several steps: sensitivity analysis, uncertainty propagation, uncertainty contribution analysis and combined sensitivity analysis. The result from each proposed step narrows the scope of the following step while producing a communicable outcome for decision makers. This method permits an analysis of the system at different scopes, from the largest picture with all processes and impact categories to a more detailed analysis of the reasons and probability for a shift in rankings between scenarios. To help practitioners in the screening of sources of uncertainty, a description of all uncertainties usually encountered in waste-LCAs was also provided.

Finally, an insight into uncertainty representation was presented which highlighted the importance of the choice of uncertainty representation, by comparing the propagation of probability distributions and fuzzy sets in a case study. A method was suggested whereby the practitioner is invited to choose one of the two representation types for each parameter, based on the level of information available, and all parameter uncertainties are propagated jointly.

The use of the new EASETECH model on two case studies has demonstrated the transparency of the model (allowing for a clear overview of all flows and data inputs), its flexibility (through the modelling of a full wastewater treatment plant) and the usefulness of the uncertainty analysis methods implemented. Further developments will focus on tools for economic analysis, an improved graphical display of results, the design of new process templates, the provision of an external editor of process templates and the development of new functionalities for the impact assessment phase.

DANSK SAMMENFATNING

Livscyklusvurdering (LCA) er siden slutningen af 1990'erne i stigende grad blevet anvendt inden for affaldshåndtering til vurdering af direkte, indirekte og undgåede miljøpåvirkninger fra forskellige behandlingsmuligheder. Kortlægning af input og output i affaldssystemer adskiller sig fra klassisk produkt-LCA ved, at (1) disse systemer normalt håndterer en heterogen blanding af forskellige affaldsfraktioner, (2) den optimale behandling varierer for de forskellige fraktioner på grund af deres kemiske og fysiske egenskaber og (3) emissioner fra den endelige bortskaffelse kan forekomme over lang tid, afhængigt af teknologivalg, hvorfor de dermed skal modelleres i stedet for at moniteres direkte (f.eks. ved deponering eller anvendelsen af affald på landbrugsjord). Derfor er der et behov for LCA-værktøjer, der kan håndtere disse udfordringer og muliggøre korrekt modellering af affaldshåndteringssystemer.

Denne ph.d.-afhandling består af flere dele. Første del er en evaluering af alle publicerede LCA-studier af affaldssystemer offentliggjort inden medio 2012. Dette har givet et samlet overblik over teknologier og affaldsfraktioner, som har tiltrukket opmærksomhed inden for branchen, og har samtidig muliggjort en analyse af den metodiske udvikling, brugen af værktøjer og databaser samt anvendelse af metoder for usikkerhedsanalyse inden for området.

Det vigtigste resultat af ph.d.-projektet har været udviklingen af en ny LCA-model (EASETECH), som bygger på erfaringer med eksisterende LCA-værktøjer og i særdeleshed EASEWASTE modellen. Inden den egentlige implementering har arbejdet inkluderet en designfase med overvejelser af relevante krav og behov samt implementering af den konceptuelle model i en beregningsmæssig prototype for at sikre modellens konceptuelle idé. Fokus i udviklingsprocessen har primært været på:

- At tilbyde en række metoder til at modellere forskellige fordelingsfunktioner relevant for affaldsbehandlingsteknologier. Disse masse overføringsfunktioner angiver, hvordan stoffer i inputstrømme overføres til outputstrømme og det omgivende miljø (jord, vand, luft) og omfatter eksempelvis processer til anaerob nedbrydning og produktion af gas i lossepladser.

- At udvikle en fleksibel brugerflade, hvor brugeren frit kan forbinde alle processer samt kombinere dem for at konstruere nye behandlingsteknologier og i sidste ende scenarier.

- At holde styr på affaldsstrømme, i form af matricer af fraktioner og kemiske og fysiske egenskaber der balanceres for hele scenarier.

- At illustrere udviklingen af strømme over tid, når det er nødvendigt f.eks. af gas og perkolat emissioner fra lossepladser.

- At give mulighed for import af nye databaser og livscykluspåvirkningsvurderings-metoder i modellen.

- At inkludere værktøjer til usikkerhedsanalyse.

På baggrund af den indledende evaluering af hidtidige udgivende affaldsrelaterede LCA-studier blev der udviklet en systematisk metode til udførelse af kvantitativ usikkerhedsanalyse som inkluderer sensitivitetsanalyse, usikkerhedsberegning, usikkerhedsbidrags-analyse, og kombineret sensitivitetsanalyse. Resultatet af hvert af de foreslåede trin indsnævrer fokus for det efterfølgende trin og giver samtidig et mere kommunikerbart resultat til beslutningstagerne. Denne metode giver mulighed for at analysere et system på forskellige niveauer og med varierende opløsning, fra det overordnede niveau med alle processer og miljøpåvirkningskategorier til en mere detaljeret analyse af årsager og sandsynligheden for at der sker et skift i rangering mellem forskellige scenarier. Som en hjælp til brugeren medfølger der samtidig en beskrivelse af de specifikke kilder til usikkerhed, som normalt findes i LCA på affaldssystemer.

Endelig blev usikkerhedsrepræsentation præsenteret, hvilket fremhævede vigtigheden af valget af usikkerhedsrepræsentationen ved at sammenligne beregninger af sandsynlighedsfordelinger og fuzzy tal i et casestudy. Der blev forslået en metode, hvor brugeren for hver parameter kan vælge en af de to repræsentationstyper, baseret på den tilgængelige information, og derefter beregne den samlede resultatsusikkerhed.

Den nye EASETECH model har igennem to casestudier bevist gennemsigtighed (giver klart overblik over alle strømme og input-data), fleksibilitet (ved modellering af et komplet rensningsanlæg) og anvendelighed af de implementerede metoder for usikkerhedsanalyse. Det videre arbejde vil inkludere udvikling af værktøjer til økonomisk analyse, forbedring af den grafiske præsentation af resultater, design af nye processkabeloner, udvikling af en ekstern editor for processkabeloner samt udvikling af nye funktionaliteter for miljøkonsekvensvurderingsfasen.

LIST OF CONTENTS

1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Since the 1960s, waste management has evolved greatly from simple disposal in open dumps to complex systems which combine treatments adapted to the mix of waste fractions they receive. In a context of increasing focus on sustainability, the sector has learnt that it cannot only reduce its emissions through better pollution control systems, but it can also have a beneficial impact on the environment through, for example, the production of energy or materials.

Tools are needed to quantify these benefits in a rigorous way, and life cycle assessment (LCA) represents a good way of integrating knowledge from different scientific disciplines in a framework that has been agreed on internationally. Indeed, to allow for the most accurate assessment of impacts from products and systems, LCA uses results from many environmental sciences such as air pollution, climate change, water pollution, chemistry, toxicity and water resources. The power of LCA lies in the fact that it brings results from these high-level disciplines to a common level that is generic enough to allow for comparison between impacts at the decision making level.

In parallel to good impact assessment modelling, good modelling practices are required on the emission inventory side. Indeed, as explained in more detail in Section 2.1, LCA modelling can be divided into two steps: the modelling of systems until emissions into the environment are quantified (called life cycle inventory, LCI) and the modelling of impacts on the environment based on these emissions' fate and effects (called life cycle impact assessment, LCIA). When modelling the LCI of waste management systems (WMSs), the challenge is again to find the right balance between a high degree of detail and the model's convenience of use. In fact, the impacts from waste management technologies can often be related to the different parameters of incoming waste composition and plant operation. Therefore, adapted tools are required which optimally use the data with which waste management experts are familiar and integrate up-to-date knowledge from the field of waste management.

At DTU the development of a tool designed for the LCA of WMS was started in 2000. The objective was to be able to model streams of waste fractions, characterised in content, collected in various bins and brought to different treatment technologies that could handle the diverse fractions in different ways. Generic LCA tools allow for (to different extents) the use of properties but not of fractions. Besides, some waste management technologies require specific

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calculations, as their impacts depend on the properties of the different waste fractions treated. For example, the generation of biogas in landfills is based on the biodegradable carbon content of the different fractions, while the rates of the different fractions' degradation depend on the landfill technology. This kind of modelling could have been modelled outside the LCA tool, e.g. in an Excel file, but we wanted to provide a complete tool that integrates all specific aspects of waste management. The objective was also to make LCA more attractive and accessible for experts within the waste management sector.

The EASEWASTE model was developed around the concept of waste fractions, and the first release integrated the modelling of landfilling and incineration. Thanks to the new perspective offered by EASEWASTE on WMS, research was carried out which led to the development and integration of new processes. At the same time, the number of users increased, thus encouraging the implementation of additional features. In 2009, a point was reached where (1) it became more and more difficult to implement new technologies in the original framework and to improve existing ones, (2) LCI databases had greatly evolved and some offered large amounts of datasets that could not be imported easily into the model (this was also the case for newly developed impact assessment methods), (3) the construction of scenarios was limited to predefined sequences of technologies and (4) uncertainty analysis tools were lacking.

Indeed, the quantification of uncertainties is a crucial step in making LCA more reliable and transparent (Finnveden et al., 2009). However, as will be shown in Section 3.3, uncertainty analysis is not always performed in a systematic way and the level of transparency and completeness varies a lot among studies. This is usually due to a lack of time and resources available at the end of studies or to a preconception that uncertainty analysis is too complex to be performed. Therefore, a focus of this thesis is to investigate how uncertainty analysis should be conducted in waste-LCA studies and to provide tools for this purpose.

1.2 RESEARCH OBJECTIVES

The objectives of this thesis were to:

- Specify features, facilities and structure of the next generation of EASEWASTE, including the mathematical structure, and to develop specifications for programming. The new system should be more flexible allowing for the construction of more complex technologies and scenarios and adaptable to individual needs and future adjustments.

- Identify uncertainties in waste-LCA studies.

- Investigate how uncertainty analysis should be performed and provide a systematic method to make it accessible and adaptable to different needs and resources.

- Demonstrate the flexibility of the new model by modelling a number of complex technologies and systems.

The thesis is structured in five sections:

- Section 2 describes the context, defines LCA and presents a review of how it has been applied to WMS up to now and which tools have been used in waste-LCAs (Papers **I** and **II**).

- Section 3 presents the work performed on uncertainty analysis in waste-LCA studies (Papers **II**, **III** and **IV**).

- Section 4 presents how the new EASETECH (Environmental Assessment System for Environmental TECHnologies) model was developed and how it answers flexibility needs and incorporates tools for uncertainty analysis (Paper **V**).

- Section 5 presents an example of system modelling in the new EASETECH model (Paper **VI**).

- Section 6 gives conclusions and recommendations for further work.

2 CONTEXT

2.1 LIFE CYCLE ASSESSMENT (LCA)

As introduced briefly, LCA is a tool based on scientific knowledge, which aims at quantifying the impacts of products and systems on the environment. Different entities have provided guidelines on how to perform LCA, the most common of which are ISO standard 14040 (ISO, 2006) and the ILCD handbooks (EC, 2010a). The LCA framework, as defined by the ISO, is presented in Figure 1. LCA is an iterative process whereby four main phases can be identified: the goal definition phase aims at defining the objectives of the study in detail, the scope definition phase describes the systems under study as well as the modelling assumptions, the inventory phase takes place when all data are gathered at the level defined in the previous phase and the impact assessment phase occurs when all impacts from the systems are calculated. Interpretation can be performed at all stages and several iterations are usually performed to redefine the goal or the scope of the study, or to refine data collection.

As presented in Paper **V**, the objective of LCA computations is "to quantify emissions and resource uses related to a functional unit (e.g. the production of a good or the provision of a service within a specified context). For this purpose, data need to be collected at the unit process level, e.g. an environmental technology or facility. These data consist of a simple mass flow model relating material outputs to material inputs and an inventory of emissions and resource uses (called elementary exchanges), but references to other processes are also included, such as electricity consumption, the consumption of a product or the provision of a service. The first step of LCA, called life cycle inventory (LCI),
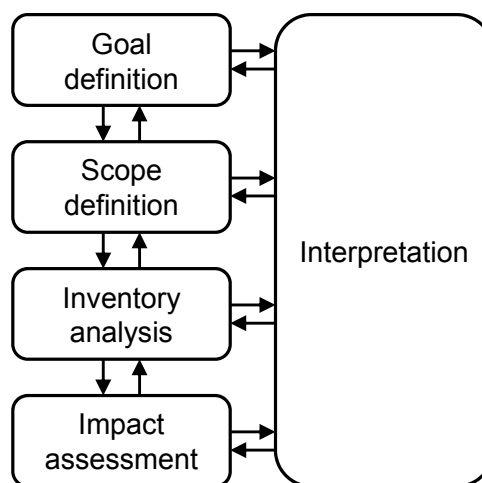
Figure 1. Framework for LCA (ISO, 2006)

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involves calculating the full inventory of elementary exchanges (both direct and indirect via the use of other processes) associated with the functional unit. Note that elementary exchanges consist of both a substance (e.g. "carbon dioxide") and the part of the environment that this substance is emitted/extracted to/from, called a "sub-compartment" (e.g. "air/unspecified" and "natural resource/in ground"). In order to quantify the impacts of a product or a service, emissions need to be converted into impacts, in the impact assessment step, which is divided into characterisation, normalisation and weighting steps. Characterisation is performed for each impact category by multiplying each emission by a factor quantifying the impact of this emission on the impact category relative to a reference compound, known as the "characterisation factor". For example, the emission of methane into the "air/unspecified" sub-compartment will contribute to the impact category "climate change" with a characterisation factor of 25kg CO_2-eq/kg methane (Forster et al., 2007, 100 years). Normalisation is performed by dividing the characterised impact by certain normalisation references, which enable one to scale the impact relatively to the impact of, for example, a population, thus allowing for some degree of comparison across categories. Finally, the weighting step attributes weights to the different impact categories, to help in obtaining a single score. Several life cycle impact assessment (LCIA) methods have been developed which provide sets of characterisation factors for different impact categories and sometimes include normalisation and weighting factors."

2.2 LCA OF WASTE MANAGEMENT SYSTEMS (WMSs)

LCA was first developed for the assessment of products, but it rapidly adapted to WMS. The goal of the LCA of products is to compare the complete life cycles of various products, which typically consist of the resource extraction, production, use and end-of-life of the product. In the LCA of WMS (also called "waste-LCA"), the waste produced is usually taken as a starting point and different waste management scenarios are compared.

In Papers **I** and **II**, an exhaustive review of all waste-LCA studies published in peer-reviewed articles until mid-2012 was performed. A total of 196 scientific articles were identified (details of the criteria used for inclusion are provided in **I**), while 15 public reports were also included. Mapping of the studies revealed that more than 70% of the selected papers originated from the European Union (EU). The evolution over time of the scientific publication of waste-LCA studies is presented in Figure 2. A rapid increase can be observed between 2003 and 2009, which seems to correlate well with the inclusion of legislation striving for

more life cycle thinking (LCT) in decision making in the EU. Indeed, in 2005, the EU thematic strategy on the prevention and recycling of waste was the first to introduce the use of LCA for quantifying impacts related to WMS. This thematic strategy was followed by the EU Waste Framework Directive (EU Directive 2008/98/EC), which established the need for LCT in waste management planning.

The scopes of the studies were analysed to observe general trends. Figure 3 presents the material fractions that were investigated as well as the source from which they originated. A strong focus on household waste can be observed, which might appear peculiar due to the fact that this waste stream usually represents less than 20% of total waste production based on mass. However, this waste stream represents an interesting object of study due to the amount of information available compared to other waste types, the fact that it is usually handled by public authorities and due to its complexity and heterogeneity.

Figure 4 shows the types of technologies that were assessed. The most studied technologies were unsurprisingly landfilling, incineration and recycling. These are the most used technologies in the EU (Eurostat, 2013) – landfilling usually represents the baseline scenario, while incineration and recycling have both benefited from great incentives aimed at reducing landfilling in the EU. Several management options were underrepresented, however, such as waste prevention and open dumps, which are still common in many developing countries.

2.3 TOOLS FOR LCA OF WMS

As explained in Section 3.3.1 of Paper **II**, specific aspects require particular attention when modelling WMS:

- Waste is a heterogeneous material, influenced by various local parameters.

- WMSs usually handle several streams of waste of varying quality, depending on the applied waste collection systems.

- Many trace pollutants need to be tracked over the full WMS, to follow their final fate in light of diverse waste treatment technologies.

- Emissions from final disposal places may occur over a very long time, depending on technology choice, and thus they have to be modelled rather than monitored as in classical LCA.

Proper modelling can be achieved by different means, as long as the local specificities of the systems are taken into account. Figure 5 shows which LCA tools were used in the studies reviewed in Paper **II**. While generic tools may
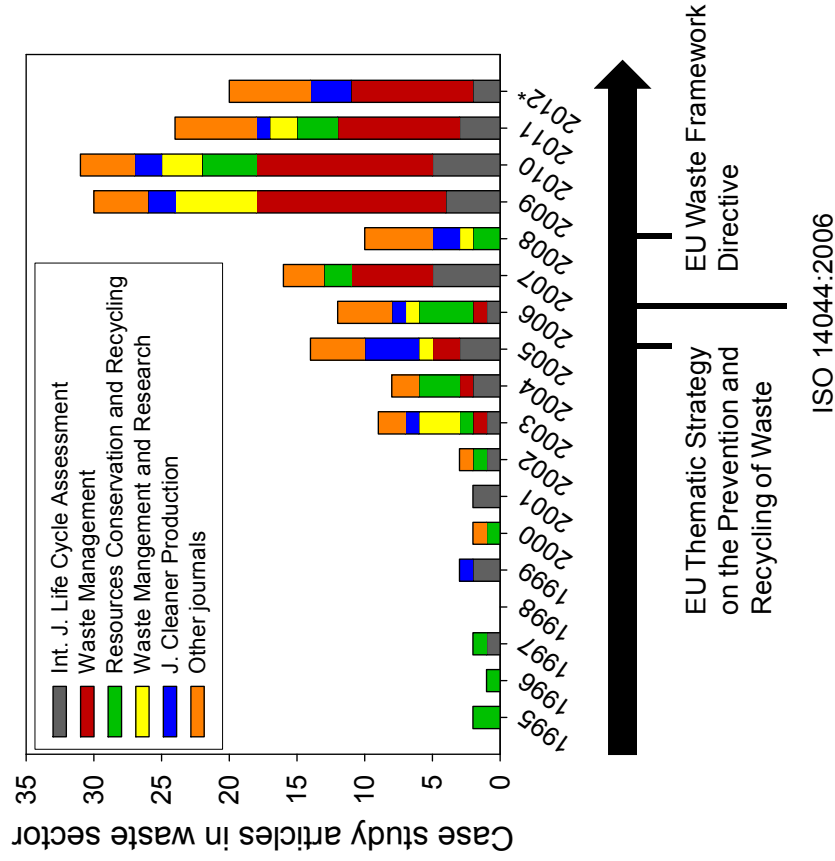
Figure 2. Distribution of publications describing the LCAs of SWMS across journals (total of 189 articles). For multiple articles describing the same case study, only the main article supporting the case was accounted for. The literature search was stopped mid-2012, so 2012 is an incomplete year (indicated by "*" on the graph) (from Paper **I**).
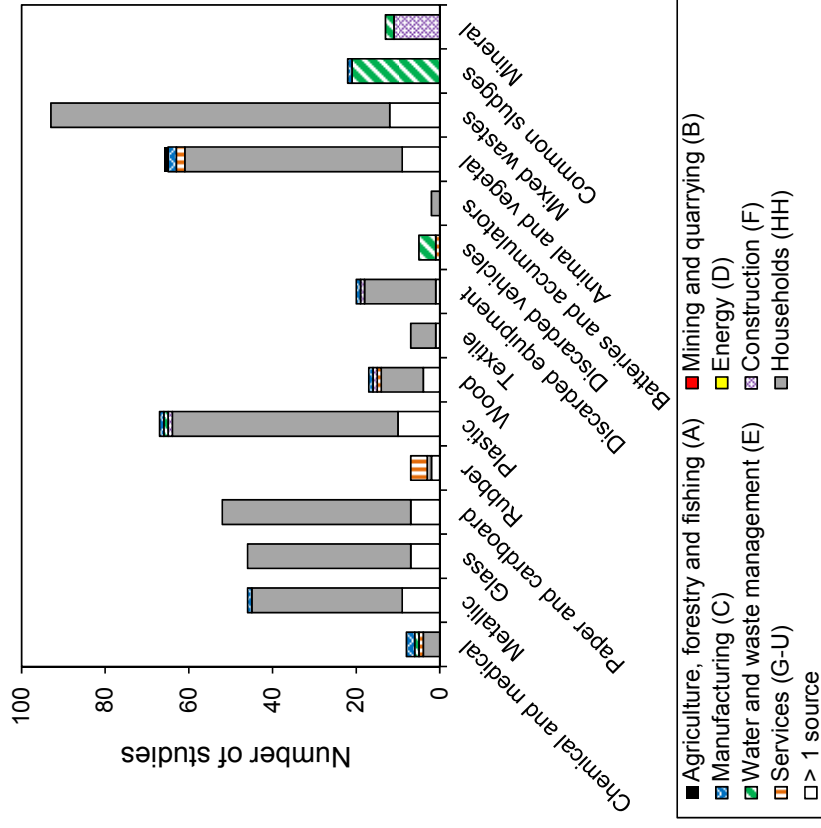
Figure 3. Number of studies for each assessed type of waste, disaggregated into source types (total of 204 studies). Some studies encompass several waste types, so the displayed total exceeds the number of studies. Classification for waste types and waste sources from EUROSTAT (2008) and EC (2010b) (from Paper **I**).

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appear attractive due to their broader use, specific tools offer an adapted framework focused on an easy overview of the WMS and the specific modelling of waste treatment technologies. Figure 5 shows that generic tools were used in approximately half of the studies, while the other half chose specific LCA software.
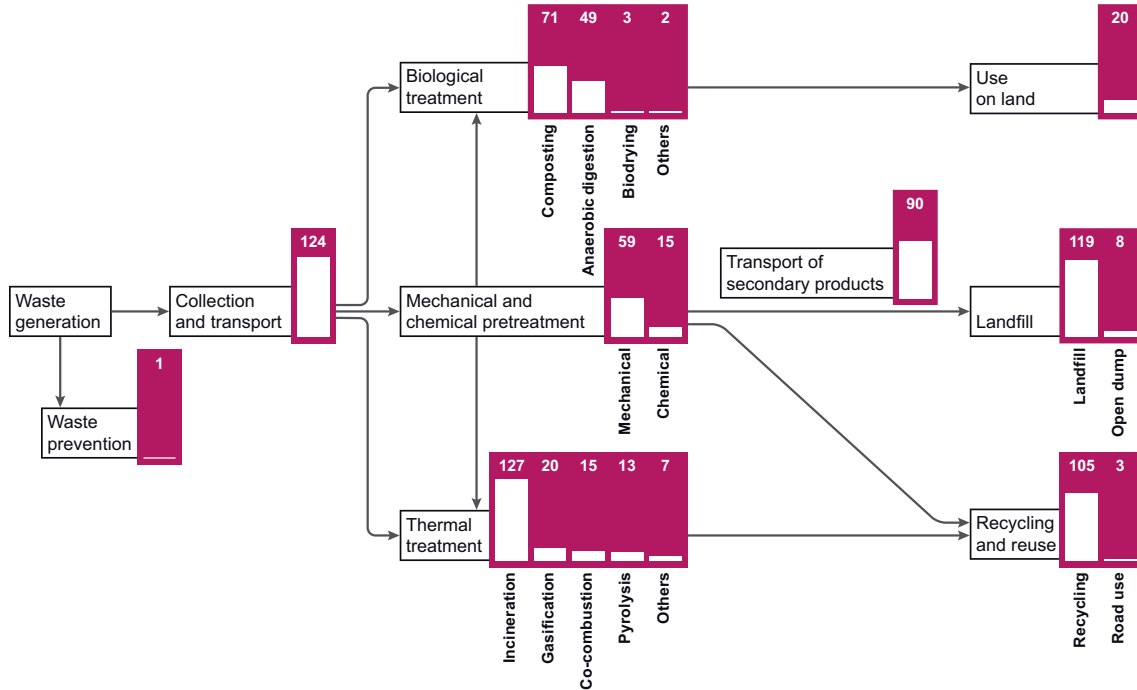
Figure 4. Waste management technologies assessed in the studies, expressed as numbers of studies (total of 204 studies). Arrows are for indicative purposes: several studies are limited to assessing specific components of SWMS; hence, the number of studies indicated in a given upstream process does not necessarily correspond with the sum of the number of studies indicated in the downstream processes (and vice versa) (from Paper **I**).
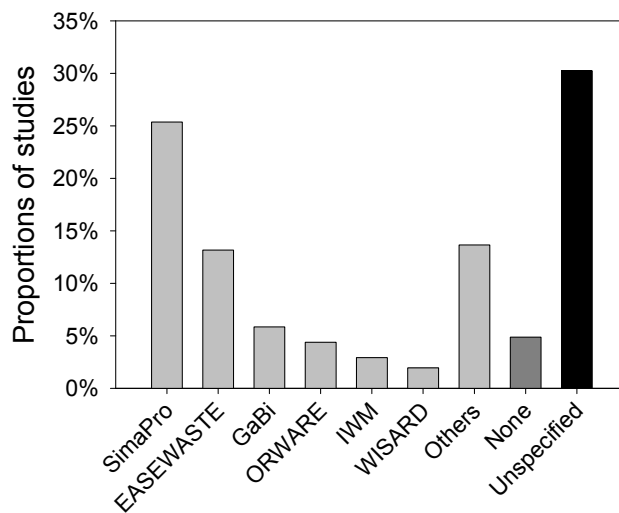
Figure 5. LCA software used in studies (total of 204 studies). The category "Others" includes DST, TEAM, TRACI, UMBERTO, GEMIS, WRATE, LCAiT, JEMAI-LCA, EIME, WAMPS software (from Paper **II**).

3 UNCERTAINTY ANALYSIS IN WASTE-LCA

3.1 BACKGROUND AND OBJECTIVES

The results of an LCA study are uncertain. Although this uncertainty might appear unfortunate, it is nevertheless a general rule when attempting to model reality. Different strategies can be adopted by modellers to assess uncertainties. What usually matters for decision makers is to determine initially whether this uncertainty is so large that it places the final decision in doubt or if it is acceptable. In a second phase, they are interested in identifying the input data that contribute the most to the uncertainty, e.g. for the purpose of uncertainty reduction. These are the two main objectives of uncertainty analysis, referred to as "uncertainty quantification" and "sensitivity analysis".

The ISO standard and the ILCD handbook require that an uncertainty analysis be performed to assess the reliability of results (ISO 2006, EC 2010a). This analysis, called "sensitivity check", consists mainly in an expert judgement on the different assumptions made and their impacts on the final outcome of the study, possibly accompanied by an uncertainty calculation. However, in practice the field of uncertainty analysis is difficult to comprehend, and many different methods are available, each of which has different purposes, degrees of complexity, computational expenses, data requirements and means of calculation. As outlined briefly above, uncertainty quantification, also called uncertainty propagation, aims to quantify the overall uncertainty of the result, while the objective of sensitivity analysis is to identify the input parameters that influence the result the most. It is often recommended to run those two analyses in parallel, ideally starting with uncertainty quantification and followed by sensitivity analysis (Saltelli et al., 2008).

Propagating uncertainties in a model involves parameterising the model, representing the uncertainty of each parameter or choice, running simulations and then calculating and interpreting the uncertainty of the result. However, uncertainty can be represented in different ways, the most classical of which involves the use of probabilities. Paper **IV** provides definitions of probability distributions and a description of their propagation methods. The most common one is Monte Carlo analysis, as used, for instance, by Huijbregts et al. (2003) or Sonnemann et al. (2003). Other sampling methods are more adapted to large datasets, such as the Latin hypercube, as used by Thabrew et al. (2008). Another possibility is to propagate uncertainties analytically using Taylor series

expansions to approximate the result's uncertainty, as implemented by Hong et al. (2010) and Imbeault-Tétreault et al. (2013).

Possibility theory offers another way of representing lack of information through the use of fuzzy sets. This representation is very rarely chosen, though, and usually the difference between propagation of probability distributions and fuzzy sets is not well understood. Paper **IV** and André and Lopes (2012) provide detailed descriptions of fuzzy sets and how to propagate them accordingly. In brief, fuzzy sets (also called possibility distributions) assign degrees of likelihood to intervals of values rather than precise values. The simplest example is the well-known min-max interval, which states simply that a parameter value is in an interval without any further information. When richer information is available, fuzzy sets can be used whereby degrees of likelihood can take all values between 0 (impossible) and 1 (very likely). Some examples of implementations in LCA studies can be found in Weckenmann and Schwan (2001), Gonzàlez et al. (2002), Ardente et al. (2004), Benetto et al. (2008) and Tan (2008).

Sensitivity analysis can also be performed by employing different methods, the simplest and most common of which is scenario analysis, which consists in changing one factor at a time (OFAT) and observing the change in the result. A variation of this method is called perturbation analysis, where all parameters of the model are ranked according to their influence on the results (Heijungs and Kleijn, 2001). Most other methods require performing uncertainty propagation first. Compared to OFAT methods, these methods enable a more complete exploration of the input space, as they simultaneously take into account all input variations, but it should be noted that they do require much more calculation efforts than scenario analysis. Saltelli et al. (2008) provide a very complete description of these methods, while Morgan and Henrion (1990) provide a good overview on all uncertainty analysis methods.

LCA practitioners may not feel comfortable with all the mathematical concepts and the different methods available. Therefore, there is a need for guidance on how to perform uncertainty assessment, here in particular applied to waste management systems. The sub-objectives in this thesis are to (1) provide an overview of the uncertainties specifically inherent to waste-LCA studies, (2) review how uncertainty analysis was performed in former waste-LCA studies, (3) investigate the representation of uncertainties using probability distributions and fuzzy sets and (4) provide a tiered approach for uncertainty analysis in the LCA of WMS.

3.2 UNCERTAINTIES IN WASTE-LCA STUDIES

When modelling WMS, LCA practitioners are faced with not only the usual uncertainties present in any LCA study but also with specific uncertainties. Based on literature and experience acquired over the last decade, these uncertainties have been inventoried and are presented in Table 1. Paper **III** provides explanations on each element of the table.

Uncertainties are presented using the framework developed by Huijbregts (1998), which divides LCA uncertainties into model, scenario and parameter uncertainties. Model uncertainties are related to the mathematical models underlying the LCA calculations. Different models can be adopted to describe waste management processes, in particular for the degradation of organic matter and the leaching of pollutants when waste is applied on land. Scenario uncertainties occur due to the choices made by modellers when building scenarios. These include choices made mainly during the scope definition phase and, for example, the choice of a specific process to represent a technology. Finally, parameter uncertainties refer to the uncertainty of single values due to, for instance, inherent variability, measurement imprecision or paucity of data, which are found everywhere in WMSs, particularly in waste composition and in waste treatment technologies. The table and the discussion included in Paper **III** can be used as a screening tool to identify the different sources of uncertainty in waste-LCA studies.

3.3 REVIEW OF PAST PRACTICE

The review in Paper **II** investigated how uncertainty analysis was performed in the 204 selected studies. Table 2 shows that approximately half of the studies did not report any sort of uncertainty analysis, while the other half performed scenario analysis. Practitioners have tested both parameters internal to the WMS (transport, waste composition, landfill parameters) and external to it (energy system and material substitution), with the purpose of demonstrating the robustness of their results.

While practitioners generally agree that quantifying the overall uncertainty of LCA results is necessary, Paper **II** showed that in practice very few studies performed uncertainty propagation – only 5% – and to different levels of detail and quality standards. Reasons for such a low implementation are multiple and can be grouped as: (1) complexity of terms and concepts, (2) absence or limitations of propagation tools in LCA software and (3) lack of time and/or data

Table 1. Uncertainties in the LCA of waste management systems (from Paper **III**).

Process	Model uncertainty	Scenario uncertainty	Parameter uncertainty
General	• Linearity of emissions • Modelling of waste- and process-specific emissions	• System boundaries • Database for energy and material productions • Time horizon (inventories) • Allocation	
Impact assessment	• Model for substances' fate and effects (characterisation factors) • Linearity of response	• Time horizon (impact characterisation) • Normalisation method and reference • Weighting method and reference	• Characterisation factors
Waste composition		• Choice of waste composition	• Waste fractions distribution • Chemical composition of fractions
Collection	• Model for collection	• Choice of collection scheme (e.g. separate or common collection)	• Fuel consumption; emissions from fuel combustion • Sorting efficiencies
Transport			• Distance; fuel consumption; emissions from fuel combustion
Material recovery facility		• Choice of technology	• Sorting efficiencies; consumption of materials and energy
Thermal treatment		• Choice of technology (e.g. dry/wet flue gas cleaning) • Choice of technology for outputs' treatments	• Electricity and heat recoveries; consumption of materials and energy; substances flows; output composition
Biological treatment	• Model for biodegradation (e.g. based on CH_4-potential or on hemi-celluloid material) and CH_4/CO_2 ratio in biogas	• Choice of technology	• Degradation rates of organic matter; N distribution; gas cleaning efficiencies; biogas composition; materials and energy consumption; energy recovery; leakages
Use on land	• Model for plant uptakes and fertiliser substitution • Model for leaching	• Choice of technology (e.g. on sandy or loamy soil)	• Substitution rate of compost / fertilisers; carbon binding; N distribution; run-off; leaching
Landfill	• Model for gas generation • Model for leachate generation and leaching to groundwater	• Choice of technology (e.g. conventional or bioreactor) • Choice of gas utilisation • Choice of technology for leachate treatment	• Gas composition; collection, utilisation and oxidation rates • Leachate composition; collection rate; removal efficiencies at leachate treatment; • Materials and energy consumption; emissions and energy recovery of gas engine
Recycling		• Choice of technology for the recycling plant and the avoided material production	• Substitution rate; materials and energy consumption of recycling plant and substituted process

Table 2. Overview of past practices for uncertainty and sensitivity analyses in LCA studies of solid waste management systems (total of 204 studies) (from Paper **II**).

Practices [a]		Number of studies
Sensitivity analysis method	**Uncertainty propagation method**	
Scenario analysis	-	92
Scenario analysis + perturbation analysis	-	1
-	Monte Carlo analysis	3
Scenario analysis	Monte Carlo analysis	1
Uncertainty contribution analysis	Monte Carlo analysis	2
Scenario analysis	Taylor series	2
-	Rough calculation of uncertainty	1
-	Fuzzy sets	1
Special case: reporting of ranges of results		1
Not addressed or only qualitative discussion included		100

[a] Some studies used either sensitivity analysis methods or uncertainty propagation methods alone (rows marked with a "-"). Others used a combination of both.

to represent the uncertainties. Only one study implemented fuzzy sets, and only in the normalisation and weighting steps. In the other nine studies, LCI uncertainties were modelled as probability distributions, using literature, expert knowledge and/or pedigree matrixes for the selection of these distributions. However, possibility theory (and the use of fuzzy sets) can offer flexibility in the choice of uncertainty representation. This theory is not known well enough and practitioners are usually reluctant to use it due to the absence of propagation tools in LCA software; however, it could offer a great opportunity to make choosing distributions easier and also be more adapted to experts' vocabulary. This is why Paper **IV** investigated how fuzzy sets could be implemented in LCA and if they could be used in combination with probability distributions.

3.4 UNCERTAINTY REPRESENTATION WITH PROBABILITY DISTRIBUTIONS AND FUZZY SETS

What is commonly referred to as "uncertainty" can usually be divided into two categories: epistemic uncertainty, which is the result of our incomplete knowledge of the world, and aleatory uncertainty, which occurs due to the inherent variability of processes in the world. It is usually advised to calculate the uncertainty of LCA results by using Monte Carlo analysis, e.g. by the ILCD handbook (EC, 2010a). This implies that uncertainties are represented by probability distributions. However, while the choice of probability distributions should be based on proper information on this uncertainty, LCA practitioners are often faced with epistemic uncertainty and do not have sufficient information on the uncertainty. Therefore, probability distributions are very often chosen based on expert judgement or estimates.

Possibility theory provides a framework for conveying such types of information using possibility distributions or fuzzy sets (Dubois and Prade, 2009). As such, two questions emerge when considering LCA:

- What does it change to represent uncertainties with probability or possibility distributions?

- There are often situations where information is rich on part of the data, while the rest of the data is only based on expert judgements, so could a joint propagation method be applied?

These are the two questions Paper **IV** answers, by providing detailed explanations of the theories and by implementing propagation methods in an LCA case study. The approach consisted of comparing results obtained by propagating uncertainties with a probabilistic method (Monte Carlo), a possibilistic method and a joint propagation method called the Independent Random Set (IRS) method, developed by Baudrit et al. (2006). The same distribution shape (trapezoidal) and parameters were used for each parameter in both representations, to allow for comparison. The objective of the case study was to assess benefits relating to the global warming potential of cultivating a biocrop (willow) on Danish agricultural land for the production of bioenergy (by co-combustion).

Figure 6 presents the results obtained from the three different methods. Whenever at least one fuzzy set is propagated, two cumulative distribution functions (cdfs) are obtained. As explained in more detail in Paper **IV**, these two cdfs are the lower and upper bounds of the family of distributions resulting from the propagation. They represent the most optimistic and pessimistic cdf obtainable, respectively, when all most favourable and all least favourable values are combined. The distance between the two cdfs represents the gap in knowledge, while the horizontal extent of each cdf represents the aleatory variability of the known parameters. In the IRS method, the more parameters represented by probability, the narrower the gap between the two cdfs. This illustrates well the shift from epistemic uncertainty to informed uncertainty.

To make results easier to communicate, a confidence index can be used which attributes weights to the optimistic and pessimistic cdfs. In Figure 6, a confidence index of 1/3 has been applied, i.e. giving twice more weight to the pessimistic estimate than the optimistic one. Such an index can reflect the decision maker's aversion to risk.
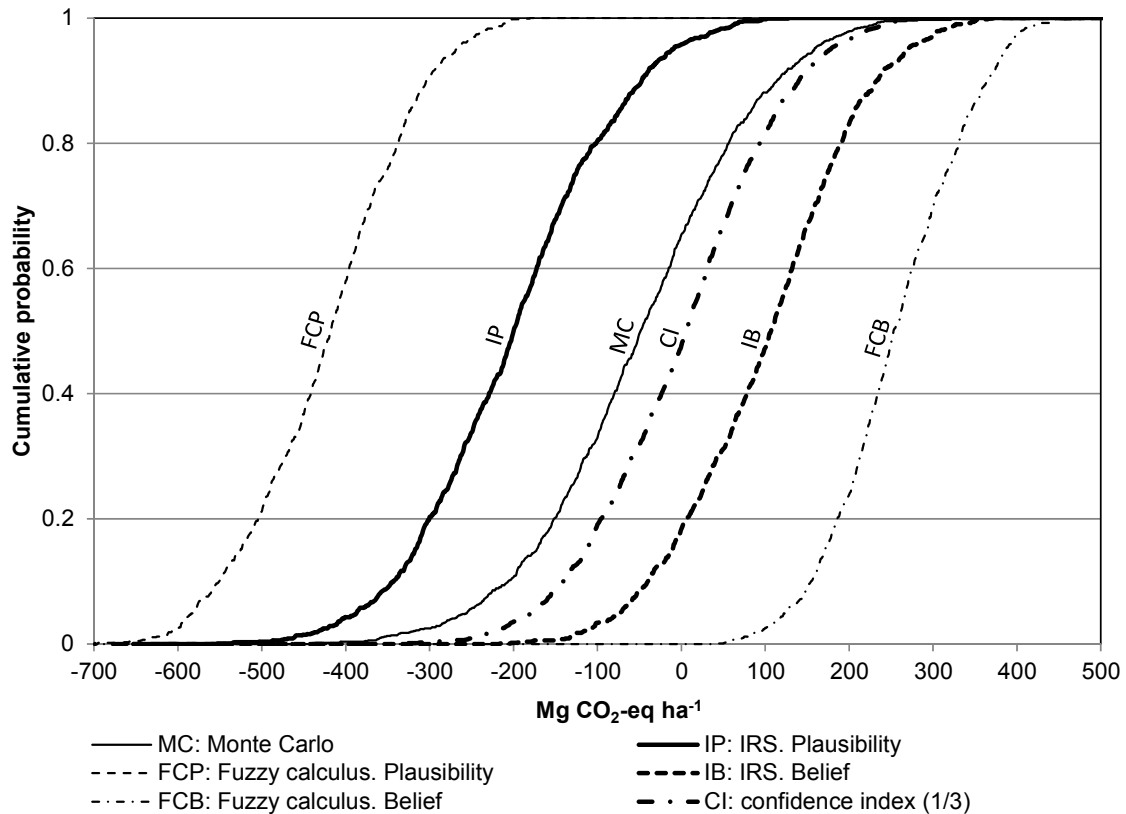
Figure 6. Cumulative distribution functions of greenhouse gas emissions from the cultivation and co-combustion of willow (in Mg CO_2-eq ha^{-1}) obtained from three uncertainty propagation methods: Monte Carlo, fuzzy calculus and IRS method (1,000 runs) (from Paper **IV**).

Paper **IV** highlighted the fundamental difference between imprecise information and precise variability and proved that they should ideally be represented by possibilistic and probabilistic distributions, respectively. The investigation also showed that a joint propagation was possible in an LCA study. The uncertainty obtained was found to be larger than the one obtained by Monte Carlo analysis, because a purely probabilistic propagation avoids combinations of extreme values of ranges which are in reality completely plausible when no information is available for some parameters. However, it has been acknowledged that the implementation of such a method in LCA software would require substantial computation power to be able to model more complex systems.

3.5 A TIERED APPROACH FOR UNCERTAINTY ANALYSIS IN WASTE-LCAS

The approach presented in this section is the result of the work in Papers **III** and **IV**. In the first instance, it consisted of testing different uncertainty analysis methods on a case study, in order to understand their specificities and how they could be used in combination. The outcome of this work is presented in Figure 7

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of Paper **III**. The experience of using the method and the work on uncertainty representation led to adjustments to the method. Indeed, it was realised that step 4 was greatly appreciated by decision makers, and as it did not directly require results from steps 2 and 3, a bypass from step 1 to step 4 was added in the case of limited resources. Additionally, an important outcome of uncertainty analysis lies in the identification of needs for refined data collection, which has been added to the general method. The final recommended method is presented in Figure 7.
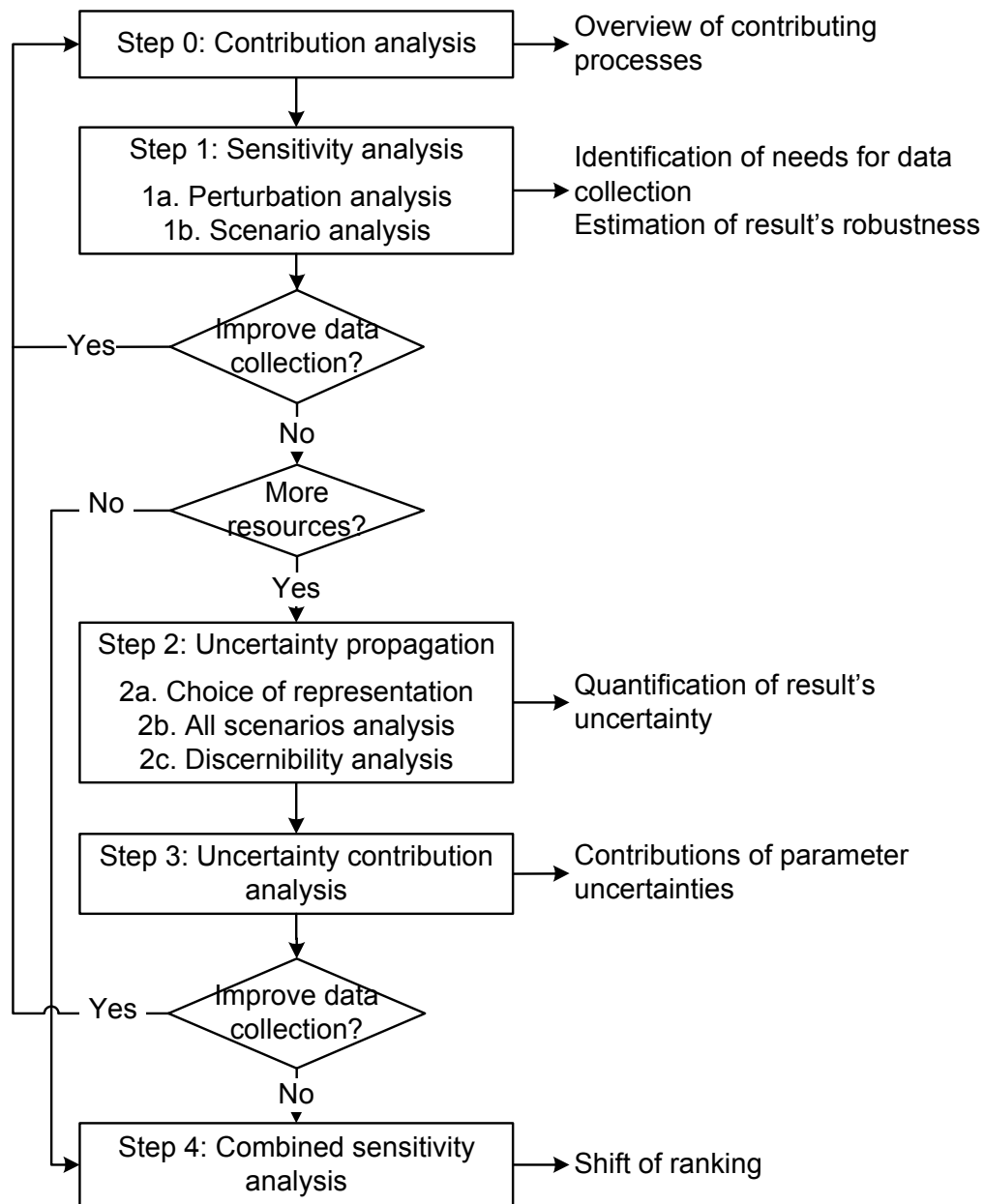
Figure 7. A sequential approach for uncertainty analysis.

3.5.1 PRESENTATION OF THE METHOD

The suggested method is a tiered approach developed to fit the specific characteristics of LCA modelling:

- LCA results usually consist of many impact categories and many processes.

- LCA modelling is, in general, relatively linear.

- Practitioners are limited in time and resources for data collection and propagation algorithm implementations.

- Results should be easy to communicate to decision makers.

The approach involves four consecutive steps where the results from one step are used in the subsequent step. The objective is that each step should produce a communicable result so that the method can always be used partially. The method starts by investigating all impact category results at Step 0. Step 1 is a sensitivity analysis step whereby parameters are tested by perturbation analysis and scenario uncertainties by scenario analysis. Only parameters appearing as sensitive in Step 1 are included in step 2. Indeed, steps 0 and 1 do not require extra software tools nor data collection, while uncertainty data are required in step 2, as well as a propagation tool. Step 3 consists of quantifying the contribution of each parameter to the overall uncertainty. Finally, step 4 involves observing the shift of ranking between scenarios when varying two parameters.

3.5.2 CONTRIBUTION ANALYSIS

This method details the contributions of all processes to the total impact obtained for each impact category and whenever a process has both beneficial and detrimental impacts to split them. This preliminary step might appear superficial, but it is actually a crucial step because it will limit investigations at Step 1 to the processes and impact categories that contribute the most.

3.5.3 SENSITIVITY ANALYSIS

In most cases, a good sensitivity analysis provides sufficient information for the uncertainty analysis. To illustrate this point, a case study is used which quantifies the impacts of applying digestate on Danish agricultural land on nutrient enrichment (by the EDIP97 impact assessment method). Different scenarios were modelled, which tested:

- Two types of soils: clay and soil.

- Two types of climate: western and eastern Denmark.

- Three substitution rates of applied nitrogen: 30%, 40% and 50%.

- Time horizon of inventory between 1 and 100 years.

The results, presented in Figure 8, show the high sensitivity of the impacts to the type of soil (impacts 3 to 5 times higher for clay soils) and moderate sensitivities to substitution rates (a 40% increase between two scenarios) and the climate (a 20% increase in eastern Denmark). It was also observed that after 20 years, impacts remained almost constant. In this case major uncertainty contributors were identified through a simple scenario analysis, which was sufficient to inform the decision maker of the need to choose carefully the type of soil for the application of processed waste.

3.5.4 UNCERTAINTY PROPAGATION

Step 2 consists of selecting a representation for the uncertainty of all selected parameters based on available information, propagating uncertainties through the model via adapted methods and then interpreting the results. In the case of probability distributions, it is advised to propagate via Monte Carlo analysis, as exemplified in Paper **III**. A propagation tool has been implemented, for example, in EASETECH (see Section 4.4). When only scarce information is available, modellers can choose fuzzy sets and use the IRS method presented in Paper **IV**. The applicability of the IRS method is rather limited for now, though, as no propagation tool is available in LCA software; however, if practitioners can
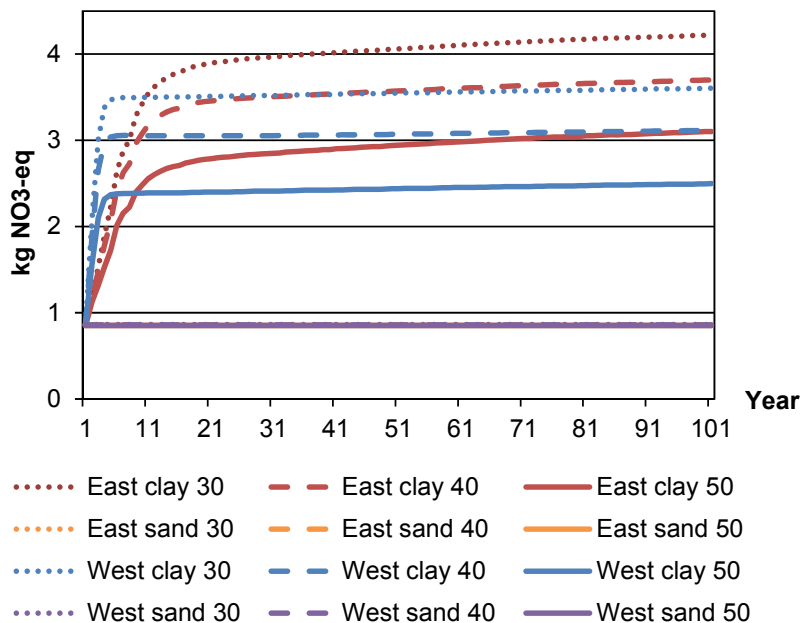
Figure 8. Potential impacts on nutrient enrichment of the 12 scenarios for application of digestate on Danish agricultural land (each line refers to a specific set of conditions, in terms of climate, soil and nitrogen application rate.

express LCA results as functions of their parameters, they can use the MATLAB code of the IRS method provided as supplementary information in Paper **IV**.

One of the most important lessons learnt during this work on uncertainty is the importance of correlations. Indeed, pressing a "Run Monte Carlo analysis" button is rather simple; the real difficulty is to parameterise systems well and to have the right impacts of uncertainty inputs on the outputs. This is related closely to the modelling software used (see Section 3). Furthermore, identifying and representing correlations is complicated, an example of which is provided in the case study used in Paper **IV**, where different impacts of direct land use change were found to be strongly correlated. For example, the cultivation yields of the baseline crop (barley) and the alternative crop (willow) are uncertain, as they are both related closely to various local parameters. In such a case, it is important to model the two parameters as correlated, otherwise the results' uncertainty will appear greater than it is in actuality.

Finally, step 2 is the most costly in terms of data collection needs and calculation tools. It is therefore very important to use the preliminary steps to narrow the scope of step 2 correctly.

3.5.5 UNCERTAINTY CONTRIBUTION ANALYSIS

Paper **III** provides a simplified calculation to determine the contribution of each parameter to the total uncertainty. This method can only be applied in the case of fully probabilistic uncertainty propagation. In the case of fuzzy sets, a direct identification is advised by implementing the fuzzy sets separately. Once steps 1 and 2 have been performed, step 3 is relatively inexpensive and provides useful information.

3.5.6 COMBINED SENSITIVITY ANALYSIS

This method involves depicting the shift of ranking between scenarios when two parameters vary. An example is presented in Figure 9. To produce this result, the difference between two scenarios has to be calculated with different sets of values for the two parameters. Contour lines can then be plotted at several levels, e.g. every 50 kg CO_2-eq / tonne, as seen in Figure 9. As this sensitivity analysis method can be applied without additional data and tools, it is suggested to perform it directly after Step 1 if no further resource is available for uncertainty propagation.
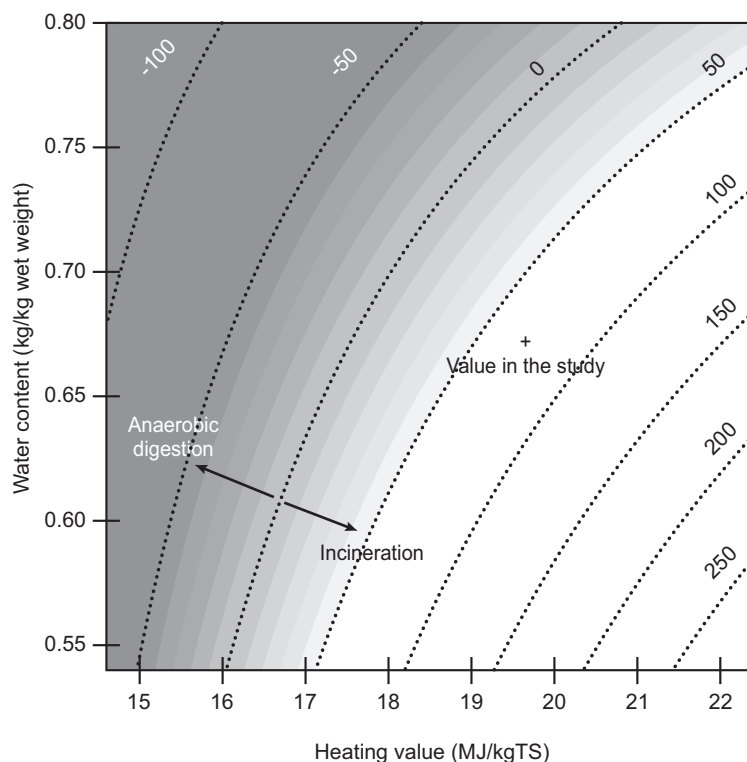
Figure 9. Contour lines of the difference between the two scenarios' global warming factors (in kg CO$_2$-eq / tonne) with two parameters' variations. The bottom-right area shows the conditions where incineration should be preferred, while in the top-left anaerobic digestion should be favoured (from Paper **III**).

3.5.7 BENEFITS AND LIMITATIONS OF THE METHOD

The method fits well with the constraints of LCA practitioners, in that it is realistic in terms of resource needs, it is scientifically rigorous, it can be adapted to the complexity of LCA and it is focused on the communication of useful results. Finally the choice of the methods and the underlying assumptions have been justified and explained in detail, which enables direct usability.

To help waste-LCA practitioners, an appropriate tool is needed that enables such modelling and implementation of uncertainty tools.

4 DEVELOPMENT OF A FLEXIBLE PROCESS-BASED LCA MODEL

As explained in the introduction, restructuring the EASEWASTE model was required, in order to keep its better points (the scenario flow modelling, the LCI modelling of waste technologies and the useful features that have been added over the years) while allowing for more flexibility, new features and better import/export facilities. This section first presents the overall development process of the EASETECH (Environmental Assessment System for Environmental TECHnologies) model, which occurred between January 2010 and June 2013, and then establishes how specific waste management challenges have been answered, how flexibility has been implemented in the EASETECH model and finally which tools are offered for uncertainty analysis purposes. A detailed description of the developed software is presented in Paper **V** and its supplementary material.

4.1 THE DEVELOPMENT PROCESS

The development process started by analysing current experience with the use of EASEWASTE with respect to how the tool was applied, user flexibility, input/output needs, etc. Then the mathematical structure of each technology module was analysed in order to identify common features and differences in the existing model (EASEWASTE). From July 2010 a prototype started being designed with a focus on defining process modelling and the conceptual model of the future system. The implementation was followed by several cycles of testing and design readjustment, after which the actual implementation of the EASETECH model took place by following an agile software development method which divided software requirements into small incremental items to be implemented and tested immediately after implementation. In this subsection, four important aspects of the development were developed: requirement definitions, process modelling design, user responsibility in modelling and the general structure of the model.

4.1.1 DEFINING REQUIREMENTS FOR A NEW WASTE-LCA TOOL

The objectives for the new LCA tool were to implement the same general concepts as EASEWASTE but in a more flexible environment. The software should first be able to cope with waste management specificities in a way at least as good as the EASEWASTE model and incorporate:

- Generation of waste as a list of fractions characterised in many properties.

- Specific handling of waste fractions in processes (e.g. collection systems).

- Tracking of substances over the entire WMS.

- Modelling of specific treatment technologies (e.g. landfilling, use on land, anaerobic digestion).

In addition, it was understood that the framework to be developed could be useful in other environmental fields, due to similar needs in terms of LCI modelling. For example, energy systems and wastewater treatment often involve heterogeneous material flows, whose modelling also requires a definition of multiple material fractions (e.g. several fuels) with specific parameters. Therefore, close collaboration took place with different actors in these fields, to ensure proper feature development in the current and future versions of the EASETECH model.

Targeting the user group is a crucial step in the development of new software products. EASETECH is intended for use by a trained public consisting of researchers and consultants. This choice implies that the design allows as much freedom as possible (e.g. modelling of processes which are not physically possible is allowed) and that more efforts have been given to advanced functionalities (e.g. uncertainty analysis tools) than to some graphical functions (e.g. displaying LCA results). Users are invited to use the advanced functions offered by software such as Excel until such functionalities are implemented in EASETECH.

Other features that were important to implement in the new framework include uncertainty analysis methods (as explained in Section 3) and compatibility with other LCA software suites and databases, to ensure the safe import and export of datasets and the inclusion of LCIA methods. Finally, this restructuring represented a good opportunity to make the process of scenario construction more intuitive and the graphical user interface (GUI) more user-friendly.

4.1.2 PROCESS MODELLING

This phase began with a thorough analysis of the EASEWASTE model, i.e. its general structure, strengths and weaknesses. One of the key features of EASEWASTE compared to other LCA software was that it offered to its users a library of waste treatment technologies that they could adapt to their own parameters. EASEWASTE provided 14 technologies (in addition to waste generation and waste sorting) which had been developed over time. Sometimes newly developed processes reused part of the code of a former process, but in general each process had its own design and purpose. The objective of EASETECH was to build a more generic model that would allow for applications

in other areas and more flexibility in the construction of new technologies. Consequently, the work began by analysing all of the processes, in order to identify their core transfer functions and the particular LCI calculations they hold. This task involved going from concrete technologies to more abstract ones, so that core functionalities could be combined to model any possible future technology.

When investigating all EASEWASTE processes, common patterns were identified, such as:

- Most processes allowed for the use of external processes and for process-specific emissions (i.e. emissions per tonne of waste input).

- Collection and transport processes had the same material transfer function (input = output), which was called "Basic" process.

- Waste source-sorting and material recovery facilities (MRF) had the same material transfer function consisting of transferring full masses of waste fractions to different bins or outputs. This was called "Mass transfer to outputs".

- The process of composting could be modelled easily as a transfer of biogenic carbon and nitrogen of degradable waste fractions to an output called "Degraded matter". This material transfer function then became very similar to that of incineration, which also consists of transferring substances of material fractions to different outputs or environmental compartments. This was called "Substance transfer per fractions".

- Several processes, such as incineration or anaerobic digestion, offered the possibility to adjust the water content of their outputs, as these were determined by external parameters. This function was isolated and called "Water content".

- Several technologies, such as anaerobic digestion and mixed waste landfilling, included the same sub-module for gas utilisation. In order to be able to use it in various places, it was decided to split gas generation from its utilisation. This meant that gas became a material flow that could be brought to any process; the same was decided for leachate.

- The landfilling of mixed waste differed from the landfilling of mineral waste, but only by the inclusion of biogas generation, so it was decided to consider it as a separate process.

- Leaching was used in both landfill technologies, but also in the use of processed waste in road construction. As such, it was decided to make it a separate process.

Finally, 14 processes identified from the 16 EASEWASTE waste technologies were referred to as process templates because they can be used to model particular technologies or be combined with other templates. Later, three more templates were added: an energy generation process to fit with energy systems modellers' needs and two alternative data inputs for the processes "Material generation" and "Substance transfer". All templates are presented in Table 3. An example of how mixed waste landfilling is modelled is illustrated in Figure 10, while other examples of how EASEWASTE technologies can be modelled in EASETECH are provided in Paper **V**.

The choice was to have all flows designed in the same structure so that the output of any process could become the input of any other, thus adding a great deal of flexibility into scenario construction. This also added some difficulties because different flows have very different properties and contain different substances (e.g. waste vs. gas). Therefore, special features were added to the material properties catalogue, in order to allow for the selection of the substance one wants to include in the assessment and to select which substances should be displayed when asking for the composition of a waste flow or gas flow.
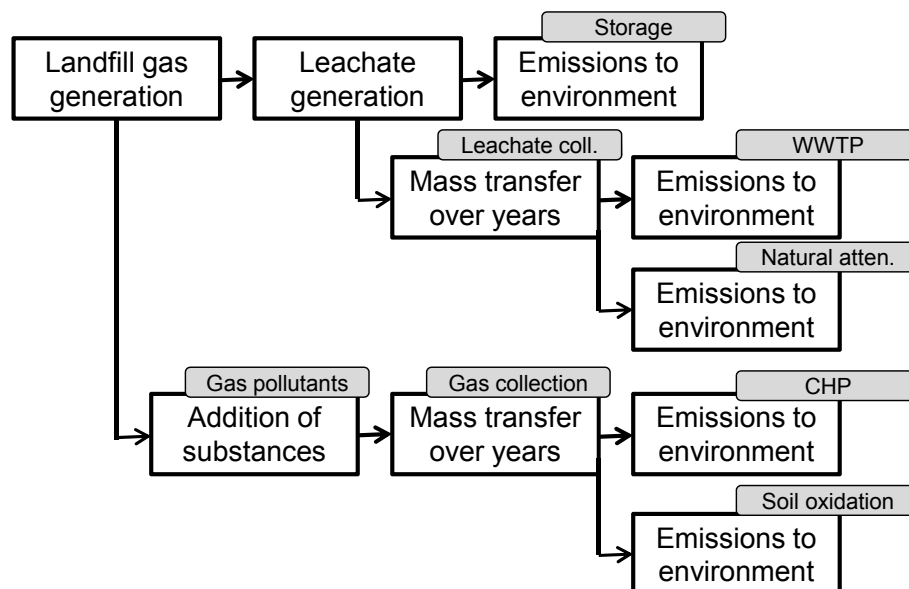
Figure 10. Modelling of landfilling in the EASETECH model. Each box is an independent module. Grey boxes are explanations of actual processes (from Paper **V**).

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Table 3. Overview of all templates available in EASETECH version 1.0 (from Paper **V**).

Template name	Description	Material transfer function in flow calculation layer	Input-specific emissions added to the LCI calculation layer *
Material generation	Create a material flow (two possible data input methods: using a library of material fractions or direct input)	Start	Upstream impacts can be included
Energy generation	Create an energy flow (with associated mass and substances)	Start	Upstream impacts can be included
Basic process	Keep the flow unchanged	Equal	-
Water content	Modify the water content of the input flow	Modify	-
Change of energy content	Modify the energy content of the input flow	Modify	-
Addition of substances	Add substances to the input flow	Modify	-
Mass transfer	Split the input flow according to total mass	Split	-
Substance transfer	Split the input flow according to different properties (two possible data inputs: fraction specific or default)	Split	Possible emissions of substances to environment compartments
Mass transfer over years	Split the input flow according to years	Split	-
Anaerobic digestion	Produce a gas and a digestate out of an anaerobic digester	Specific	-
Landfill gas generation	Degrade organic matter according to exponential first order decay, creating a landfill gas and remaining waste	Specific	-
Leachate generation	Define leachate generation and remaining waste	Specific	-
Use on land	Distribute C, N and P from input flow and create an avoided flow	Specific	Emissions of C, N and P compounds to air, water and soil compartments
No output	Has no output	End	-
Emissions to the environment	Translates input flow into release to an environmental compartment	End	Emissions of substances to environment compartments

*: All templates have basic process exchanges (elementary exchanges and external process use) contributing to the material process's LCI.

Another difficulty was having landfill gas as a flow and keeping the feature of EASEWASTE that showed gas composition over years. In fact, as flows in EASETECH were already a two-dimensional matrix of material fractions and material properties, adding a third dimension of year fractions would have become very expensive in terms of calculation speed. Therefore, a compromise was found whereby whenever a flow was specified in time (by "year fractions") it would lose its material fractions. This implies that it is not possible to track back the origin of the biogas's methane content in terms of waste fraction, which was considered a minor loss.

4.1.3 USER RESPONSIBILITY

Experience with the EASEWASTE model highlighted the need to pay attention to the role a model gives to its users. Indeed, by providing hard-coded functions in several processes, the EASEWASTE model exposed itself to the risk of users thinking that the provided model was a magic black box that would calculate everything automatically. In several ways, EASETECH places more responsibility onto the user because:

- By choosing to have more generic modules, the user needs to think more about how to model his/her process and realise his/her assumptions (however, the software is accompanied by a database which contains a number of predefined treatment technologies).

- By having a clear view over the full WMS, the user realises unconnected flows more easily.

- By using the catalogue of material properties, the user chooses which substance will be included in the impact assessment.

- By actively declaring the probability distribution of each parameter, the user realises his/her assumptions in the Monte Carlo analysis (see Section 4.4).

4.1.4 EASETECH STRUCTURE

EASETECH's structure is the result of many iterations of the design-implementation-test cycle. It can be visualised in terms of GUI in Figure 6 of Paper **V**. The idea was to gather in "catalogues" any data which did not need to be edited very often by the user, i.e. material fractions, elementary exchanges, impact categories, LCIA methods, interfaces, constants and material properties. All material processes are stored in a "library", as well as all external processes and scenarios. Finally, the main window serves as a graphical tool to build scenarios, while the bottom-right area is where all data input is performed and all results are visualised.

Figure 11 presents the organisation between the different data storage places and how information is pulled from these different catalogues and libraries to build scenarios and assess them using various LCIA methods. Examples of elements in each catalogue are given for the sake of clarity, while the calculation process is explained in more detail in Figure 12. Figure 12 presents the three types of data material processes have and when they are used in the calculation process. The first layer involves calculation of all flows throughout the scenario and uses therefore only "Material transfer" data of the different material processes. In the

LCI layer, all calculated flow compositions are used, as well as the "Process exchanges" data and potential additional emissions originating from the "Material transfer" data of specific material processes (see Table 3). Finally the characterisation, normalisation and weighting layers apply LCIA methods on results from the LCI layer. The main difference between this model and other LCA tools lies in the first calculation layer, called the "flow layer", where all flow compositions are calculated prior to any LCA calculation.

4.2 A TOOL ADAPTED TO WASTE-LCA SPECIFICITIES

EASETECH has been designed particularly for waste-LCA, and thus it provides an answer to each waste-LCA-specific need.

4.2.1 GENERATION OF WASTE AS A LIST OF FRACTIONS

In EASETECH, waste flows are created via a process called "Material generation", which uses material fractions that are pulled from a catalogue. This catalogue contains approximately 70 material fractions in EASETECH version 1 and the user can add as many as needed. The flow is shown as a matrix of material fractions with different material properties.

4.2.2 TRACKING OF SUBSTANCES OVER THE ENTIRE WMS

Flows can be tracked all over the WMS by selecting them or by using a Sankey diagram tool. In Sankey diagrams, each flow's width is proportional to its total mass or to its content in the selected substance.

4.2.3 MODELLING OF PROCESSES BASED ON MATERIAL FRACTIONS

Processes such as source-sorting or incineration allow for the specification of transfer coefficients (TCs) to various outputs or environmental compartments. These TCs can be defined for each material fraction, while a default behaviour is always included.

4.2.4 MODELLING OF INPUT AND PROCESS SPECIFIC EMISSIONS

Emissions occurring in the "Material transfer" tab are labelled "input-specific" because they originate directly from the use of transfer coefficients. On the contrary, emissions occurring in the "Process exchange" tab are always labelled "process-specific". It was originally only possible to relate these emissions to the total amount, hence their name. However, in EASETECH, it is now possible to relate them to any material property; for example, an emission of carbon dioxide into the air can be related to the content of fossil carbon in the treated waste.
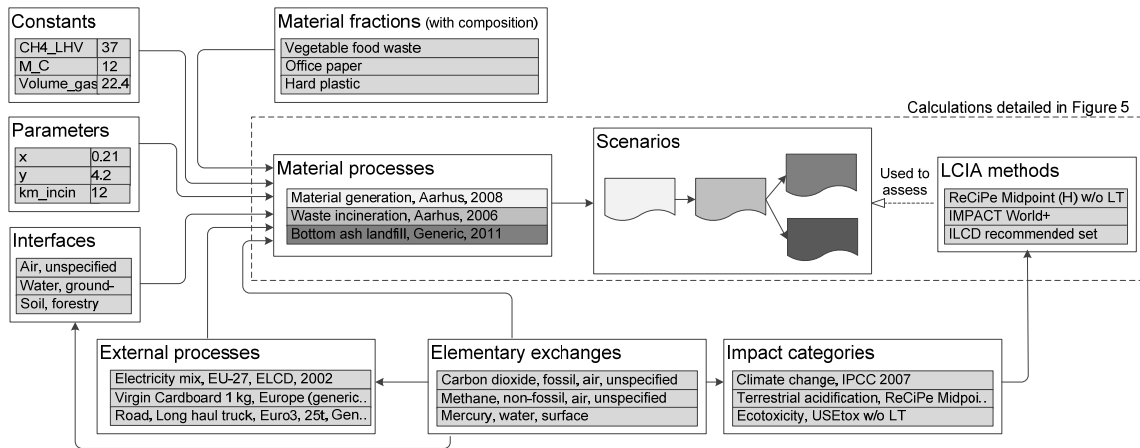
Figure 11. Interactions between the different data catalogues. An arrow going from box A to box B indicates that an element in catalogue A can be used in an element in catalogue B. Examples from the database are given in each box in the table (from Paper **V**).
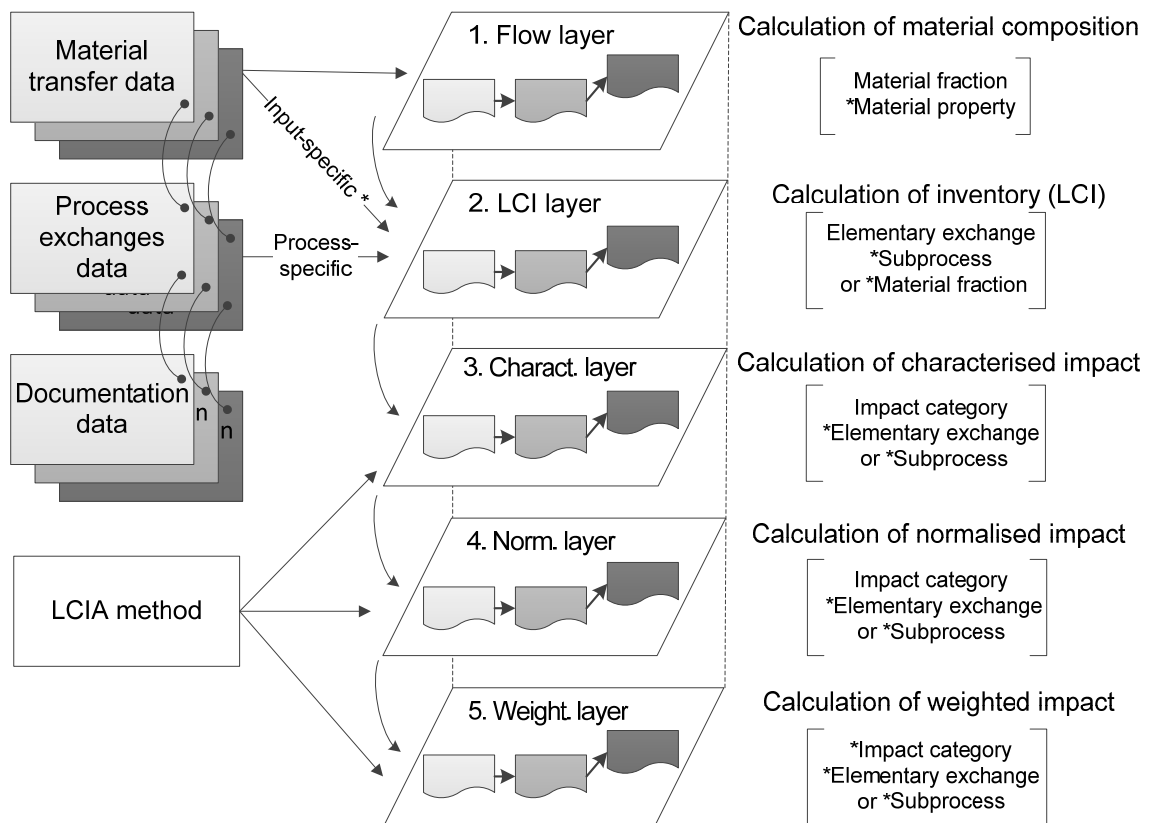
Figure 12. Data and calculations in the different results' layers. Arrows show the flows of information needed for calculations. The different layers represent parallel calculations.* Input-specific emissions are specific to each of these material process templates: substance transfer, emissions to the environment and use-on-land (from Paper **V**).

4.2.5 MODELLING OF LANDFILL GAS GENERATION

A first-order decay approach was adopted for landfill gas generation modelling (IPCC, 2006 and Cruz and Barlaz, 2010). For each material fraction, the user specifies decay rates for the degradation of biodegradable organic matter. Default decay rates from Cruz and Barlaz (2010) are provided.

4.2.6 MODELLING OF USE-ON-LAND (UOL)

UOL has been programmed in a more generic way, in that the user can now choose to model it as a combination of two UOL processes (direct and avoided impacts) or as the difference between the two scenarios as modelled in EASEWASTE.

4.2.7 LCI TIME SCOPE

Both landfilling and use-on-land of waste induce long-term emissions. As illustrated in 3.5.2, the choice of time horizon for LCI modelling is of significant importance; therefore the possibility of changing the time horizon of the LCI was implemented in EASETECH. In landfill gas and leachate generation, the user can specify the number of years to be included, with a default value of 100 years.

4.2.8 ZERO BURDEN ASSUMPTION

In waste-LCA, a zero burden assumption is often taken, meaning that all impacts from the production and use of goods before their disposal are excluded from the study. However, their inclusion can be required in certain cases, typically for the assessment of waste prevention strategies. Therefore, it is possible to include these upstream impacts in the material generation process of the EASETECH model.

4.3 A FLEXIBLE TOOL FOR WASTE-LCA

The concept of flexibility can be defined in different ways, and in this case it refers to the adaptability of a software product to future changes in requirements. Several examples are presented to illustrate EASETECH's flexibility:

1. The toolbox of processes enables the user to model many existing and future technologies. Waste management technologies are modelled as combinations of basic processes.

2. Emissions can be written as formulas using constants and parameters. Hard-coded equations for LCI emissions are avoided as much as possible.

3. The development of the software enables the easy addition of new processes in the toolbox and therefore in the whole framework.

4. The building of scenarios is flexible because any process in the library can be linked to any other process.

These decisions mean that the EASETECH model will be useable in many different applications in the future. On the other hand, the software is provided with some technologies which enable an easy and fast grasp of the basic features of EASETECH already implemented, in order to remain accessible while enabling complex modelling.

4.4 IMPLEMENTING UNCERTAINTY ANALYSIS TOOLS

The objectives of implementing uncertainty analysis tools in EASETECH were to be able to test both lists of values and probability distributions for the needs of sensitivity analysis and uncertainty propagation, respectively. It was decided to base the uncertainty analysis tools on using parameters in all data input fields. These parameters have to be declared first in the table of parameters attached to each scenario. In this table the user needs to provide a default value (to be used when the calculations are running in "normal mode", i.e. without uncertainty analysis) and to specify either a list of numbers (separated by commas) or a distribution (with its characteristics, e.g. mean and standard deviation for normal distributions).

When lists of numbers are used for all parameters, they are propagated along the calculations and a list of numbers of the same count is obtained in all result fields. When probability distributions are used, the program propagates the computations through Monte Carlo analysis, i.e. values are sampled in the distribution of each parameter and propagated as a list of numbers. The results represent a distribution from which important parameters can be extracted, such as the mean or the 95% confidence interval.

The obligation to declare each parameter means that currently the user cannot ask for an automatic propagation of all uncertainty information contained therein (e.g. as in the ecoinvent database). Nevertheless, this also emphasises the responsibility of the modeller to control his/her assumptions, because having to specify each distribution one by one makes the modeller think about the probability distributions he/she is using as inputs into the Monte Carlo simulation.

5 LCA OF WASTEWATER AND SLUDGE TREATMENT USING THE EASETECH MODEL

The objective of this work was to use the newly developed EASETECH model on a different type of system to what it had been initially designed for and then to evaluate its flexibility. This also presented a chance to show how the model can be used in a practical setting using data measured in the field.

The objective of the whole case study was to evaluate environmental impacts deriving from the treatment of wastewater, including sludge incineration, in a specific plant in Denmark. The first part of the project consisted of an extensive measurement campaign where samples of water and sludge were taken from 12 places in the plant. Monitoring certain emissions and energy and chemical consumption also happens routinely at the plant, in order to optimise operations and apply regulations. Thus, a lot of different data were taken to allow for the most accurate environmental assessment possible. In a second step, MFA/SFA was performed with the STAN software package, to map all substances through the plant, close mass balances and calculate reconciled standard errors. All results from this preliminary work are presented in Yoshida et al. (n.d.).

In the third step, a model of the whole plant was implemented in the EASETECH model. Modelling wastewater treatment is similar to modelling solid waste management in many ways; for example, flows of many substances need to be tracked through different processes. Moreover, several processes from solid waste management can be used for the purpose of sludge treatment. However, some dissimilarities exist, namely some specific substances need to be added (e.g. DEHP and LAS), there are no material fractions as such, as the flows are almost perfectly mixed, and some flows are sent back to upstream processes, which is rather uncommon in waste management.

Different adjustments were required to model the wastewater treatment plant in EASETECH:

- The WWTP process was modelled using the "Substance transfer – default", template as preliminary work included MFA/SFA of the system and transfer coefficients could be calculated.

- The WWTP had three different output flows in addition to the effluent: fats, oils and grease (FOG), primary sludge (PS) and secondary sludge (SS). In the plant, these three flows are mixed before entering the dewatering process. Therefore, a new process was required to model the

mixing of flows, but as it was not developed at the time of the modelling, the three flows were considered as a mixed output from the WWTP.

- Reject water from the dewatering process is sent back to the beginning of the WWTP; however, flow loops are not allowed in EASETECH because current calculation procedures do not include equation solving for finding equilibrium in flows, unlike MFA tools. Nonetheless, the backflow was modelled by copying the WWTP process, as presented in Figure 12.

Figure 13 presents the final modelling of the full plant, which starts from the reference flow, i.e. a tonne of wastewater entering the system, and is followed by the WWTP, anaerobic digestion, gas utilisation, dewatering, incineration of sludge and landfilling of ashes processes. All modelling details are provided in Paper **VI** and its supplementary information.

Normalised impacts for the full system, applying ILCD recommended methods for LCIA, are presented in Figure 14. The figure also shows the contribution of the different processes to the net total.
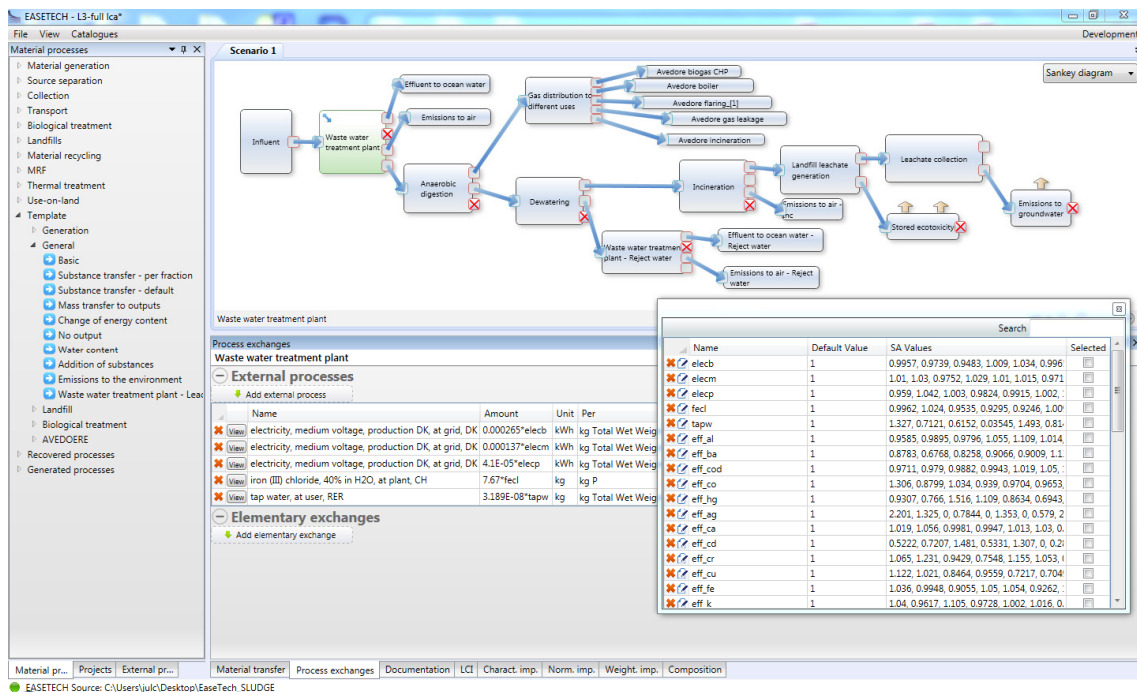
Figure 13. Modelling of the whole waste water and sludge treatment plant in the EASETECH model. The top right window shows all connected processes, the bottom right window presents the use of material and energy in the selected process (called "waste water treatment plant"), the pop-up window indicates all the parameters used in the scenario (name, default value and sensitivity analysis' list of values).
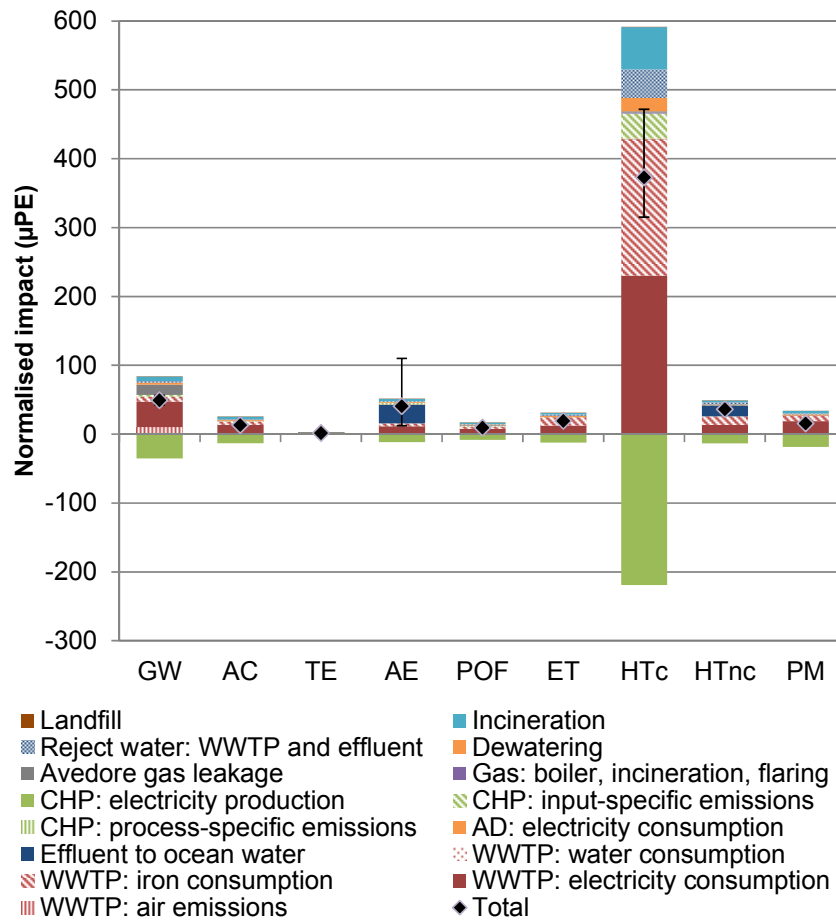
Figure 14. Normalised impacts for the whole WWTP plant, for the treatment of one tonne of waste water. Net totals are presented with 95% confidence intervals (adapted from Paper **VI**).

In order to evaluate the uncertainty of these results, all plant-specific parameters were associated with uncertainty. Standard errors were calculated based on the measurement campaign results, then reconciled using the MFA tool STAN, wherein normal distributions are assumed, and finally input into EASETECH. As the direct input of uncertainty distributions was not possible at the time of this study, a thousand values were sampled randomly using an Excel-based tool which gives lists of comma-separated numbers randomly sampled in any desired uncertainty distribution. These lists of 1,000 numbers were then input easily into the EASETECH model for 60 parameters, as presented in Figure 13. Figure 14 presents the 95% confidence intervals of the net total obtained in all impact categories.

During the modelling process, the main difficulty was establishing how to relate the measured emissions to the right input parameters, so that future variations in parameter values would prompt the right variations in the output results. Indeed, life cycle modelling needs to assess fully and only the effects of the reference

flow. LCA is a forward modelling exercise where, for example, in a single process, the user enters inflow composition (with uncertainty range) and transfer coefficients (also with uncertainty range) so that the system computes emissions. However, in the field one can only measure inflow and outflow compositions (both with uncertainty ranges) and deduct a transfer coefficient for each substance and its uncertainty range. It would not be correct to directly use the uncertainty of the inflow composition and the uncertainty of the transfer coefficient, because this would lead to an artificially high uncertainty regarding outflow composition. To solve this problem, transfer coefficients were calculated as fixed values and the reconciled uncertainty of the outflow composition (calculated by STAN) was input as an output flow variation. This uncertainty combines the variability of the data, the uncertainties of the sampling process and one of the reconciliation processes.

The implementation of the full system did not present any great difficulties, while the facilitated input of lists of numbers made the testing of all parameters very systematic and a Tornado diagram was produced rapidly. Immediately after this case study, new functionalities were implemented which enable the direct input of probability distributions (e.g. "ND(10,2) for a normal distribution of mean 10 and standard deviation 2), which would make the modelling even faster.

6 CONCLUSIONS

6.1 ACHIEVEMENTS OF THE DOCTORAL WORK

A review was carried out on all LCA studies of waste management systems published before mid-2012. This provided a global overview of the technologies and waste fractions which have attracted focus within the industry while enabling an analysis of methodological tendencies, the use of tools and databases and the application of uncertainty analysis methods.

Additionally, all uncertainties usually encountered in waste-LCAs were identified and described thoroughly, with the intention of guiding LCA practitioners in the screening of sources of uncertainty.

An insight into uncertainty representation was presented by comparing in a case study the propagation of probability distributions and fuzzy sets. A method was suggested whereby the practitioner is invited to choose one of the two representation types for each parameter, based on the level of information available, and to propagate jointly all parameter uncertainties.

To guide practitioners in the process of uncertainty analysis, a tiered approach was developed which adapts the objectives to available resources. Each proposed step produces results which narrow the scope of the following step while producing communicable results for decision makers. This method permits an analysis of the system at different scopes, from the largest picture with all processes and impact categories to a more detailed analysis of the reasons and probability for a shift in rankings between scenarios.

The framework of a new LCA model was developed, with a focus on the modularity of processes, each of them designed for specific transfer functions of input flows to outputs and environmental compartments. This newly developed software allows for the modelling of complex systems in a transparent and flexible way while keeping track of flows defined as a matrix of fractions and properties. At the same time, all classical LCA calculation functions were implemented, as well as import functions from external databases, and tools to apply the tiered approach for uncertainty analysis described above.

Three case studies were used throughout the work to exemplify (1) the issue of uncertainty representation, (2) the tiered approach for uncertainty analysis and (3) the use of the EASETECH model with an extensive measurement campaign.

6.2 How does one build a good LCA tool?

The experience of developing the EASETECH model highlighted major steps in the design of a good LCA tool:

- **Positioning**: defining software requirements is the most important step in the development process. The challenge is to know what core novelty of the tool to develop and to identify which features are needed and what will not be implemented. A good tool cannot do everything well, but it does need to be good at what it was designed for. For example, the EASETECH model does not do MFA because other tools perform it well already and they can be used in parallel. Also, the EASETECH model does not aim at importing full networks of external processes (e.g. electricity consumption) from the ecoinvent database because other LCA tools already offer this feature. EASETECH is specialised in the modelling of systems that handle complex flows of materials, which ic typical within environmental technologies.

- **User friendliness**: a clear structure of the different parts of the software is required, which will help the user understand the logic of the modelling tool and ensure transparency. In EASETECH, all processes are built the same way and the different input fields and result tables are clearly identified.

- **User responsibility**: the design of the tool should make the user aware of his/her responsibility in the modelling process. In the EASETECH model, a first example is that fewer calculations are hard-coded, while a second one is that uncertainty distributions need to be entered manually.

- **Compatibility**: the data format should allow easy import and export of data from/to other software and databases.

- **Flexibility**: it is important to develop a flexible structure that will allow for new developments in the future according to new needs.

All these aspects are particularly important to take into account, not only in the planning phase but also throughout the iterative development process, as the perspective on the tool evolves over time through user needs, the implementation of features and their testing and user feedbacks. This is ably demonstrated by the Agile software development methods used during EASETECH development.

6.3 FUTURE PERSPECTIVES

The work revealed the need for further research, especially:

- More focus on waste streams other than municipal solid waste and on different technologies such as waste refineries and lower-tech solutions applied in developing countries, to increase the EASETECH database and the usefulness of applying the software in these areas.

- More application of the tiered approach for uncertainty analysis, to demonstrate the different levels of details which can be achieved depending on available resources.

- The implementation of the joint propagation method in an LCA tool, to measure the computation time on larger systems and to have the method tested and evaluated by more practitioners.

Planned improvements in the EASETECH model are numerous and include:

- Consideration of economic impacts.

- Improvement of the graphical display of results, including results from uncertainty analysis and a comparison between scenarios.

- Design of new process templates, for example one to merge several input flows into one output. The need for new processes will also come from the application of EASETECH to different fields, e.g. energy systems or water treatment.

- Development of an external editor to give advanced users the chance to design new process templates with specific transfer functions.

- Development of new functionalities for impact assessment. While the focus has been placed on LCI so far, effort will be applied to the impact assessment side in the future, to include recent developments, e.g. in the regionalisation of impacts, their time-dependency and the quantification of uncertainties related to this step.

- Many small improvements are also planned to make the use of the software easier.

- Finally, the development of the database is a crucial aspect and facilities could be implemented to facilitate the submission of data by users to the database administrator.

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8 PAPERS

The following papers are included in the thesis:

I.   Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H.: Review of LCA applications to solid waste management systems – Part I: Key learnings and perspectives. Submitted to Waste Management.

II.   Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H.: Review of LCA applications to solid waste management systems – Part II: Methodological guidance for a better practice. Submitted to Waste Management.

III.   Clavreul, J., Guyonnet, D., Christensen, T.H.: Quantifying uncertainty in LCA-modelling of waste management systems. Waste Management, 32, 2482-2495, 2012.

IV.   Clavreul, J., Guyonnet, D., Tonini, D., Christensen, T.H.: Stochastic and epistemic uncertainty propagation. International Journal of Life Cycle Assessment, DOI 10.1007/s11367-013-0572-6. Published online April 2013.

V.   Clavreul, J., Baumeister, H., Christensen, T.H., Damgaard, A.: EASETECH, an Environmental Assessment System for Environmental TECHnologies. Submitted to Environmental Modelling and Software.

VI.   Yoshida, H., Clavreul, J., Christensen T.H., Scheutz, C.: Influence of data collection schemes on Life Cycle Assessment: the case of a municipal wastewater treatment plant. Manuscript.

In this online version of the thesis, the papers 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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