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published in

Waste Management

2019

DOI (link to publisher)

[10.1016/j.wasman.2019.05.023](https://doi.org/10.1016/j.wasman.2019.05.023)

document version

Publisher's PDF, also known as Version of record

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citation for published version (APA)

Inghels, D. A. M., Dullaert, W., Heijungs, R., & Aghezzaf, E. H. (2019). Towards optimal trade-offs between material and energy recovery for green waste. *Waste Management*, 93, 100-111.
<https://doi.org/10.1016/j.wasman.2019.05.023>

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Towards optimal trade-offs between material and energy recovery for green waste

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ARTICLE INFO

Article history:

Received 22 October 2017

Revised 1 March 2019

Accepted 14 May 2019

Available online 24 May 2019

Keywords:

Multiple objective modeling

Green waste valorization

Material conservation

Waste-to-energy

Decision support tool

ABSTRACT

Green waste is a type of biomass consisting mainly of grass, leaves and fresh prunings originating from gardens and parks. It can be used as feedstock for composting, or for energy recovery. The EU Waste Directive 2008/98/EC advocates composting to prevent waste. This directive allows green waste to be used for (renewable) energy valorization only if a better overall environmental outcome can be demonstrated. In this paper, we propose an assessment procedure based on examining the Pareto front of optimal trade-off combinations for maximizing composting and energy recovery of green waste while minimizing environmental impact and minimizing particulate matter emission. The Pareto optimal front is determined by solving a multi-objective optimization problem using the ϵ -constraint method. Previous research on green waste valorization using Life Cycle Analysis (LCA) shows that either energy recovery or composting is the preferred option depending on how environmental impact is assessed. In contrast to the full assignment to one of these recovery methods produced by LCA, we demonstrate, using the case of green waste valorization in the Netherlands and Belgium, that the proposed assessment procedure provides optimal solutions in a range between full allocation to compost or energy recovery. The proposed methodology supports the selection of optimal solutions taking the decision makers' preference into account that allows complying with Directives that have opposite goals on green waste valorization. Finally, computational results show that the assessment of the "better environmental outcome" requested by the EU waste Directive 2008/98/EC is influenced by the life cycle impact categories and the policy makers preferences with respect to the valorization options taken into account. Since the EU waste Directive 2008/98/EC does not specify how to execute the outcome assessment of valorization alternatives, this can lead to ambiguity.

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Abbreviations: AHP, Analytical Hierarchy Process; AUGMECON, Augmented Epsilon Constraint method; DM, Decision Maker; DRSA, Dominance-baes Rough Set Approach; DSD, Direct Search Domain; ELECTRE, ELimination and Choice expressing The REality; GAMS, General Algebraic Modeling Language; GWVP, Green Waste Valorization Problem; LCA, Life Cycle Analysis; LCIA, Life Cycle Impact Assessment; LHV, Lower Heating Value; MAUT, Multi Attribute Utility Theory; MAVT, Multi-Attribute Value Theory; MCDA, Multi-Criteria Decision Analysis; MOOP, Multi Objective Optimization Problem; NC, Normal Constraint; NCV, Net Calorific Value; NBI, Normal Boundary Intersection; NBI_m, modified Normal Boundary Intersection; OR, Operations Research; PM, Particulate Matter; PROMETHEE, Preference Ranking Organization Method for Enrichment of Evaluations; RES, Renewable Energy Source; SMART, Simple Multi-Attribute Rating Technique; SPO, Successive Pareto Optimization; WTE, Waste To Energy.

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1. Introduction

Green waste is a type of biomass consisting mainly of grass, leaves and fresh prunings originating from gardens and parks. It can be used as feedstock for composting, or for renewable energy production. Two different EU Directives encourage both valorization options. In this paper we present a framework for determining the optimal assignment of green waste valorization to each option, to provide decision-making support for policy makers.

Composting green waste is regarded as waste prevention and is therefore promoted by the EU Waste Directive 2008/98/EC (EP&C, 2008). This directive advocates a waste hierarchy ranking that recommends, in decreasing order, prevention over re-use, recycling or incineration with energy recovery, and incineration or landfill. It

obliges EU Member States to take measures to encourage the option that delivers the best overall environmental outcome. This may require specific waste streams to depart from the waste hierarchy, if the overall lower environmental impacts of the generation and management of such waste across its entire life cycle justify this.

Green waste incineration with energy recovery is an alternative valorization option if it can be proven to perform better than composting from an environmental standpoint. This option advances the goals of another EU Directive 2009/28/EC on the promotion of the use of renewable energy (EP&C, 2009), which obliges EU Member States to cover at least 20% of their energy needs from a renewable energy source (RES) by 2020. In the EU, the share of energy from renewable sources in the gross final consumption of energy was 17% in 2016. While the EU as a whole is on course to meet its 2020 targets, some Member States such as Belgium and the Netherlands will need to take additional efforts to meet their obligations for the share of energy from renewable sources in the gross final consumption of energy (Eurostat, 2019). As a result, these countries are under growing pressure to valorize biomass for energy purposes. Energy valorization of green waste could help them meet the EU RES targets by 2020 and therefore we will use the green waste LCA data of Belgium and the Netherlands in the case study discussed in this paper. Anaerobic digestion of green waste is not considered as a renewable energy source because of its poor economic viability (VITO, 2017; Pick et al., 2012).

The EU advocates life cycle thinking and life cycle assessment (LCA) to ensure the identification of the best environmental outcome (EC, 2015) (i.e. the criterion for diverting from the preferred options mentioned in the EU Waste Directive 2008/98/EC (EP&C, 2008)). An LCA approach (ISO 14040+44, 2006 a+b) is traditionally used to assess the environmental impact of products and services. ISO 14040+44 permits only a comparative assertion, i.e. an environmental claim regarding the superiority or equivalence of one product versus a competing product, if both perform the same function. The two green waste valorization processes (composting and incineration with energy recovery) are comparable when considered from the perspective of solid waste management since both composting and incineration of green waste are forms of solid municipal waste management.

LCA is a widely used tool for environmental impact assessment of products and processes. However, it has some drawbacks that are relevant to the comparison of waste management options. Focusing on a single product function (e.g., managing waste) and omitting secondary functions (e.g., producing compost or generating energy) might yield a functional unit that fails to reflect reality well (Reap et al., 2008a). Furthermore, the outcome of an LCA applied to green waste valorization will prefer one valorization option above another (i.e., either composting or energy recovery). Finally, it bears noting that not all life cycle impact assessment (LCIA) methods evaluate the human health damage per mass of particulate matter (PM) emitted (Humbert et al., 2011). It is well known that wood-fuelled domestic stoves and boilers could have adverse air quality impact on PM (AQEG, 2018; EEA, 2016) leading to increased mortality in case of long term exposure (Annesi-Maesano et al., 2007). However, in this paper, we discuss incineration of green waste in industrial waste incinerators using filters that reduce PM₁₀ to a level far below the limit value of 10 mg/m³ (Van Caneghem et al., 2012) of the EU Directive 2000/76/EC (EP&C, 2000). Therefore PM will not be taken into account.

Extending LCA with multi-criteria decision analysis (MCDA) methodologies is a recently emerging field of scientific research that overcomes the aforementioned problems (Vadenbo et al., 2017; Banasik et al., 2016; Jacquemin et al., 2012). Since policy and decision makers spend most of their time on decision making and implementation, they would derive greater benefit from

decision analysis tools such as MCDA than from tools such as LCA used solely for environmental assessment (Kiker et al., 2005). Better tools could assist policy decision-makers in choosing the best overall environmental outcome for the valorization of green waste. Contacts with waste policy officers working for the Belgian government, in the context of gathering data and insights for our research on green waste management, revealed the need for a decision support model for the assignment of green waste to composting and renewable energy production. In this paper, we will apply methods from MCDA to derive optimal green waste valorization from an environmental standpoint.

One reason for the limited use of OR techniques is that the traditional focus of OR is minimizing costs (Dekker, 2012). Another reason is that many LCA-studies seek to describe a system in terms of its impacts, rather than optimizing it. Further, most LCA-studies are done with specialized software that lacks OR-type algorithms. This paper therefore also aims to promote the use of OR techniques in support of sustainability-related decision making. More specifically, in this paper, we examine the impact on environmental decision making of extending LCA with MCDA versus the more traditional technique of using LCA on its own. A real-life case in Belgium and the Netherlands is used to illustrate how to determine optimal environmental green waste assignment to compost and energy valorization based on certain environmental criteria. Computational results show that extending LCA with MCDA, thereby minimizing the most common life cycle impact categories, while maximizing compost and energy valorization, results in the assignment of green waste to combinations of composting and energy valorization depending on the importance assigned to each objective. Moreover, this study demonstrates that differences in the decision makers' preferences on the environmental impact categories and the decision makers' preference for composting or energy recovery might lead to differences in assigning green waste valorization to composting and energy recovery. This stresses the importance of unambiguous guidelines on the selection of environmental impact categories and the weighing factors linked to the valorization options in the EU Waste Directive to avoid that diverting from composting green waste is based on specifically selected environmental criteria aimed to support a targeted outcome of optimal green waste valorization.

The remainder of the paper is structured as follows: Section 2 presents a literature review on the limitations of the LCA approach and on multi-criteria decision making. Section 3 discusses the objectives and constraints of the green waste valorization problem (GWVP). The approach taken to the solution of this problem and the results obtained from the case study are presented in Section 4. In Section 5 the results are discussed and finally conclusions are presented in Section 6.

2. Literature review

2.1. LCA approach, potential and limitations

LCA is an established analytical method for quantifying the environmental impacts of a product, service or production process. The method is traditionally used to study four types of problems: assessment of individual products to understand their environmental impact, comparison of process paths in the production of substitutable products or processes, the comparison of alternatives for delivering a given function (Jacquemin et al., 2012) and to analyze the phases of the product or service life cycle that have more considerable environmental impact also known as "hot-spots" (Piekariski et al., 2013). As a decision support tool, LCA combines preference values and science, and therefore precludes the existence of uniquely correct methods and results (Hertwich et al., 2000).

ISO 14040+44 (2006 a+b) gives a clear and structured description to practitioners of how to conduct an LCA. ISO 14040+44 (2006 a+b) states LCA to be “one of the several environmental management techniques (e.g., risk assessment, environmental performance evaluation, environmental auditing, and environmental impact assessment) and might not be the most appropriate technique to use in all situations.” So ISO 14040+44 (2006 a+b) does not claim LCA to be the sole methodology for assessment of environmental impact.

Although LCA is generally considered to be a good environmental assessment tool, it does have drawbacks. Readers interested in a complete overview of drawbacks and potential solutions to overcome them are referred to the literature reviews of Pryshlakivsky and Searcy (2013), Jacquemin et al. (2012), Finnveden et al. (2009), Reap et al. (2008a+2008b) and Hertwich et al. (2000), and to the work of Lazarevic (2018) and Lazarevic et al. (2012). Laurent et al. (2014a+2014b) discuss specifically flaws and best practices on conducting LCA studies of solid waste management systems, the waste group to which green waste belongs. The primary weaknesses of LCA, relevant to the subject of this paper, can be summarized as follows.

To begin, it has limitations as a method for conducting a comparative assertion. The ISO 14040+44 standard does not permit the use of LCA as a basis for a comparative assertion for competing products that do not perform the same function. However, the definition of competing products is inadequately formulated (Klöppfer, 2013). As an example, composting and energy recovery of green waste deliver two competing products resulting from the green waste valorization of a same batch of green waste (i.e. the same function for both competing products). However, these products are competing on different markets resulting in different trade-offs to be taken into account in the LCA: green waste compost competes with other kinds of fertilizers such as peat and the recovered energy from green waste competes with energy originated from e.g., coal or wind. Moreover, the ISO 14040+44 standard does not give supplementary guidelines on how to determine whether a product or service performs the same function, which can lead to ambiguity (Klöppfer, 2012). Therefore, LCA practitioners should be encouraged to give a quantitative description of the primary function fulfilled by the systems under study concerning the study's goal and scope (Reap et al., 2008) including the local specifications to guarantee their comparability (Laurent et al., 2014b). For example, the composition of 1 ton of green waste in the Low Countries may differ from 1 ton of green waste in Africa. A consequential LCA¹ has been argued to be the relevant method to reflect the consequences of choosing one or the other product (Frischknecht and Stucki, 2010).

A drawback specific to waste management is that clear-cut and undisputable results may not be expected given the many stakeholders that are involved (Lazarevic et al., 2012). As an example, consider the assignment of green waste to compost or energy valorization by Kranert et al. (2010) versus the one performed by SenterNovem (2008), an agency of the Dutch Ministry of Economic Affairs charged with implementing policies in the fields of innovation, energy and climate, environment and spatial planning. Based on separate LCAs, Kranert et al. (2010) conclude that both valorization methods are on par on CO₂ emissions, while SenterNovem (2008) clearly favors incineration with energy recovery.

Current comparative LCAs lack robust methods of interpretation to help decision makers understand and identify trade-offs in the selection process (Lopez, 2013). While using normalization enables

different units of impact categories to be converted into one dimensionless unit for easier comparison, selecting appropriate normalization methods is still controversial (Bare, 2010). Further, a full comparison requires an additional weighting step, which is even more controversial (Finnveden et al., 2009). The process of normalization and weighting eventually leads to a selection of one green waste valorization process as optimal, thereby leaving no room to search for an optimal partial assignment to both valorization options resulting in lower greenhouse gas and particulate matter emissions.

There is a growing consensus on the need to expand the ISO 14040+44 LCA framework by integration and connection with other concepts and methods to increase its usefulness for sustainability decision making (Vadenbo et al., 2017; Banasik et al., 2016; Jacquemin et al., 2012; Jeswani et al., 2010; Helias et al., 2004). The review of Jacquemin et al. (2012) finds that LCA results are often used as an input for the multi-objective optimization of processes: practitioners use LCA to obtain the life cycle inventory and insert the results into the optimization model. It also shows that most LCA studies undertaken consider the unit processes as black boxes and build the inventory analysis on fixed operating conditions. Moreover, according to Jeswani et al. (2010) multiple-criteria decision analysis (MCDA) could help broaden LCA to consider, among other factors, social and economic impacts, as was done by Inghels et al. (2016) for green waste valorization. Furthermore, in relation to LCA, MCDA can be used for interpretation of the obtained results, which come in different units of measurement and often manifest goal conflicts (Jeswani et al., 2010; Helias et al., 2004).

The next subsection reviews MCDA, as it plays a central role in the methodology presented in this paper, and discusses the integration of LCA and MCDA as well.

2.2. Multiple-Criteria Decision Analysis (MCDA)

Multiple-criteria decision analysis (MCDA), also known as multi-criteria decision making (MCDM), is a sub-discipline of Operations Research and Management Science that supports decision makers (DMs) by structuring and solving decision and planning problems involving multiple criteria. There are several good handbooks and reviews on the subject (see for example Fandel et al., 1985; Bana e Costa, 1990; Roy, 1985, 1996.). MCDA is a collection of methods to support decision makers, according to their preferences, in complex situations where criteria are conflicting and no single ideal solution simultaneously satisfies the DM across them. In such instances, an optimal trade-off must be sought between the objectives to be achieved in accordance with the preferences of the DM. Kiker et al. (2005) provided an overview of different types of decision support tools based on MCDA used in environmental management.

In this paper, we use a mathematical process of determining optimal trade-off solutions, known as multi-objective programming (MOOP; see, e.g. Stadler, 1979 or Steuer, 1986). Solving a MOOP delivers optimal trade-off solutions that are called Pareto optimal or Pareto-efficient if none of the objectives can be improved in value without deteriorating the values of some other objectives. We prefer to formulate the problem of assigning green waste to composting or energy recovery as a multiple-objective programming problem since there is a set of Pareto optimal solutions from which the DM can choose, ranging between full assignments to either composting or energy recovery.

In general, three types of approaches to solve a MOOP can be distinguished based on the timing at which the DM states his preferences (Van Veldhuizen and Lamont, 2000): (i) an a priori preference articulation in which the DM decides how to combine differing objectives into a scalar function prior to the optimization

¹ The consequential approach is a system modeling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit. (See for more details: <https://consequential-lca.org/clca/why-and-when/>)

process, (ii) a progressive preference articulation in which decision making and optimization are intertwined and (iii) an a posteriori preference articulation in which the DM is presented with a set of Pareto optimal candidate solutions and chooses from that set. Approaches (i) and (iii) are commonly used to solve a MOOP.

In this paper, we will use the augmented ε -constraint method (AUGMECON), a widely used a posteriori preference approach, to solve the MOOP used in the case study. The augmented ε -constraint method is a novel version of the conventional ε -constraint method providing remedies for its well-known pitfalls such as generating weak Pareto optimal and redundant solutions (Mavrotas, 2009). In the ε -constraint method, one of the objective functions is optimized while the other objective functions are used as constraints. Finally, it results in the exact calculation of the Pareto optimal front. The Pareto optimal front is the set of Pareto optimal solutions. The AUGMECON method is available in a number of different modeling languages, including GAMS (general algebraic modeling language, www.gams.com). The interested reader is referred to Mavrotas (2007, 2009) for further details of the AUGMECON method.

Integrating LCA with MCDA or in MOOP is a new and emerging research field (Banasik et al., 2016). Attempts to integrate a fully consequential LCA perspective in an environmental multi-objective optimization problem formulation are scarce in the literature (Vadenbo et al., 2017). There are already case studies in the domain of waste management and the use of biomass resources for energy and material recovery supporting the potential of this approach. Vadenbo et al. (2017) develop a multi-objective optimization model to systematically identify the environmentally optimal use of biomass for energy under a given system's constraints. Minciardi et al. (2008) use Multi-objective optimization of solid waste flows to determine environmentally sustainable strategies for municipalities. The results of this study can help stakeholders formulate sustainable material supply strategies that minimize the associated environmental impacts and material costs while meeting demand and emission targets.

To the best of our knowledge combining LCA with MCDA or in MOOP has not yet been considered for the assignment of green waste to material and/or energy valorization. Green waste valorization has been studied in the literature from a sustainability point of view, taking into account the three areas of sustainability assessment, people-planet-profit, (Morrissey and Browne, 2004; Inghels et al., 2016), as well as from a single environmental standpoint (Kranert et al., 2010).

Given that a comparative LCA according to ISO 14040+44 (2006 a+2006b) results in the preferred selection of one green waste valorization process (i.e., either composting or energy recovery) and given that the assignment of green waste to composting and/or energy recovery is not to be classified into a finite set of alternatives in advance, the optimal trade-off, assuming green waste is used for both products, may be formulated as a MOOP. Depending on the situation, decision makers can assign green waste to composting or to energy recovery, or to a combination of both, taking all other relevant objectives such as the minimization of particulate matter into account. This approach is described in the next section.

3. A MOOP formulation for the green waste valorization problem

The process of green waste management is best evaluated on its own as a gate-to-gate system since green waste is a natural product, in contrast to products in general, which have a complete product life cycle (Grant, 2003). Therefore we consider only the processes that deal with composting and incineration with energy

valorization in the green waste valorization problem, further denoted as GWVP. We do not take into account the collection and transport of green waste, as this is the same for both valorization options applied to the case study of the densely populated countries of Belgium and the Netherlands (OVAM, 2016; SenterNovem, 2008). In general, the influence of collection and transportation on the final results of LCA studies on solid waste management is limited (Laurent et al., 2014b). Only in some regions where waste collection is widely spatially distributed also spatial considerations should be considered (Raviv et al., 2018). However, we do take into account the environmental effects of substituting green waste for composting (i.e. peat replacement) and energy valorization (i.e. replacement of coal). To assess environmental impact to divert from the EU Waste Directive 2008/98/EC (EP&C, 2008), environmental impact indicators must be selected. To support environmental policies, the European Environmental Agency (EEA, 2014) maintains an extensive set of 137 environmental indicators, based on statistics from international organizations and EU partners, as well as on national data indicators. Among the set of indicators, those for air pollution, climate change and energy are relevant for the subject of this paper.

The GWVP consists of finding a set of best-decision vectors over a single planning period that maximizes the output of compost and waste-to-energy by means of incineration with energy recovery (referred to hereafter as waste-to-energy, WTE) and minimizes the environmental impacts (see Section 3.4. for the life cycle impact categories taken into account) subject to several constraints. The outcome of the MOOP is a set of Pareto optimal solutions guaranteeing the best outcome for the options under study and complying with the EU waste Directive 2008/98/EC (EP&C, 2008), which allows diversion from the waste hierarchy and prefers composting to incineration with energy recovery if it leads to an equivalent or better environmental outcome. A batch of one ton of green waste of average composition for the Low Countries (i.e. the Netherlands and Belgium) will be taken as functional unit.

3.1. The basic system and its notation

Fig. 1 provides an overview of the waste flows and introduces the necessary notation. The decision variables in the constrained optimization problem are the mass amounts (in tons) of three different green waste components to be sent to two different destinations, denoted as $x_{c,d}$ (c = component and d = destination). The green waste components $c = \{w, l, g\}$ are wooden prunings, indexed as “w”, leaves “l” and grass “g” (in general the components w, l and g are referred to as component n in the blend of green waste) and the destinations $d = \{c, i\}$ are composting “c” and incineration “i”. The total amount of a component or the total destination is denoted as “*” (e.g., the total amount of wooden material is

Fig. 1. Overview of the green waste management system.

Table 1
Characteristics of main components of green waste (source: Phylis database; the following numbers indicated with “#” refer to the number in the Phylis database; Excess fraction wood from organic domestic waste composting plant x_w (#1295), Grass, x_g (#613), Withered leaves, x_c (#3065)).

Component n	Carbon content C_n [%wt]	Nitrogen content N_n [%wt]	Dry energy content $LHV_{dry,n}$ [MJ/kg]	Moisture content M_n [%]	Wet energy content $LHV_{wet,n}$ [MJ/kg]
Wood (w)	30.63	0.92	12.60	9.90	11.11
Grass (g)	18.58	0.53	17.04	60	5.35
leaves (l)	20.23	0.69	11.93	32.95	7.20

denoted as $x_{w,*}$ and the total amount of green waste to be composted is denoted as $x_{*,c}$.

The green waste batch will be composted and/or incinerated with energy recovery, which is also known as Waste To Energy (WTE). During the composting process gases and water are emitted. Process gases are also emitted during WTE as result of incineration. Fig. 1 refers to the goal functions Z_j ($j = (1, 2, 3)$) that will be explained in the next sections.

We make use of the Phylis database (ERCN, 2017) to determine the carbon, nitrogen and moisture content, which are important parameters for the composting process, as well as the Lower Heating Value (LHV) to determine the energy valorization of green waste as depicted in Table 1. The effect of the moisture content in biomass on the LHV is expressed by Eq. (3.1) (see Fowler et al., 2009) in which M_n is the moisture content of component n in the blend expressed in %.

$$LHV_{wet,n} = LHV_{dry,n} \cdot (1 - M_n) - 2.442 \cdot M_n \quad (3.1)$$

The mass of the green waste $x_{*,*}$ is assumed to be fully composted and/or incinerated. This is expressed in Eq. (3.2).

$$x_{wi} + x_{wc} + x_{gi} + x_{gc} + x_{li} + x_{lc} = x_{*,*} [\text{ton}] \quad (3.2)$$

3.2. First objective function: maximizing composting yield

Following the EU waste Directive 2008/98/EC (EP&C, 2008), the material in the green waste mixture should be assigned to composting. During composting, gasses and water are emitted to the ambient environment resulting in a weight loss expressed in the compost yield factor γ_c , which is dependent on the green waste blend (see Section 3.6). Therefore the first objective is:

$$\text{Maximize } Z_1 = x_{*,c} \cdot \gamma_c = (x_{wc} + x_{gc} + x_{lc}) \cdot \gamma_c [\text{ton}] \quad (3.3)$$

3.3. Second objective function: maximizing waste to energy

The objective function for the energy valorization of green waste by incineration, Z_2 , is given by Eq. (3.4) using the lower heating values (LHV), also known as net calorific values (NCV) or lower calorific values (LCV), for wooden prunings, grass, and withered leaves (see Table 1). LHV calculations assume that the water component of a combustion process is in a vapor state at the end of combustion and that the latent heat from water vaporization in the fuel and reaction products is not recovered. Note that in Table 1 the LHV is expressed in [MJ/kg] and that the mass $x_{n,*}$ of component n is expressed in tons resulting in an outcome expressed in [GJ] in Eq. (3.4). By taking the energy conversion efficiency η into account, Z_2 expresses the net electrical power that is generated by the incineration of green waste. The energy conversion efficiency η is defined as the ratio between the useful output (in this case electrical power and heat) of an energy conversion machine and the input (in this case green waste) in energy terms. Taking these considerations into account, the second objective is expressed as:

$$\text{Maximize } Z_2 = (LHV_{wet,w} \cdot x_{wi} + LHV_{wet,g} \cdot x_{gi} + LHV_{wet,l} \cdot x_{li}) \cdot \eta [\text{ton}] \quad (3.4)$$

The functions Eq. (3.3) and Eq. (3.4) represent opposing trends. The more green waste mass is assigned to energy recovery, the less it will be assigned to compost according to Eq. (3.2).

Practically, green waste could be used as co-firing in coal-fired energy plants in Belgium and the Netherlands. In general, the energy conversion efficiency of a steam turbine of a coal-fired power plant ranges between 39 and 47% whereas a conventional biomass-fired power plant ranges between 30 and 40% and a pure waste-fired power plant ranges between 22 and 28% (VGB, 2003). Since green waste can be considered as biomass in case of fuel used for the production of power (VITO, 2007), we use an energy conversion efficiency of $\eta = 35\%$ in the GWVP case.

3.4. Third objective function: minimizing the environmental impact

For the environmental impact, we rely on the outcome of the SenterNovem (2008) LCA representing the total normalized environmental impacts of composting and energy valorization expressed in dimensionless points [pt] by comparing them with the total environmental impact related to the economic activities in the Netherlands in 1997. The life-cycle impact (LCI) categories taken into account are abiotic depletion, global warming, ozone layer depletion, acidification, eutrophication, photochemical oxidant, and eco-toxicity. The total normalized environmental impact of composting and energy recovery is represented by:

$$\text{Minimize } Z_3 = l_c \cdot (x_{wc} + x_{gc} + x_{lc}) + l_i \cdot (x_{wi} + x_{gi} + x_{li}) [\text{pt}] \quad (3.5)$$

where l_c is the total environmental impact per kg of composted waste and l_i is the total environmental impact per kg of incinerated waste. Senter Novem (2008) gives estimates of these coefficients: $l_c = -575$ pt/kg and $l_w = -1710$ pt/kg.

The negative sign denotes the net savings in total environmental impact. Although composting and incineration have impacts on the environment, they also lessen environmental impact by avoiding impacts from primary production. Both for composting and incineration, on balance, more impact is saved than created.

3.5. The first constraint

The objectives described above are subject to several constraints. First, we assume an optimal composition for composting. Compost practitioners divide material to be composted into brown and green mass. Material with a carbon/nitrogen (C/N) ratio larger than 30 is called ‘brown’ mass and material with a C/N ratio less than 30 is called ‘green’ mass². Composting green waste needs a proper ratio of carbon-rich materials called ‘browns’ such as dried leaves and prunings, as well as nitrogen-rich materials called ‘greens’ such as grass. If the C/N ratio of compost deviates from the optimal ratio, negative environmental impact arises. A too high C/N ratio results in a loss of nitrogen in the soil and a too low C/N ratio results in a compost product that does not help to improve the structure of the soil (Bhange et al., 2012). The C/N ratio, indicated by R , in our case is given as:

² See: www.homecompostingmadeeasy.com

$$R = \frac{x_{wc} \cdot C_w \cdot (100 - M_w) + x_{gc} \cdot C_g \cdot (100 - M_g) + x_{lc} \cdot C_l \cdot (100 - M_l)}{x_{wc} \cdot N_w \cdot (100 - M_w) + x_{gc} \cdot N_g \cdot (100 - M_g) + x_{lc} \cdot N_l \cdot (100 - M_l)} \quad (3.7)$$

To obtain a desired R ratio, Eq. (3.7) can be solved exactly for a mixture of two materials, whose carbon, nitrogen and moisture contents are known. Mixtures of three or more materials can be solved for the mass of the third material if the first two are specified. Given the carbon, nitrogen and moisture content of each material in the compost blend, the desired amount of the third material to comply with a desired R ratio is given by Eq. (3.8). The mass of the prunings, x_{wc} , is chosen as the third material to be assigned to composting since this is the main material to be incinerated.

$$x_{wc} = \frac{R \cdot x_{gc} \cdot N_g \cdot (100 - M_g) + R \cdot x_{lc} \cdot N_l \cdot (100 - M_l) - x_{gc} \cdot C_g \cdot (100 - M_g) - x_{lc} \cdot C_l \cdot (100 - M_l)}{C_w \cdot (100 - M_w) - R \cdot N_w \cdot (100 - M_w)} \quad (3.8)$$

The yield obtained from composting a certain mass of green waste, $x_{wc} + x_{gc} + x_{lc}$, derived from the incoming batch of green waste of mass $x_{w,*}$ is dependent on the composition of the blend according to [Vlaco \(2010\)](#) based on experiments carried out at a composting site in Flanders, Belgium. Following the insights of composting practitioners, the maximum compost yield $\gamma_c = 0.35$ is reached when the amount of brown mass in the green waste blend equals the amount of green mass. Moreover, high-quality composting is impossible if only brown or green mass is used in the green waste blend. In this paper, we assume that compost practitioners will strive for the optimal R -ratio of about 30, which corresponds to common practice. In [Section 4](#) we calculate the R -ratio for the case study.

3.6. Other constraints

There are also limitations on the amount of green waste to be assigned to composting or waste recovery. A conventional blend of green waste consists of a wooden fraction, $x_{w,*}$, of fresh prunings, grass, $x_{g,*}$, and leaves, $x_{l,*}$, that can be assigned either to composting or energy recovery:

$$x_{wc} + x_{wi} = x_{w,*} \quad [\text{ton}] \quad (3.9)$$

$$x_{gc} + x_{gi} = x_{g,*} \quad [\text{ton}] \quad (3.10)$$

$$x_{lc} + x_{li} = x_{l,*} \quad [\text{ton}] \quad (3.11)$$

Finally, all masses are positive numbers.

$$x_{wc}, x_{gc}, x_{lc}, x_{wi}, x_{gi}, x_{li} \geq 0 \quad [\text{ton}] \quad (3.12)$$

4. Solving the green waste valorization problem

4.1. Generating the Pareto front

The green waste valorization problem, GWVP, has conflicting objective functions. The objective functions and constraints are linear in the decision variables. This allows using the ε -constraint method to generate the efficient frontier and solve the multi-objective problem. The problem-solving approach will be illustrated using the practical case of green waste valorization in the Low Countries (Belgium and the Netherlands). The optimal assignment of a batch of green waste with $x_{w,*} = 1$ ton (the functional unit) to composting and/or WTE will be taken as an example. According to [SenterNovem \(2008\)](#), the regular green waste composition of 1 ton green waste is $x_{w,*} = 0.6$ ton wooden prunings, $x_{g,*} = 0.2$ ton grass and $x_{l,*} = 0.2$ ton leaves. Following Eq. (3.7) this corresponds with an R ratio of $R = 32.83$. Given this R ratio, the compost yield

may be assumed to be equal to $\gamma_c = 0.35$ which corresponds with the maximum yield ([Vlaco, 2010](#)).

Since we assume that compost practitioners always strive for an optimal blend, the mass fractions to be composted are calculated using the carbon, nitrogen and moisture content of the ‘regular’ compost mixture depicted in [Table 1](#) and $R = 32.83$. Using these input values, Eq. (3.8) can be rewritten as Eq. (4.1):

$$x_{wc} = \frac{162.45 \cdot x_{lc} - 47.20 \cdot x_{gc}}{38.41} \quad (4.1)$$

In the ε -constraint method, one of the objective functions is optimized using the other objective functions as constraints. For the GWVP case, the objective function Eq. (3.3) to maximize composting will be optimized, and the other linear objective functions Eq. (3.4) and Eq. (3.5) will be incorporated with the other constraints. As a result, the set of constraints remains linear.

Since all objective functions must be written as maximization objectives, the minimization objective Eq. (3.5) is transferred into maximization objectives using the duality principle *Minimize $Z_j = \text{Maximize } (-Z_j)$* . The problem can then be reformulated as follows.

Following [Mavrotas and Florios \(2013\)](#) and [Mavrotas \(2009\)](#), the ε -constraint method forces a constrained problem to produce only efficient solutions by adding a factor to the first objective function. Furthermore, the ranges of the objective function are divided into equal intervals proportional with the number of grid points chosen. Since 10 grid points are used in the case study presented, each of the ranges is divided into 10 equal intervals. The right-hand-side value of the objective functions Z_2 and Z_3 are assigned a value e_2 and e_3 . These e -values range proportionally between the lowest and highest value in the payoff table for Z_2 and Z_3 . Furthermore, the ranges of the respective objective functions Z_j are r_2, r_3 ; a range r_j is the difference between the highest and lowest value in the payoff table for Z_j . Finally, S_2, S_3 are the slack or surplus variables of the respective constraints and $\varepsilon \in [10^{-6}, 10^{-3}]$.

The problem defined in [Section 3](#) can now be applied to the practical case study that is solved using the ε -constraint method. This results in the following Linear Programming model:

$$\text{Maximize } (x_{wc} + x_{gc} + x_{lc}) \cdot 0.35 + \varepsilon \cdot \left(\frac{S_2}{r_2} + \frac{S_3}{r_3} \right) \quad (4.2)$$

Subject to:

$$3.89 \cdot x_{wi} + 1.87 \cdot x_{gi} + 2.52 \cdot x_{li} - S_2 = e_2 \quad (4.3)$$

$$575 \cdot (x_{wc} + x_{gc} + x_{lc}) + 1710 \cdot (x_{wi} + x_{gi} + x_{li}) - S_3 = e_3 \quad (4.4)$$

$$x_{wc} + x_{wi} = 0.6 \quad [\text{ton}] \quad (4.5)$$

$$x_{gc} + x_{gi} = 0.2 \quad [\text{ton}] \quad (4.6)$$

$$x_{lc} + x_{li} = 0.2 \quad [\text{ton}] \quad (4.7)$$

$$38.41 \cdot x_{wc} + 47.20 \cdot x_{gc} - 162.45 \cdot x_{lc} = 0 \quad [\text{ton}] \quad (4.8)$$

$$x_{wc}, x_{gc}, x_{lc}, x_{wi}, x_{gi}, x_{li} \geq 0 \quad [\text{ton}] \quad (4.9)$$

Efficient solutions to the problem are obtained by parametric variation of the variables on the RHS of the second and third constrained objective functions (e_2 and e_3) (see [Mavrotas, 2009](#)). Solving the MOOP results in a payoff table, expressing the results of individual optimization of objective functions, as depicted in [Table 2](#). According to [Deb \(2009\)](#), the optimal objective values of each single-objective optimization model Z_j form the components of the ideal point vector f_j^* for the multi-objective problem under investigation.

Table 2
payoff table GWVP case study.

	Z_1 : Compost [ton]	Z_2 : Energy [GJ]	Z_3 : Normalized environmental impact [pt]
Max Z_1	0.350 (f_1^*)	6.205×10^{-5}	−575.028
Max Z_2	0	3.212 (f_2^*)	−1710.000
Min Z_3	0	0	−1710.000 (f_3^*)
Range r_2		3.212	
Range r_3			1135.014

The ε -constraint module of GAMS (www.gams.com) is used to solve the problem formulated above. This module is based on linear programming.

The results of the GAMS optimization procedure with 10 grid points for ε_j lead to the Pareto optimal front shown per objective in Fig. 2. Since we depict a three dimensional Pareto front in a two-dimensional figure, the total number of solutions exceed 10. The Pareto optimal front depicted clearly shows the conflicting objectives: the more green waste is assigned to compost, the less it is assigned to energy recovery and, consequentially, the less CO_{2e} is emitted.

4.2. Determining a final single solution

If a single optimal solution is to be determined on the Pareto optimal front, a decision maker can assign ex-post to each criterion j (corresponding to an objective function) a weighting factor, w_j , representing its importance so that the total of all weighting factors equals 1. Next, for each single-objective solution s of the optimal solutions set, the distance to the ideal point f_j^* is weighted by the chosen weights f_j^* to obtain a weighted percentage deviation factor (WPD_s). The value f_j^* of the j th objective function is then calculated for all solutions s of the Pareto optimal set, and compared with the ideal point value of the j th objective function f_j^* . This ideal

point value is formed by the optimal results per objective function of each assessed alternative depicted in the payoff table.

$$WPD_s = \sum_{j=1}^3 w_j \cdot \left[\frac{|f_j^s - f_j^*|}{f_j^*} \right] \quad (5.1)$$

This method is applied to the Pareto optimal front population of the case discussed in Section 3 and the results are depicted in Table 3.

The outcome with the lowest WPD_s factor is the preferred outcome since this corresponds with the weighted sum of all outcome objectives lying closest to the ideal points for all objectives. All solutions depicted in Fig. 2 belong to the Pareto optimal front. Table 3 shows that if the three objectives are equally weighted ($w_j = 1/3$ for all j), WTE is preferred ($s = 1$). Moreover, Table 3 shows the effect of varying the weighing factors assigned by the policy makers to represent their preference. The optimal outcome shifts depending on the assigned weighting factor values representing the importance assigned to each of the four objectives. If equal importance is assigned to composting and energy recovery ($w_{1,2} = 0.5$), and if no importance is assigned to life cycle impact categories ($w_3 = 0$), 29% of the green waste is assigned to compost and the reminder to energy recovery ($s = 6$).

If compost is promoted above WTE and little importance is assigned to life cycle impact categories ($w_1 = 0.6$, $w_{2,3} = 0.2$), composting is preferred above WTE ($s = 20$).

If WTE is preferred above composting and little importance is assigned to life cycle impact categories ($w_2 = 0.6$, $w_{1,3} = 0.2$), the preferred option is WTE ($s = 1$). An identical outcome is obtained when the highest importance is assigned to the outcome of the life cycle impact categories and lower importance is assigned to both compost and WTE ($w_3 = 0.6$, $w_{1,2} = 0.2$).

The GWVP case study shows that, depending on the decision makers' preferences, the presented methodology allows assignment of green waste valorization to a variety of fractions of

Fig. 2. Pareto optimal front of the GWVP case study separately depicted for each objective for 20 solutions of the MOOP solver in GAMS, the Y-axis dimensions for each objective are reported in the legend between brackets.

Table 3

WPDs values of the GWVP case study discussed in Section 3 for five sets of weighing factors. The lowest WPDs value, indicated in bold, corresponds with the preferred compost and WTE valorization fraction.

Nr s	Compost [ton]	WTE [GJ]	LCI [pt]	WPD _s				
				$w_{1,2,3} = 1/3$	$w_{1,2} = 0.5, w_3 = 0$	$w_1 = 0.6, w_{2,3} = 0.2$	$w_2 = 0.6, w_{1,3} = 0.2$	$w_3 = 0.6, w_{1,2} = 0.2$
1	0.00	3.21	−1710.00	0.334	0.500	0.600	0.200	0.200
2	0.03	3.01	−1596.5	0.348	0.489	0.574	0.234	0.235
3	0.06	2.89	−1529.2	0.345	0.464	0.538	0.247	0.249
4	0.07	2.81	−1483.01	0.353	0.463	0.532	0.262	0.265
5	0.10	2.54	−1369.51	0.374	0.462	0.510	0.308	0.304
6	0.10	2.57	−1378.89	0.369	0.457	0.507	0.302	0.299
7	0.13	2.25	−1278.41	0.393	0.464	0.488	0.356	0.337
8	0.14	2.18	−1256.01	0.396	0.461	0.477	0.366	0.344
9	0.16	1.93	−1177.93	0.418	0.471	0.468	0.410	0.375
10	0.17	1.81	−1142.51	0.428	0.475	0.462	0.431	0.389
11	0.20	1.61	−1077.44	0.432	0.464	0.431	0.459	0.407
12	0.21	1.45	−1029.02	0.449	0.474	0.429	0.489	0.429
13	0.23	1.28	−976.96	0.458	0.472	0.412	0.515	0.446
14	0.24	1.09	−915.52	0.480	0.487	0.414	0.552	0.474
15	0.26	0.96	−876.48	0.482	0.479	0.392	0.570	0.484
16	0.28	0.73	−802.02	0.501	0.486	0.381	0.610	0.513
17	0.29	0.64	−775.99	0.506	0.486	0.372	0.624	0.522
18	0.31	0.36	−688.53	0.533	0.501	0.366	0.675	0.559
19	0.32	0.32	−675.51	0.530	0.493	0.352	0.678	0.560
20	0.35	0.00	−575.03	0.555	0.500	0.333	0.733	0.598

compost and WTE, rather than to only one of them, as is the case with LCA assessment.

Next, we examine the sensitivity of the outcome of the MOOP by selecting only CO_{2e} emissions since this the most important life-cycle impact category on which to assess environmental impact as specified by the EU Waste Directive. According to SenterNovem (2008) and Kranert et al. (2010) both composting and incineration with energy recovery of green waste result in net CO_{2e} savings. Moreover, Vaughan et al. (2011) report that green waste compost has the potential to reduce emissions of N₂O, an important greenhouse gas. Green waste used as biomass feedstock for co-firing in conventional energy plants substantially reduces the CO₂ emission of power production compared to regular power production (Baxter, 2005; Kwant, 2003). Since the report of SenterNovem does not disclose specific data for these CO_{2e} savings, we rely on the data published by Kranert et al. (2010) and Boldrin et al. (2009). Following Kranert et al. (2010) for a green waste mixture with a high fraction of woody material and a small fraction of herbaceous material, which is most similar to the composition used in this paper, the net CO_{2e} savings for green waste as a substitute for peat fertilizer is 675 kg CO_{2e}/ton green waste. Depending on the origin of peat and the related transport distances, Boldrin et al. (2009) report CO_{2e} savings from 77 up to 838 kg CO_{2e}/ton green waste. Taken the high variation in CO_{2e} savings into account, we use a mean value of 530 kg CO_{2e}/ton green waste CO_{2e} savings. For the substitution of coal by green waste as an energy source, we take an LHV of hard coal of 25.75 MJ/kg into account (Staffell, 2011) and an LHV = 13.354 MJ/kg for green waste for the composition as discussed in Section 4.1. Following WNA (2011), the mean CO_{2e} emission for electricity generation using coal is 888 kg CO_{2e}/MWh and for biomass 45 kg CO_{2e}/MWh. Therefore the substitution of coal by green waste for power production will induce savings of 801 kg CO_{2e}/ton green waste.

These data are used in the equation for the minimization of CO_{2e}, Z₃, replacing Z₃:

$$\text{Minimize } Z'_3 = -530 \cdot (x_{wc} + x_{gc} + x_{lc}) - 801 \cdot (x_{wi} + x_{gi} + x_{li}) [\text{kgCO}_{2e}] \quad (5.2)$$

Solving the GWVP MOOP with the alternative third objective Z₃, results in the alternative payoff table depicted in Table 4 and an alternative Pareto optimal front depicted in Fig. 3, for 10 grid points resulting in 20 solutions.

Table 4

Alternative payoff table for the GWVP case study taking into account only CO_{2e} for the third objective Z₃.

	Z ₁ : Compost [ton]	Z ₂ : Energy [GJ]	Z ₃ : CO _{2e} [kg]
Max Z ₁	0.350 (f₁)	6.205 × 10 ^{−5}	−530.007
Max Z ₂	0	3.212 (f₂)	−801.000
Min Z ₃	0	3.212	−801.000 (f₃)
Range r ₂		3.212	
Range r ₃			270.993

The execution time for the revised GWVP MOOP in GAMS is 27 s on a personal computer with a 1.66 GHz processor and 10.99 GB RAM. The outcome of the data points on the Pareto optimal front and the preferred solution using the WPDs approach is depicted in Table 5.

The results depicted in Table 5 indicate the same preference for assigning green waste valorization to either composting or to energy valorization as depicted in Table 3 apart from the decision makers' preference to assign the same weight to composting, WTE and CO_{2e} emissions. In case w₁ = w₂ = w₃ = 1/3, the optimal outcome is to assign 17% to compost and the remainder to WTE. This differs from the situation where all life cycle impacts were taken into account (see Table 3 for w₁ = w₂ = w₃ = 1/3) showing a clear preference for full assignment to WTE. This is caused by the fact that when only considering the CO_{2e} emissions, the impact on CO_{2e} saving is less explicit between full composting and full WTE valorization compared with taking all the life cycle impacts into account.

5. Discussion

This paper examined whether MCDA could be used as a methodology for environmental policy makers to support them in assigning green waste to compost and energy valorization taking conflicting objectives into account. Two European Directives have conflicting goals with respect to the valorization of green waste: The Waste Directive promotes composting and the Renewable Energy Directive calls for incineration with energy recuperation. Both valorization options have different net savings in total environmental impact. Using LCA as a tool will result in either allocat-

Fig. 3. Alternative Pareto optimal front for the GWVP case study taking into account only CO_{2e} for the third objective Z_3 , the Y-axis dimensions for each objective are reported in the legend between brackets.

Table 5

optimal solutions of the GWVP MOOP using the alternative objective function Z_3 representing only the CO_{2e} impact associated with composting and WTE.

Solution nr. s	Compost [ton]	WTE [GJ]	CO _{2e} [kg]	WPD _s				
					$w_{1,2,3}=1/3$	$w_{1,2}=0.5, w_3=0$	$w_1=0.6, w_{2,3}=0.2$	$w_2=0.6, w_{1,3}=0.2$
1	0.00	3.21	−801.00	0.334	0.500	0.600	0.200	0.200
2	0.03	3.01	−773.90	0.337	0.489	0.568	0.227	0.216
3	0.06	2.89	−757.83	0.328	0.464	0.528	0.237	0.218
4	0.07	2.81	−746.80	0.331	0.463	0.519	0.249	0.226
5	0.10	2.54	−719.70	0.342	0.462	0.491	0.289	0.246
6	0.10	2.57	−721.94	0.338	0.457	0.488	0.283	0.242
7	0.13	2.25	−697.95	0.352	0.464	0.463	0.331	0.263
8	0.14	2.18	−692.60	0.352	0.461	0.451	0.340	0.265
9	0.16	1.93	−673.96	0.367	0.471	0.437	0.380	0.284
10	0.17	1.81	−665.50	0.373	0.475	0.430	0.399	0.292
11	0.20	1.61	−649.97	0.372	0.464	0.395	0.423	0.299
12	0.21	1.45	−638.40	0.384	0.474	0.390	0.450	0.312
13	0.23	1.28	−625.97	0.388	0.472	0.370	0.473	0.320
14	0.24	1.09	−611.30	0.404	0.487	0.368	0.507	0.337
15	0.26	0.96	−601.98	0.402	0.479	0.344	0.522	0.341
16	0.28	0.73	−584.21	0.414	0.486	0.329	0.558	0.357
17	0.29	0.64	−577.99	0.417	0.486	0.319	0.570	0.361
18	0.31	0.36	−557.11	0.436	0.501	0.307	0.617	0.383
19	0.32	0.32	−554.00	0.431	0.493	0.293	0.619	0.382
20	0.35	0.00	−530.01	0.446	0.500	0.268	0.668	0.403

ing green waste completely to compost or energy recovery. Using a consequential LCA approach, the environmental impact of both valorization options could be compared with each other but the outcome will never lead to an allocation of both green waste valorization options. Minimizing the life cycle impact of composting and energy valorization of green waste together with maximizing compost and energy valorization in a MOOP allows generating a set of Pareto-optimal solutions that simultaneously optimize all objectives of the policy decision maker. The final selection of the optimal allocation to compost and /or energy valorization depends on adding the decision makers' preference based on the relative importance of the objectives to be optimized. The outcome of the

case study discussed, is that in particular cases the proposed MCDA methodology could lead to an optimal allocation of a part to compost and the remainder to energy recovery. In the discussed case study, this is the case when the decision maker has good reason to allocate equal importance to compost and energy valorization and ignoring the associated life cycle impact or CO_{2e} emissions (see Tables 3 and 5). Depending on the situation other preference weights can be assigned leading to another optimal outcome. In any case, the presented methodology guarantees the selection of an outcome for the decision maker that is Pareto-optimal meaning that there is no better optimal solution given the objectives and constraints.

In extension, the presented methodology enables to also take social, economic, policy or any other objective into account. Hence, this approach allows policy decision makers to make balanced decisions knowing that the outcome will be optimal giving the objectives to be met simultaneously. As such, the approach can be considered as a vehicle for carrying out life cycle sustainability analyses (LCSA), an approach that is in line with ISO's observation that LCA may be extended to social and economic objectives (ISO 14040+44, a & b), and which has been popularized by Klöpffer (2008). Often in decision-making, decision-makers have multiple goals that have to be satisfied and therefore they need to be supported with techniques enabling them to make these balanced decisions. Therefore, this methodology is better suited for policy makers than a comparative LCA method that leads to the exclusive assignment of green waste to either compost or energy valorization without taking other non-environmental objectives into account.

Belgium and the Netherlands are both countries that have difficulties to comply with the EU Directive 2009/28/EC on the promotion of the use of renewable energy. Using the proposed methodology in this paper, policy makers of these countries could argue to divert partially or completely from the allocation of green waste to compost in case their preferences for the objectives can be justified. This approach complies with the Waste Directive 2008/98/EC that obliges EU member states to select the valorization option that delivers the best environmental outcome. The EU advocates life cycle thinking in determining the best environmental outcome but does not impose LCA as the sole methodology. Combining the life cycle impact assessments of an LCA on green waste valorization with the objectives of compost and energy valorization of green waste can be considered as a methodology that yields a set of optimal environmental outcomes including life cycle thinking.

It should be noted that the results of the case study discussed in this paper are first of all applicable to Belgium and the Netherlands. The conclusion of Laurent et al. (2014) based on a comprehensive literature review on LCA studies of solid waste management systems (SMWS) is therefore also applicable to this case study. Laurent et al. (2014a) conclude that the strong dependence of each SMWS on its context or local specificities prevents a consistent generalization of LCA studies. In Belgium and the Netherlands, the infrastructure is available for composting and energy valorization of green waste. Both countries have a good infrastructure in place to collect green waste and have a good track record in recycling and recovering of Municipal Solid Waste, the waste category to which green waste belongs (EEA, 2013). This is e.g. not the case for some other EU Member States, such as Greece, Malta and Latvia that also face difficulties to meet the EU 2020 renewable energy targets and where more than 80% of municipal waste is still landfilled (EPSU, 2017). In this paper, we discussed composting and incineration with energy recuperation as valorization options for green waste. In general, the waste management options for green waste and bio-waste, include prevention at source, anaerobic digestion and composting, incineration, and landfilling. The environmental and economic benefits of different treatment methods depend significantly on local conditions such as population density, infrastructure, and climate as well as on markets for energy and composts (Interreg Europe, 2017).

6. Conclusions

Traditionally the ISO 14040+44 (2006 a+b) standard on comparative life-cycle assessment (LCA) is the preferred method for assessing the environmental impact of products and processes. This paper, using green waste valorization as a case study,

demonstrates that decision makers could benefit from using a multi-objective optimization approach, in which the LCA assessment outcome is used as an input for the environmental objective along with other relevant objectives.

To the best of our knowledge, the presented approach is the first to offer the possibility of detecting a range of optimal assignments of green waste both to composting and to energy valorization, rather than limiting the choice to a single assignment to one of these two processes as LCA does.

Moreover, the study demonstrates the importance of selecting the environmental impact categories to represent the environmental impact as required in the EU Waste Directive. In the case of green waste valorization, minimizing the most common life-cycle impact categories, while maximizing compost and energy valorization, results in assigning green waste to different combinations of composting and energy valorization depending on the assigned weighting factors associated to the three objectives.

This insight is important since, according to the EU Waste Directive, one may divert from composting green waste if it can be proved that the total environmental impact of an alternative solution is better. Because it is not prescribed how to determine the environmental impact, policy makers can present different optimal assignment solutions based on the life-cycle impact categories they select to determine environmental impact. This stresses the importance of defining more strictly how to determine the environmental impact.

The approach presented in this paper could be extended with objective functions representing the economic and societal impacts of composting and energy recovery of green waste. Moreover, this methodology can be applied to any other waste stream. In this way, the presented approach could be used as a generic method for sustainability assessment.

Acknowledgments

This research was partially funded by research project 5598 of the University of Antwerp, Belgium. This support is gratefully acknowledged.

Dirk Inghels has prepared the manuscript under supervision of Wout Dullaert; El-Houssaine Aghezzaf and Reinout Heijungs contributed with revising the manuscript based on their expertise in Multi Criteria Decision making and Life Cycle assessment.

Disclaimer

The views presented in this paper reflects the view of the authors on this subject and have no other intention than stimulating the debate on the use of Operations Research techniques in achieving sustainable development. These views do not necessarily reflect the opinions of the organizations cited or the stakeholders involved.

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