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Application of LCA modelling in integrated waste management

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Abstract

Life cycle assessment (LCA) has been used in waste management for the last two decades and hundreds of journal papers have been published. The use of LCA in waste management has provided a much-improved holistic view of waste management including waste flows and potential environmental impacts. Although much knowledge has been obtained from LCA studies, there is still a need to use LCA models in integrated waste management. This paper describes six areas where LCA is expected to play a role in waste management in the future: 1) understanding an existing waste management system; 2) improving existing waste management systems; 3) comparing alternative technologies/ technology performance; 4) technology development/prospective technologies; 5) policy development/strategic development; and 6) reporting. Illustrative examples are provided for each application area.

Keywords

LCA, waste management, modelling

1. Introduction

The first applications of life-cycle-assessment (LCA) models in waste management date back to the late 1990s, and a steep increase in published papers on the topic has been observed from 2010 and on: Laurent et al. (2014a,b) reviewed 222 papers published prior to 2013 and Khandelwal et al. (2019) reviewed 153 papers published since 2013. The introduction of LCA in waste management provided for the first time an analytical framework and a quantitative assessment of our waste management systems including the main flows and potential environmental impacts. In addition, the stringent data needed to perform LCAs stimulated a new and more consistent level of data collection on waste quantities, composition, flows and technology performance. This has contributed to the development of the science and engineering in waste management far beyond the actual LCA results obtained. Clift et al. (2000) and Ekvall et al. (2007) described how LCA can be used to describe and model the waste management system.

Over the past decades LCA results have provided us with information that today is considered common knowledge. For example, results have to a large extent confirmed the basic concepts of the waste hierarchy, but have also demonstrated a lot of complexity on major contributors to emissions and saving to the environment within the waste management system. We also learned that the waste hierarchy is a very coarse and insufficient scale for assessing the environmental aspects of a modern integrated waste management system. The LCA results have taught us many things, for example, that recycling of high quality paper usually is preferable to incineration (e.g. Schmidt et al., 2007), and that gas control and utilization is crucial to the environmental performance of landfills (e.g. Manfredi et al., 2009). Looking to the future, this manuscript addresses areas where LCA can continue to help us in developing waste management systems.

Waste management is challenged by increasing complexity of the waste entering the system and the demand for sustainable solutions that are affordable, protect the climate and contribute to a circular economy. This paper describes where LCA can help in making sound decisions in waste management reflecting the expectations of society. We base our views on the experiences we have obtained in research and consulting during the last 15 years with a perspective to the current challenges of sustainability, climate change and the circular economy. We suggest that waste management LCAs may have a role in six areas: 1) understanding an existing waste management system; 2) improving existing waste management systems; 3) comparing alternative technologies/ technology performance; 4) technology development/ prospective technologies; 5) policy development/ strategic development and 6) reporting. The following section of this manuscript provides a brief introduction to LCA. This is followed by a discussion of each of the six areas listed above.

In presenting the six application areas, we present selected examples from the literature, although this manuscript is not intended to be a critical review as published previously (Laurent et al., 2014a,b; Khandelwal et al., 2019). We do not address LCC (life-cycle-costing) and LCAs based on input-output tables. The categorization of the examples is intended to illustrate the application areas, albeit the original papers used as examples may not have specified their application area and may potentially address several application areas.

2. What is an LCA?

Life Cycle Assessment (LCA) assesses the potential environmental impacts and resources used in a waste management system that includes all of the waste types of interest and considers an integrated system that starts with waste generation and includes transport, treatment and disposal of the various fractions and residues, and exchanges of materials and energy with the surrounding society. The comprehensive scope of a waste management LCA is useful to establish an overview of all flows in the system, avoid neglecting residues and emissions, remember exchanges upstream (e.g. use of materials and energy) as well as downstream (use of recovered materials, energy and nutrients), and recognize the long time horizons associated with landfilling and with the use of residues in construction materials.

There are four phases in an LCA study: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (Finnveden et al., 2009). An extensive guideline is available on how to perform a waste LCA (JRC, 2011).

The Goal and Scope Definition includes the reasons for carrying out the study, the intended application, and the intended use of the results. The Goal and Scope Definition is critical since the appropriate LCA methodology depends on the purpose of the specific study (Consoli et al., 1993; Finnveden et al., 2009). It is also the place where the system boundaries of the study (geography, time, technology, etc.) are described and the functional unit is defined. The functional unit defines the function of a product, a process or a material (e.g., the collection and treatment of 1 metric tonne of solid waste set out at curbside) and includes the reference flow specifying the waste handled (type, amount, composition, time scale, geography, etc.).

The LCI is a compilation of all mass flows and emissions associated with the activities within the waste management system as well as upstream and downstream activities linked to the management of the waste. This includes detailed information about 1) waste types and their individual material fractions and in some cases the detailed physico-chemical composition, 2) mass balances for all relevant material fractions for all processes and technologies, 3) energy budgets for all processes and technologies, 4) emissions for all processes and technologies and 5) inventories of all relevant upstream and downstream processes. Establishing a relevant high-quality LCI is often demanding, but crucial since it establishes the technical basis for assessing the waste management system. Existing models offer some assistance and databases in setting up the LCI, but it is always important to ensure relevance and consistency in the technical data of the specific study.

The LCIA aims at understanding and evaluating the magnitude and significance of the potential environmental impacts of the studied system. The methods of the LCIA for characterizing, aggregating and normalizing the inventory information into common potential impacts (e.g. global warming, acidification, and toxicity) are not specifically developed for waste management but are generally applicable. Recommended impact assessment methods are given in JRC (2011). The normalization provides all quantified impacts in terms of person-equivalents (PE), which refer to the average impact of one citizen in one year from all activities needed to sustain the actual level of living (Benini et al., 2014). Impacts from waste management related to effects of landfills on groundwater and to the long-term emission from landfills (> 100 years) and local issue of odor are not addressed in standard impact assessments and thus often excluded from waste LCA studies.

In the Interpretation phase, the results from the previous phases are evaluated in relation to the goal and scope so to reach conclusions and recommendations. Often results of the first modelling can be incomplete, and two or three iterations are typically needed to obtain a good balance and system coverage between Goal and Scope Definition and the Interpretation. Since LCA modelling includes many approximations and assumptions, and often also insufficient data, sensitivity analysis should always be included, for example identifying critical parameters of the major processes and technologies, and which uncertain data have the most influence on the results. Bisinella et al. (2016) suggests an approach to quantify the uncertainty in waste LCAs. A specific interpretation issue is how to weigh different impact categories showing different patterns in comparative studies; often toxic impacts are given less weight because of the significant methodological uncertainty in the pathway modelling and general characterization.

3. Understanding an existing waste management system (Area 1)

Performing an LCA for the first time on a specific waste management system, a large city or a region, will result in a consistent and documented description of the regions solid waste system, which is often a significant contribution by itself. Specifically, the LCA will provide insight into what matters within the system: what are the main waste and residue flows, where are the environmental loads and where are the environmental savings? If the waste management system is a single stream system, for example focused around collection and landfilling, these questions may not be hard to answer, but most modern waste management systems involves many waste types and sources (e.g., household waste, bulky waste, garden waste, commercial waste, perhaps other streams that are treated with municipal waste), a range of collection schemes (regular curb-side collection, public recycling stations, on-request-pick-ups, etc.) and many different treatment and disposal facilities (composting plant, incinerator, landfill, etc.). The system must be represented in a comprehensive manner to properly represent all flows. Establishing the information needed to set up the mass balances, quantify the energy budgets and account for the emissions clearly reveals where data are scarce, where the uncertainties are in the system, and thus where further data collection efforts should be targeted. This quantitative inventory of a waste management system is the fundamental technical platform for managing a waste system and has in itself high value even without performing any environmental impact assessment.

An important understanding obtained from performing LCA on waste management systems, although fairly elementary, is that all waste management activities (collection, treatment, etc.) constitute a load to the environment either from the direct emission caused by the activity or through the environmental impacts of the materials and energy used to operate the system. The environmental savings come from the recovered materials and energy that are used as substitutes for other materials and energy that otherwise would have caused a load to the environment. If focus is on material and energy recovery, the LCAs performed on existing waste management systems often show that the environmental savings are larger than the loads, revealing that resource and energy recovery from waste almost always results in a net environmental benefit, despite burdens incurred by the recovery processes (e.g., Jaunich et al., 2019). This is not to suggest that waste prevention is not important; the environmental value of waste prevention is the avoided energy, emissions and material consumption from not producing something that will ultimately become waste. Our functional unit assumes that waste has been generated.

Understanding the flows and environmental emissions of an existing waste management system should be the desire of any company or utility managing waste in a region, as well as of the authorities responsible for waste management or for regional and national governments responsible for regulating and guiding waste management principles and approaches.

The improved understanding of existing waste management systems obtained by LCA modelling is illustrated by a few examples.

Waste management in Hangzhou, China (Zhao et al, 2009): The annual management of approximately 1.3 million tons of municipal solid waste (MSW), including nearly 0.3 million recyclables collected by the informal sector, was modelled and selected results are shown in Figure 1, where positive numbers are loads to the environment and negative numbers are savings. The major loads to the environment were landfill gas emissions and energy use at the transfer stations and material recovery facilities (MRF). Savings were primarily from paper and metal recycling, but also from the three incinerators that generated energy. The emissions from collection vehicles were significant with respect to photochemical ozone formation (POF; a smog precursor) due to the assumed low emissions standards for the collection vehicles; actual data on the vehicle exhaust were not available and this became a recommendation for future work, since the LCA modelling suggested that the environmental contribution could be significant.

Environmental profile of European waste management (Bassi et al., 2017): Managing one tonne of MSW in seven European countries representing different waste compositions, waste management systems and energy systems showed highly different environmental profiles (results not shown). With respect to global warming, Germany, Denmark, UK and Italy showed net savings while France, Poland and Greece showed net loads. The major net contributing processes were material recycling, energy and metal recovery from waste-to-energy and landfilling, but their significance varied among the seven countries. Paper recycling was the major contributor to savings related to material recycling. Further information can be obtained by disaggregating the net values: For example, the net value of waste-to-energy with respect to global warming consists of a load from the incineration of plastics and textiles and from use of fuels and electricity, while the savings come from the energy recovered in terms of electricity and heat and substituting for other energy production in society (particularly if based on fossil fuels). The study clearly showed the diversity in the environmental performance of waste management in Europe and the importance of being specific when modelling waste management systems.

Garden waste composting in Aarhus, Denmark (Boldrin et al., 2011): An LCA of a 16000 tonne/year garden waste composting plant involving shredding of the garden waste, windrow composting, maturing in stacks and free use of the compost by private gardeners revealed that the environmental load was primarily emissions from the windrows and the savings were linked to use of the compost in private gardens as a substitute for using other organic soil products (results not shown). The impacts from collection of the garden waste and the mechanical operation of the composting plant were small. However, the study could not document what was avoided when compost is used in private gardens, hence it was suggested that delivering the compost only to professional landscapers and gardeners probably would increase the benefits of using the compost and thus improve the overall environmental performance of the garden waste management system.

Other examples can be found in e.g. Starostina et al. (2014) and van Eygen et al. (2019).

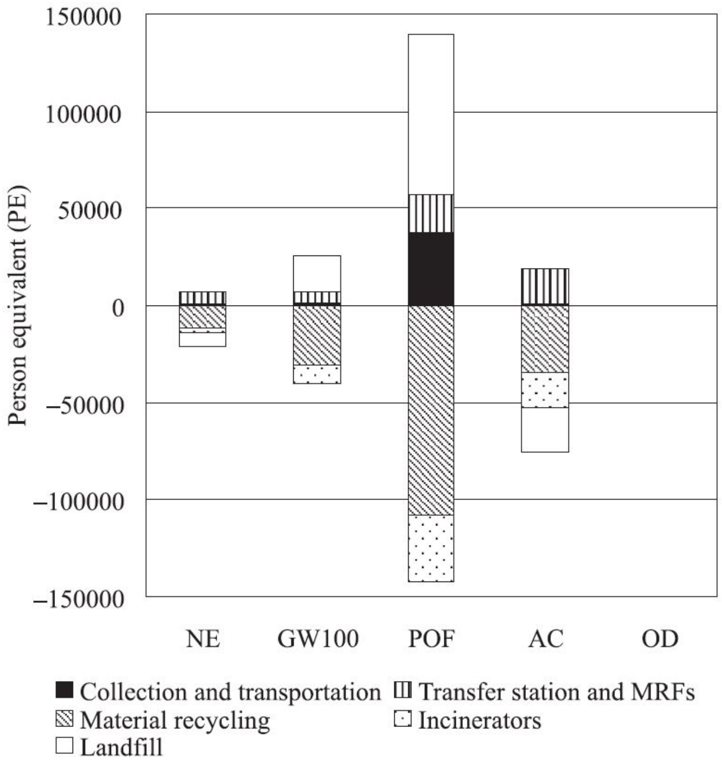

Figure 1: Contributions from the various technologies managing MSW in Hangzhou City, PR China to five environmental impact categories expressed in person-equivalents (NE: Nutrient Enrichment, GW100: Global Warming, POF: Photochemical Ozone Formation, AC: Acidification, OD: Ozone Depletion): Positive values are loads to the environment and negative values are savings. The figure is taken from Zhao et al. (2009).

4. Improving existing waste management systems (Area 2)

LCA models can show how the use of new approaches and processes can improve the environmental performance of an existing waste management system. LCA allows decision makers to estimate the environmental benefit of potential changes that could include, for example, changing the waste fractions that are collected separately, introducing more or fewer waste components to be recycled, and/or implementing biological treatment for food and garden waste.

Simulating the potential changes in a waste management system includes, by nature, estimates of how the key processes and technologies of the new initiative will perform. These estimates may be based on literature, reported experiences from other systems, expert judgement or vendor information. By introducing a range of values or ideally a statistical distribution of the critical parameters in the LCA simulations, a more robust understanding of the impacts of potential improvements is possible. Such analyses are important to ensure that the modeled improvements will hold up for realistic ranges of uncertain model parameters.

Simulating how suggested changes or coming regulation affect an existing waste management system should be of interest to any company or government entity operating a waste management system, as well as for regional and national governments responsible for regulating and issuing guidelines for waste management. Before costly investments are made it is critical to estimate the benefits and the consequences to existing facilities and services. The value of quantitative information cannot be underestimated in the preparation for the political and public process, eventually involved in deciding on and implementing the suggested improvements.

The assessment of potential improvements in existing waste management systems obtained by LCA is illustrated below.

A new waste management system for the Irkutsk region in Siberia, Russia (Starostina et al., 2018): In the Irkutsk region, the existing uncontrolled landfilled had no more capacity and Starostina et al. (2018) modelled 7 future waste management systems and showed the significant environmental improvements that potentially could be obtained. Figure 2 shows the estimated environmental impacts in PE for the management of about 135 000 tonnes of household waste. The old landfill (Scenario 0) showed environmental loads (positive values) in all impact categories, in particular climate change (CC: 10 000 PE). All new waste management systems would be major improvements: for example, introducing a new modern landfill with gas and leachate controls (Scenario 1) would significantly reduce the environmental impacts of the waste management system, while the introduction of material recycling and in particular waste-to-energy (WTE) (Scenarios 3, 4 and 5) would provide savings in most impact categories. Transport distances for recyclables, which in the Siberian region of Irkutsk may be over 1000 km by truck and train, does affect overall environmental savings, but not to the extent that it makes recycling questionable. Sensitivity analysis revealed that efficient recovery and use of energy from WTE was crucial to the savings in climate change impacts.

Diverting waste away from landfill, North Carolina, USA (Jaunich et al., 2019 and 2020): Optimization modelling was accomplished for yard and household waste in Wake County, North Carolina, USA with respect to cost, greenhouse gas (GHG) emissions and diversion of waste away from landfill by paying attention to the capacity of existing waste facilities (single stream recycling of glass, plastic, metal, and paper, composting and landfilling) and considering the potential introduction of a mixed waste material recovery facility (MRF), anaerobic digestion, and WTE. Cost tended to increase with increased landfill diversion for scenarios with the same collection scheme (results not shown). Within a given diversion range (e.g. 40−45% less waste going to landfill), there was a large difference in cost and net GHG offsets. The primary driver of the cost difference was the collection scheme used. In general, a combination of mixed waste MRF and WTE provided GHG emissions reductions at a moderate cost increase. Utilization of the mixed waste MRF was sensitive to the efficiency of material separation, operating cost and value of the recovered materials. The study also recognized the historically limited success of mixed waste MRFs.

Twenty-year development plans for waste management in Campo Grande, Brazil (Lima et al., 2019): A comprehensive LCA of waste management of approximately 270000 tons of waste per year in Campo Grande in central-west Brazil was conducted for a 20-year planning period (2017-2037) (Results not shown). The study showed that the Global Warming Potential (GWP) of the current waste management system based on selective collection of dry recyclables and a fairly new landfill would increase significantly as the population is projected to grow by 30% before 2037. However, the official development plan calls for increasing recycling from about 8% at the beginning of the planning period to 32% in 2037 and improving energy utilization at the landfill would make the waste management system close to neutral in terms of GWP by 2037. Going beyond the official plan and introducing mechanical-biological treatment and energy utilization, including upgrading of the biogas to fuels, would within few years create significant savings in GWP.

Other examples can be found in e.g. Zhao et al. (2011), Rigamonti et al. (2013), and Vadenbo et al. (2014).

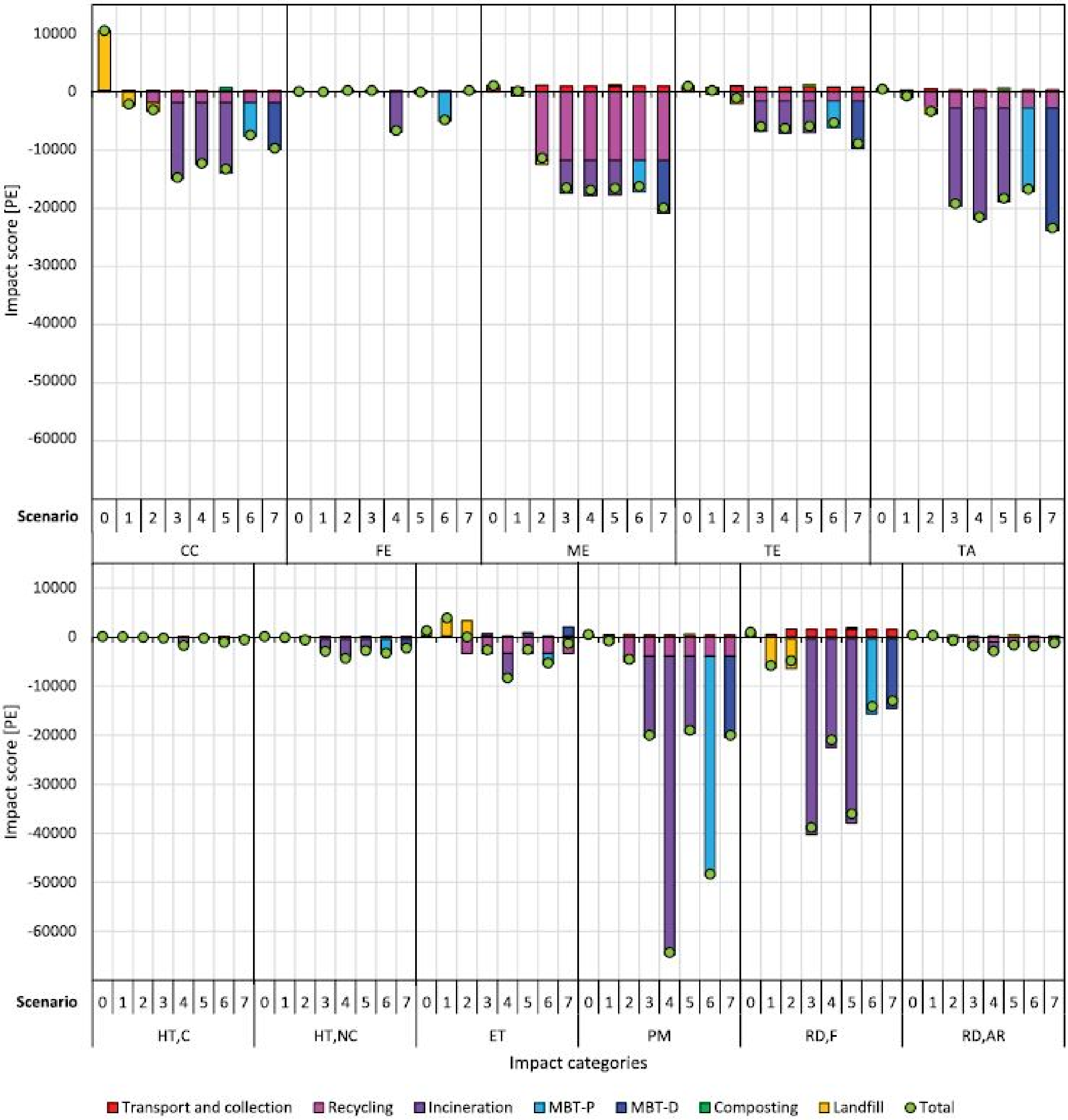

Figure 2: Environmental impacts from household waste management in the Irkutsk region, Russia for the current waste management system (Scenario 0) and 7 alternative future waste management scenarios (Scenario 1-7) expressed in person-equivalents and showing the contribution of the individual technologies (CC: Climate Change; FE: Freshwater Eutrophication; ME: Marine Eutrophication; TE: Terrestrial Eutrophication; TA: Terrestrial Acidification; HT,C: Human Toxicity, Carcinogenic; HT,NC: Human Toxicity, non-carcinogenic; ET: Ecotoxicity; PM: Particulate Matter; RD,F: Resource Depletion, Fossil ; R,AR: Resource Depletion, Abiotic Resources. Positive values are loads to the environment and negative values are savings. The figure is taken from Starostina et al. (2018).

5. Comparing alternative technologies/ technology performance (Area 3)

LCA models are useful in comparing alternative technologies: What are the flows and environmental profile of two alternatives? Of course, such a comparison is only useful if each technology has the same functional unit. A comparison can be done for a specific waste management system where the waste composition and recycling and collection schemes are specified, for example waste gasification compared to mass burn combustion. A technology comparison can also be done in a more generic way, for example using a range of waste compositions relevant for the alternative technologies, or for a general waste composition to assess how one technology performs relative to another in terms of flows and environmental profile.

When comparing alternative technologies, it is crucial that the technologies are well understood and that a functional unit is well defined. For example, care must be taken when comparing composting and anaerobic digestion as alternatives for treating kitchen waste. The fact that the technologies use different additives (composting often requires addition of a structural material such as wood chips) or have different outputs can be handled by the LCA methodology, but the household sorting guidelines for kitchen waste may differ depending on the technology chosen to treat the waste: For example plant pots with content are usually accepted for composting but rarely accepted for anaerobic digestion. Any difference in the waste treated by the alternatives must be compensated by expanding the system boundaries to include the treatment of the difference in the waste composition. In this case, the plant pots would have to be treated in a process in addition to anaerobic digestion. Alternately, the functional unit could be modified to exclude plant pots.

Simulating the environmental profile of alternative technologies or of alternative performance of a technology could be relevant for technology providers entering a new market, companies or authorities considering replacing an existing technology with a new technology, international organizations or trade associations wanting to identify the competitive profile of their own technologies, or for regional and national governments responsible for regulating and guiding waste management, for example by specifying performance criteria for certain technologies.

Assessing alternative technologies or alternative performance of a specific technology by means of LCA modelling is illustrated below.

Eight different mechanical-biological treatment (MBT) technologies (Montejo et al., 2013): Eight full-scale MBT-plants were modelled using local data on waste composition and process performance. The plants differed in their use of separation technology and in biological treatment technology. The results with respect to global warming (kg CO_2-eq. per tonne wet weight) are shown in Figure 3: The negative values are savings that are dominated by the benefits of recycling (cross-hatched) and landfilling (grey; caused by sequestering of organic carbon in the landfill) and these savings are significantly larger than the loads from transport, plant operation etc. (positive numbers); the net values (diamonds for coal based energy and crosses for natural gas based energy) show total savings of 100 to 350 kg CO_2-eq. per tonne of waste treated. The right side of figure 3 shows the results if all plants were treating waste with the same composition; here the differences are less pronounced but still suggest that the global warming impact of a MBT-plant strongly depends on the choice of technology (ranging about 150 kg CO_2-eq. per tonneof wet waste).

Plastic waste management scenarios (Rigamonti et al., 2014): Plastic waste that is incinerated as part of MSWcaused a load to global warming but a saving to acidification, the latter because of the crediting of the electricity recovered by the incinerator. Four alternative technologies for managing the plastic using various combinations of source separation and mechanical sorting showed significant savings in global warming and still ensured a significant saving in acidification (Results not shown).

End-of-life vehicle management (Gradin et al., 2013): The traditional shredding and sorting of end-of-life vehicles was shown to be much less attractive than using a manual dismantling process when assessed with respect to climate change, metal depletion and cumulative energy demand (results not shown). The latter increased the recovery of copper and polymers and increased energy recovery via incineration.

Other examples can be found in e.g. Chen & Christensen (2010), Damgaard et al. (2010), Zhao et al. (2012), Boesch et al. (2014), Arena et al. (2015), Ardolino et al. (2017), and Ardolino and Arena (2019).

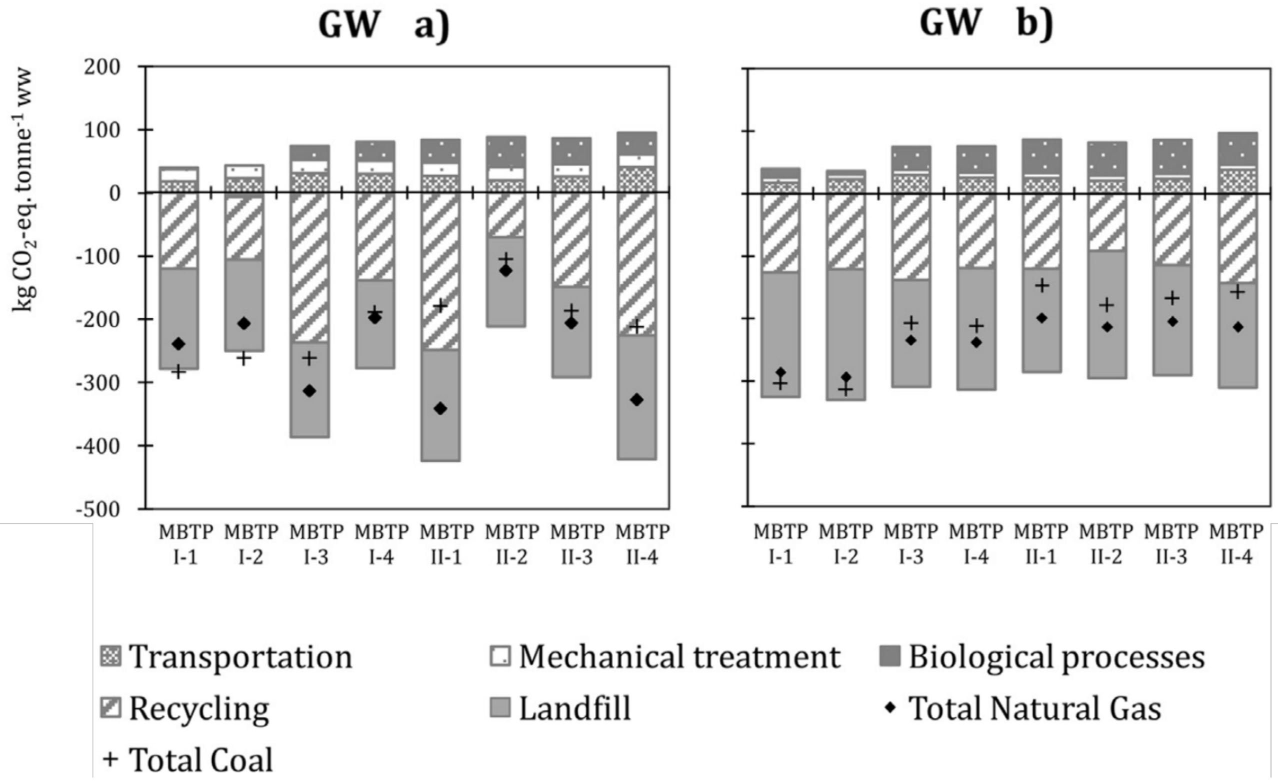

Figure 3: Global warming impacts (kg CO_2-equivalents per tonne of wet MSW) for 8 mechanical-biological-treatment plants (MBT) in Europe showing net values (♦ when using coal based energy and + when using natural gas based energy as reference) and contributions from the transportation, mechanical treatment, biological treatment, recycling and utilization of recovered materials and landfilling of residues. The left graph shows the results for the actual waste composition, while the right graph shows the results for the average waste composition managed by all 8 MBT plants. Positive values are loads to the environment and negative values are savings. The figure is taken from Montejo et al. (2013).

6. Technology development/prospective technologies (Area 4)

LCA is particularly useful for the assessment of new technologies or a new system where data are limited or not available at a relevant scale. Ideally, LCA modeling should be based on long-term data from full-scale facilities that includes a range of operating conditions. In the case of technologies under development, data may be based on theory or lab- or pilot-scale systems. In such cases, simulating the environmental performance of a process by an LCA model with a range of parameter values is useful to assess the technology, and to identify data gaps and areas where technological improvements should be targeted. Ultimately, LCA can identify the performance level that must be obtained for the technology or process to represent an improvement relative to existing processes or technologies. The complexity of the process and its behavior (e.g., non-linear) will control the sophistication of the model required to describe the process (see for example Lodato et al., 2020).

To illustrate the concepts described above, consider a comparison of gasification with mass burn waste combustion. While there is good data on waste combustion, gasification is an emerging technology with limited performance data as applied to the treatment of MSW. As such, the LCA for gasification will be uncertain. Nonetheless, the LCA could be used to determine the minimum level of performance that is required of a gasification process to show improvement relative to mass burn combustion. This can be valuable information for engineers involved with process development.

As the demand for sustainability in waste management increases, there will be increasing demand to provide data on the environmental performance of both new and potential new technologies. This may be requested by potential investors or potential buyers, thereby forcing developers to take sustainability issues into their development process at an early stage and not only focus on technological performance and costs. LCA with estimated parameter variation is a useful tool for meeting such demands and defining the next steps in process development.

In addition, companies and authorities looking for new solutions to waste management will be confronted with the surfacing of new technologies that claim to be better than the existing technologies. Here LCA simulations can be useful in quantifying how far the new technology has developed (does it provide solid data on critical parameters?) and how well it compares with the existing technology.

Assessing technologies under development by means of LCA is illustrated below.

Novel technology from extracting copper from waste electrical and electronic equipment (WEEE) (Villares et al., 2016): Metals are usually extracted from WEEE by a high temperature pyrometalurgical technology, but new research suggests that bioleaching working at ambient temperatures can be efficient in extracting copper from WEEE (>98%). The study used the results from laboratory scale experiments to upscale this prospective technology to industrial scale and used LCA to compare its anticipated environmental performance with the performance of the traditional pyrometallurgical technology. This is a relatively new application of LCA bringing systematic rigor and a system approach to an ambiguous situation at the start of development of a novel technology. The approach identified potential areas of high environmental impact for the new technology in spite of the scale and uncertainties associated with the experimental data. It also broadened the research scope bringing a systems approach, long-term view, environmental aspects, and data on energy and material inputs for the bioleaching process. Table 1 shows the result for recovering 1 kg of copper, indicating that the new bioleaching technology is environmentally inferior to existing pyrometallurgical technology for WEEE treatment.

Novel technology for producing biomethane as a fuel (Ardolino and Arena, 2019): Methane produced from organic waste could potentially be used as a transportation fuel. LCA was used to assess how a pilot-scale thermal gasification technology producing methane from agricultural waste compares to the traditional technology of anaerobic digestion and upgrading of the biogas to biomethane. The comparison was based on the production of 1 MW fuel and considered the traditional waste management that was avoided when producing biomethane. This was defined by the fact that the two technologies used different waste types and different amounts of waste. It was concluded that the novel thermal gasification technology was as least as good as the traditional biogas technology. The study also pointed out that the novel technology had a potential for further improvement.

Novel technologies for producing bioethanol from agricultural waste (Zhao et al., 2019 and 2020): Conversion of agricultural waste to bioethanol requires a pretreatment step making the digestible compounds available for fermentation to ethanol. Nearly all of the published information on the conversion of corn stover to bioethanol is at laboratory scale and often not sufficiently complete to perform a full LCA. Zhao et al. (2019) parametrized the key processes and determined their statistical distribution based on 141 datasets, allowing for LCA comparison of 7 different technologies to pretreat corn stover, paying attention to the full technology including obtaining credits for the bioethanol substituting for gasoline. The approach showed that, when considering GWP, 2 of the 7 technologies were most promising: steam-explosion and ammonia-treatment.

Other examples can be found in e.g. Joyce and Björklund (2019).

Table 1: Environmental impacts (9 categories) from recovering 1 kg of copper from WEEE (waste electrical and electronic equipment) using an existing pyrometallurgical technology and up-scaled bioleaching technology under development (3 different set-ups with different (1-20%) pulp levels). The positive values are all loads to the environment. The table is rearranged from Villares et al. (2016).

Impact category	Unit/1 kg of cathode copper	Full scale existing pyrometallurgical system	Scaled-up bioleaching system Pulp density:		
			1%	10%	20%
Eutrophication, generic	kg PO_4-eq	6.4×10^{-5}	1.1×10^{0}	1.2×10^{-1}	6.3×10^{-2}
Depletion of abiotic resources	kg antimony eq	3.3×10^{-4}	5.6×10^{0}	6.0×10^{-1}	3.1×10^{-1}
Acidification, generic	kg SO_2-eq	2.2×10^{-4}	2.7×10^{0}	3.0×10^{-1}	1.6×10^{-1}
Photochemical oxidation, high	NO_x kg ethylene-eq	2.1×10^{-5}	1.6×10^{-1}	1.7×10^{-2}	8.9×10^{-3}
Climate change, 100a	kg CO_2-eq	1.0×10^{-1}	3.5×10^{2}	4.0×10^{2}	2.2×10^{1}
Terrestrial ecotoxicity	kg 1,4-DCB-eq	1.7×10^{-6}	3.6×10^{-2}	3.8×10^{-3}	2.0×10^{-3}
Freshwater aquatic ecotoxicity	kg 1,4-DCB-eq	4.1×10^{-1}	2.6×10^{2}	2.7×10^{1}	1.4×10^{1}
Stratospheric ozone depletion	kg CFC-11-eq	7.3×10^{-9}	7.1×10^{-5}	7.5×10^{-6}	3.9×10^{-6}
Human toxicity, infinite	kg 1,4-DCB-eq	7.3×10^{-2}	1.0×10^{3}	1.1×10^{2}	5.4×10^{1}

7. Policy development/ strategy development (Area 5)

New national regulations regarding waste management as well as strategic plans for regional or MSW management systems will be used for decades due to the investment in equipment and facilities. This means that the environmental profile of new systems must be robust to changes that may occur over perhaps the next 30 years. LCA can be used to evaluate the environmental performance of solid waste management systems in responses to changes in for example, waste composition, markets for recyclable materials, energy, heat and fuels recovered from waste. In particular, the composition of waste and the composition of the fuels used to generate energy are undergoing changes. LCA modeling can also be used to evaluate the environmental performance that can be attributed to new regulations or policy. In fact, LCA represents an excellent opportunity for scientific analysis to inform regulations and policies.

Prediction of future boundary conditions (for example the waste composition and exchange with the energy system) is by nature difficult and a wide range of scenarios must be simulated. Where political targets have been set up, for example in terms of changing the national energy system towards renewable energy by 2030, a narrower envelope of future scenarios can be defined, but the crediting of the waste management system for recovered energy delivered to the energy system (the substitution) also depends on how the exchange is regulated. This leads to further variation in the future exchanges over the boundaries.

Politicians, public authorities and technology developers should be interested in such applications of LCA in waste management because it will assist in quantifying the environmental loads and benefits from waste management as waste composition changes and the offset value of the recovered materials and energy will push towards more emphasis on the material resources (more demand for resources) than energy as the CO_2 intensity of energy decreases.

Selected examples of the application of LCA to evaluate how changes in policies and boundary conditions affect waste management strategies are illustrated below.

Preventing packaging waste for pasta, cereals and rice (Dolci et al., 2016): Preventing waste by introducing loose storage of pasta, cereals and rice in stores and use of individual bags as an alternative to traditional pre-packaged food items was investigated with LCA. The plastic packaging was assumed to be recycled while the paper-based packaging would be incinerated. The results showed (Table 2) that the loose packaging is not always best from an environmental perspective. The results were significantly different for dry pasta, breakfast cereals, and rice, and depended on how the traditional and the loose distributions were implemented. If the size and the material of the packages were similar, as for pasta plastic bags, the loose distribution did not result in a reduction in waste and could even cause an increase in waste generation (up to 15%) and in potential impacts. The loose distribution of pasta provided benefits only when substituting the traditional single-use carton-board boxes; in which case the loose distribution caused a 50% waste reduction for the food item and a decrease in almost all potential impacts.

Waste management policy development in Sweden (Arushanyan et al., 2017): This paper presents a comprehensive LCA model for assessment of scenarios and waste management policy instruments in Sweden. It is unique in that it includes almost all waste flows in the country as well as waste prevention. Waste management in Sweden will continue to contribute with environmental benefits (savings), but less so in the more sustainable future scenarios, since the surrounding energy and transportation systems will be less polluting and because less waste will be produced. The results indicate that climate change, human toxicity and resource depletion are the most important environmental impact categories for the Swedish waste management system. The model assessed the environmental impacts of several policy instruments including a weight-based collection fee, incineration tax, a resource tax and inclusion of waste in a green electricity certification system. The effects of the individual policy instruments were in most cases limited, suggesting that stronger policy instruments as well as combinations are necessary to reach policy goals as set out in for example the EU action plan on circular economy.

Can European waste-to-energy (WTE) plants meet new BREF guidelines? (Ardolino et al. 2020): A “Best available techniques REFerence document (BREF) for Waste Incineration” describes requirements for waste incineration in Europe to reduce pollution, optimize energy recovery and prevent potential accidents. The study modelled a recently built European WTE plant against virtual plants that complied with the criteria of the BREF guideline and concluded that the existing newer plants were able to comply with the BREF guideline. An emphasis on the energy efficiencies was recommended, since the benefits of electricity recovery will decrease as the energy system becomes less CO_2-intensive.

Other examples can be found in e.g. Björklund and Finnveden (2007), Saner et al. (2011), Eriksson et al. (2014), and Faraca et al. (2019).

Table 2: Environmental impacts (14 categories) of the current packaging of 1 kg of cereal in a pillow bag compared to three alternative packaging systems for the same kg. The impacts of the alternatives are shown in percentages of the impacts of the current packaging. Negative values indicate lower environmental impact. The table is rearranged from Dolci et al. (2016).

Impact category	Unit per functional unit	Impact Baseline	Impact change (%) Alter1	Alter2	Alter3
Climate change	kg CO_2 -eq	1.73 E-01	10.0	-1.7	3.4
Ozone depletion	kg CFC-11 -eq	2.02 E-08	5.8	-4.9	-0.9
Photochemical ozone formation	kg NMVOC -eq	1.11 E-03	5.5	-1.6	3.6
Acidification	mole H^+ -eq	1.01 E-03	7.7	-1.7	4.3
Terrestrial eutrophication	mole N –eq	3.93 E-03	4.1	-1.6	0.7
Freshwater eutrophication	kg P -eq	3.46 E-05	10.7	-9.0	-6.3
Marine eutrophication	kg N -eq	3.96 E-04	4.6	-3.0	-1.0
Freshwater toxicity	CTUe	2.25 E-01	13.3	-8.5	7.1
Human toxicity (cancer)	CTUh -eq	8.77 E-09	8.9	-3.0	5.9
Human Toxicity (non-cancer)	CTUh -eq	1.82 E-08	7.5	-8.1	-9.5
Particulate matter	kg $PM_{2.5}$ -eq	8.51 E-05	10.8	14.7	5.6
Water resource depletion	m^3 water -eq	5.28 E-04	17.8	8.6	11.4
Mineral and fossil resource depletion	kg Sb -eq	5.83 E-04	12.7	-8.6	8.0
Cumulative energy demand	MJ -eq	3.55 E-00	12.2	-2.3	6.8

8. Reporting (documentation and communication) (Area 6)

LCA modeling of complex waste management systems provides comprehensive quantification of recovered materials and energy and of the potential impacts on the environments including loads and savings. This can be based on specific yearly data and as such provide quantitative information for annual reporting and thereby provide a basis for monitoring progress toward future targets, for example of being CO_2-neutral. This could be done for a whole system including variations in the amount of waste annually handled or per unit of waste in order to monitor technology improvements.

The initial work to set up an LCA is demanding. However, once a solid waste system is represented in an LCA, then reporting the following years will involve only few changes in key parameters and as such will be simple. An LCA could provide key data on CO_2-footprint, resource recovery, degree of circularity and/or drop in amount of waste landfilled. We have not encountered in the literature examples of this reporting application, but we are confident that it will appear in the future as citizens, policymakers and investors increase their focus on sustainability and the environmental performance of waste management systems.

A historic mapping of the retrospective impacts from the waste management in the City of Aalborg, Denmark has been described by Habib et al. (2013). Figure 4 shows the estimated GWP in kg CO_2-eqv. per tonne of MSW from 1970 to 2010. The study accounted for changes in waste composition, the introduction of new technologies and changes in the efficiencies with respect to recycling and energy recovery, as well as the substitute value of the recovered materials and energy. In 1970 the city landfilled all the waste but introduced WTE in 1980 and later also material recycling , energy recovery and composting. Between 1970 and 2010, the waste management system of the City of Aalborg changed from being a load of 600 kg CO_2-eqv. per tonne to a saving of 700 kg CO_2-eqv. per ton. The study showed that the introduction of WTE with high energy recovery contributed to the improvement.

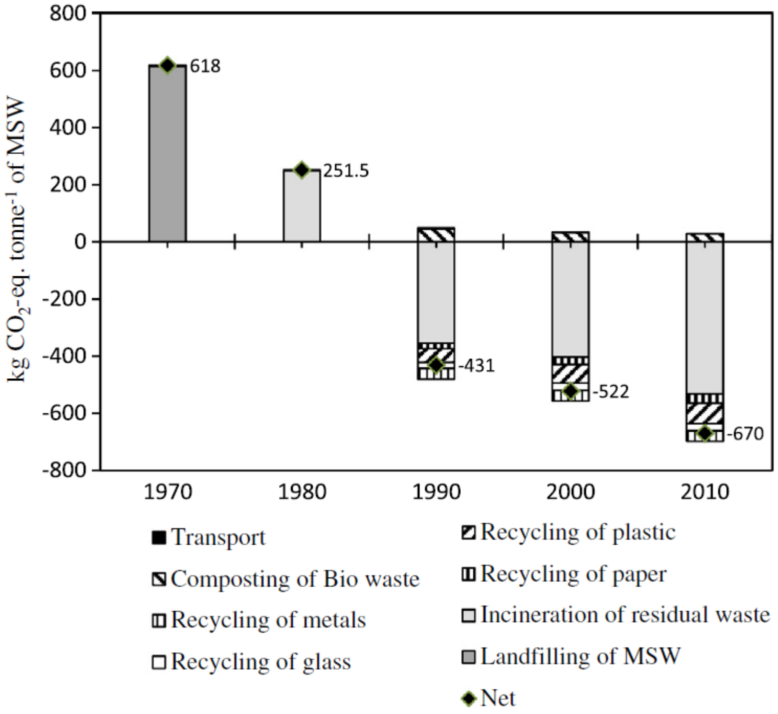

Figure 4: Global warming impacts (kg CO2-equivalents per tonne of wet MSW) of the waste management system in the City of Aalborg, Denmark estimated for a 40-year-period (1970-2010) paying attention to the changes in both waste composition and waste management technology from landfilling to material recycling, composting and incineration with energy recovery. The figure is taken from Habib et al. (2013).

9. Conclusion

More than 350 journal articles have been published over the last twenty years on the use of LCA to address important issues in waste management and significant generally applicable knowledge has been developed. Nonetheless, we believe that there are future applications where the use of LCA can support various aspects of waste management. The strength of using LCA is that it provides a comprehensive, consistent and transparent overview of flows in the waste management systems and it provides quantification of the environmental profile of the waste management system. LCA offers insights also for selected parts of the system. We see no other tool providing the same level of quantitative information. We have identified six application areas defined from a user's point of view: 1) understanding an existing waste management system, 2) improving existing waste management systems, 3) comparing alternative technologies/ technology performance, 4) technology development/ future technologies, 5) policy development/strategic development, which all have been in focus in the current literature, and 6) reporting, which refers to the use of LCA models in, for example, annual accounting and reporting of global warming impacts from a MSW management system. The latter has not yet found its way into the literature, but we expect it to gain a foothold as companies, cities and regions focus more on their environmental footprint.

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