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# Assessment of environmental and economic feasibility of Enhanced Landfill Mining

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ABSTRACT

This paper addresses the environmental and economic performance of Enhanced Landfill Mining (ELFM). Based on life cycle assessment and life cycle costing, a detailed model is developed and is applied to a case study, i.e. the first ELFM project in Belgium. The environmental and economic analysis is performed in order to study the valorisation of different waste types in the landfill, such as municipal solid waste, industrial waste and total waste. We found that ELFM is promising for the case study landfill as greater environmental benefits are foreseen in several impact categories compared to the landfill's current situation (the 'Do-nothing' scenario). Among the considered processes, the thermal treatment process dominates both the environmental and economic performances of ELFM. Improvements in the electrical efficiency of thermal treatment process, the calorific value of refuse derived fuel and recovery efficiencies of different waste fractions lead the performance of ELFM towards an environmentally sustainable and economically feasible direction. Although the environmental and economic profiles of ELFM will differ from case to case, the results of this analysis can be used as a benchmark for future ELFM projects.


## 1. Introduction

Despite the increasing amount of waste being reused, recycled or energetically valorised, landfills continue to play an important role in waste management strategies. According to Eurostat (2011), 40% of waste in EU-27 is still landfilled. Landfilling contributes to several environmental problems such as global warming, acidification, depletion of the quality of ecosystem and pollution of surface and groundwater, mainly due to long-term methane emissions and leachate production (Crowley et al., 2003; Manfredi and Christenen, 2009; Damgaard et al., 2011). Apart from the direct environmental burdens, the fact that landfills require vast land surfaces has led to land scarcity for the development of human society and ecosystems.

However, landfills can also be regarded as potential reservoirs of resources. In many regions of the world, large amounts of important materials such as metals have accumulated in landfills (Lifset et al., 2002; Kapur and Graedel, 2006; Muller et al., 2006). On a global level, it has been estimated that the amount of copper buried in such deposits (393 million metric tons) is comparable in size to the present stock in use within the technosphere (330 million metric tons) and corresponds to more than 30% of the remaining reserves in known ores (Kapur and Graedel, 2006; Krook et al., 2012). Apart from metals, landfills typically contain significant amounts of combustibles and fines that can be used as potential waste fuels and construction materials, respectively (Hogland et al., 2004; Kurian et al., 2007; Quaghebeur et al., 2013).

The concept of landfill mining has been introduced and practised around the world for over 50 years as a way of re-introducing buried resources into the material cycle and minimising the environmental burden caused by landfill emissions (Hogland, 2002). However, landfill mining has not always been performed with a focus on resource recovery. The majority of the landfill mining studies have focused on conservation of landfill space and remediation, given the difficulty of obtaining permission to develop new landfills (Spencer, 1990; Dickinson, 1995; Cha et al., 1997; EPA, 1997; van der Zee et al., 2004). Landfill mining has occasionally been used to simply restructure the landfill in more solid manner, due to landfill slope instability and inadequate landfill gas and leachate collection systems (Ayalon et al., 2006). However, the landfill mining history also includes some landfill mining projects whose main goal was materials and energy recovery (Cossu et al., 1995, 1996; Canaleta and Ripoll, 2012). There are a few exceptions

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in terms of projects that have explored possibilities for recovery of specifically valuable materials form waste deposits such as metals (Hino et al., 1998), foundry sand (Zanetti and Godio, 2006) and waste fuel for energy generation (Rettenberger, 1995; Obermeier et al., 1997).

Krook et al. (2012) highlighted that the accumulation of massive amounts of strategically important materials in the landfills challenges to change the current view on landfill mining towards a new perspective based on a strategy for extracting valuable material and energy resources. Related to this new perspective, the Enhanced Landfill Mining (ELFM) concept has been introduced with a strong focus on material and energy recuperation and recycling, and eventually regaining the land (Hogland et al., 2010; Jones et al., 2013). Jones et al. (2013) defined ELFM as "the safe conditioning, excavation and integrated valorisation of (historic and/or future) landfilled waste streams as both materials (Waste-to-Material, WtM) and energy (Waste-to-Energy, WtE), using innovative transformation technologies and respecting the most stringent social and ecological criteria". ELFM differs from traditional landfill mining in that it targets the integrated optimisation of materials and energy recovery, while bringing the final residue volume to almost zero and using various techniques to mitigate $CO_2$ emissions. The literature related to ELFM is limited due to the innovative nature of the concept. Jones et al. (2013) presented a constructive review by addressing ELFM as an opportunity for multiple resource recovery. Quaghebeur et al. (2013) presented a characterisation study in order to screen the potential of ELFM for a certain landfill, while Bosmans et al. (2013) performed a study on Waste-to-Energy technologies that could be used in ELFM. Moreover, Van Passel et al. (2013) addressed the carbon footprint and economics of ELFM considering the private and societal performance drivers. Although all of these aspects are definitely important, the knowledge about the critical factors of environmental performance of ELFM must also be developed in order to propel ELFM from the conceptual stage to the operational stage. Although ELFM has already been identified as a productive way to increase resource autonomy in the coming years, it is still necessary to assess the most sustainable exploitation routes in order to maximise the economic return and minimise the environmental burden (Van Acker et al., 2010). This requires an integrated approach that addresses the complex interactions between economic costs and returns on one hand, and environmental considerations associated with ELFM on the other. The methods and findings of the analyses performed for traditional landfill mining can be useful when assessing the environmental and economic performance of ELFM. However, as Krook et al. (2012) explained, although many studies have touched upon economic aspects of landfill mining, there is no common framework for how landfill mining should actually be evaluated; for example, which economic aspects should be accounted for and how these different parameters should be calculated. Most of the studies have discussed the social benefits of landfill mining (Ayalon et al., 2006; Jain et al., 2013; Marella and Raga, 2014; Zhou et al., 2015). Environmental analysis is also lacking for both ELFM and traditional landfill mining. Frändegård et al. (2013) described an approach for environmental evaluation of landfill mining that combined the principles of life cycle assessment and Monte Carlo simulation. The authors focused only on three scenarios comprising landfill remediation and separation of landfilled waste either on-site or off-site; this leaves room for further research to address the full life cycle of landfill mining. Krook et al. (2012) highlighted that standardised frameworks must be developed by applying a prominent systems approach, combining tools such as life cycle assessment and cost benefit analysis to evaluate the critical factors for economic and environmental performance of new landfill mining concepts. Within this framework, Van Passel et al. (2013) performed an integrated evaluation on carbon footprint and the economics of ELFM. However, their assessment is based only on greenhouse gas emission, which allows the possibility of further research on several other environmental impact categories. Furthermore, the authors divided the entire ELFM system only into two major parts: WtM and WtE, which means that identification of the relevance of each process associated with ELFM is restricted to the total environmental and economic impact.

This paper addresses the absence of a proper sustainability evaluation for the novel concept of ELFM. An integrated evaluation based on well-established existing modelling tools: life cycle analysis (LCA) and life cycle costing (LCC) has been performed for the REMO landfill, which is the case study landfill of the first comprehensive ELFM project (the so-called Closing the Circle project of Group Machiels, Belgium). This paper presents a broad evaluation of the various ELFM activities conceived for the case study landfill and the major environmental and economic drivers of ELFM.

## 2. Materials and methods

Section 2.1 describes the process flow for the general ELFM system and for the case study landfill. The evaluation methodology based on LCA and LCC is explained in Section 2.2.

### 2.1. Process flow

#### 2.1.1. General ELFM system

Traditional landfill mining involves the excavation, processing, treatment and/or recycling of deposited materials (Frändegård et al., 2013). Novel ELFM consists of the same activities, but broader attention is given to the valorisation of all types of waste streams such as wastes present in the landfill, and even the wastes generated during processing of the landfilled waste. Fig. 1 is a general and simplified process flow diagram based on these premises. The flow sheet contains six major sections: landfill, inputs, technology, products, final destinations and revenues. The "landfill" section represents the existing situation of the landfill with three types of waste: (i) municipal solid waste and assimilated industrial waste (MSW & AIW), (ii) industrial waste (IW), and (iii) mixed waste (which is applicable when the landfilled waste cannot be distinguished clearly either as MSW & AIW or IW). The "technology" section denotes the main activities identified in ELFM, which are: vegetation and top soil removal, conditioning, waste excavation, separation, transformation of intermediate products and land reclamation. The processes described in the previous landfill mining and landfill reclamation studies have been considered prior to defining the above processes in the general process flow diagram (RenoSam, 2009; Canaleta and Ripoll, 2012; Ritzkowski and Stegmann, 2012; Frändegård et al., 2013; Raga and Cossu, 2014). A detailed explanation of these processes can be found in Danthurebandara et al. (2013). The products can be categorised as (i) intermediate products, (ii) end products (materials, energy, land), (iii) waste products (solid waste and wastewater) and (iv) emissions. The intermediate products can be transformed on-site into valuable material or energy or can be sold to an external company. They can also be temporarily restored if the available technologies for further processing are not sufficient at the moment. These destinations are indicated by the "final destination" block. The disposal category signifies both the temporary disposal of intermediate products and the permanent disposal of waste products. The "revenues" component shows the environmental and economic revenues caused by the products of ELFM.

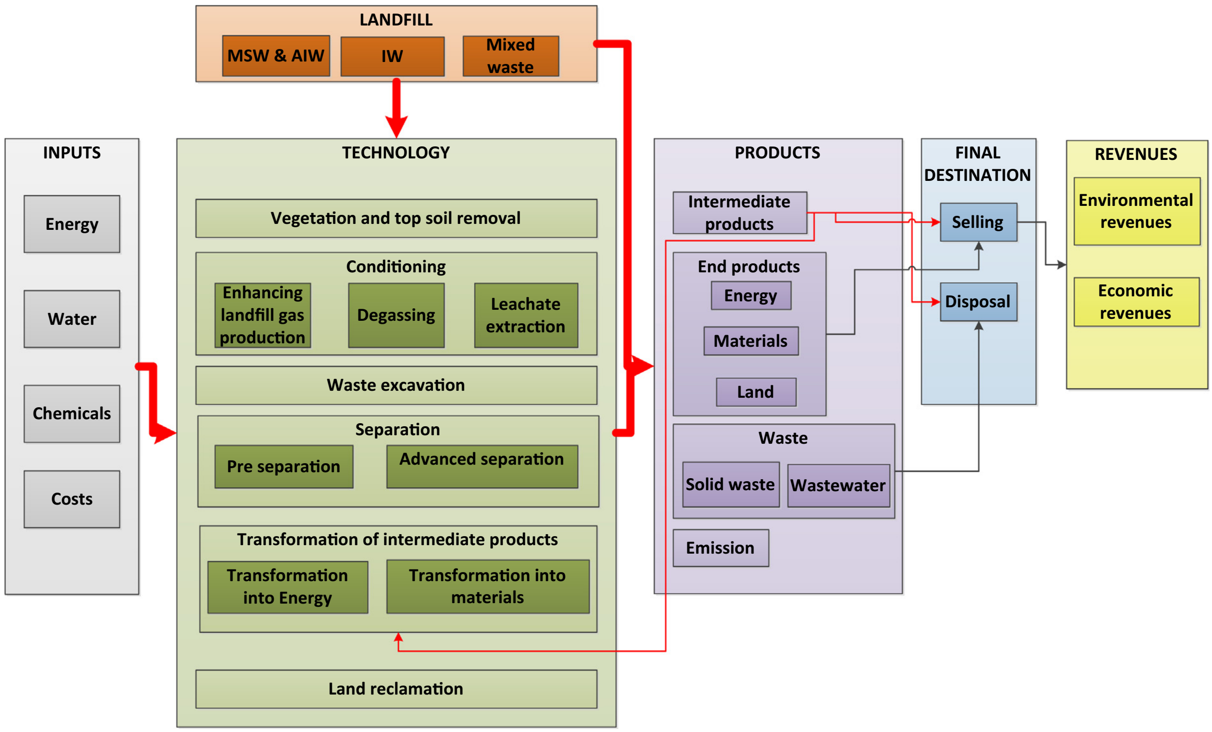


**Fig. 1.** General process flow of ELFM.

*2.1.2. Case study*

The Closing the Circle (CtC) project (Tielemans and Laevers, 2010; Jones et al., 2013) is the first case study for the ELFM Consortium to investigate the opportunities and barriers for ELFM. The project's focus is on the REMO landfill site, which is located in Houthalen-Helchteren in the province of Limburg in Belgium.

The REMO landfill site has been in operation since the early 1970s and covers an area of 130 hectares (Jones et al., 2013). More than 15 million tonnes of waste has been stored in the landfill. Approximately half of the waste is MSW and the other half consists of IW such as shredder material from the recycling of end-of-life-vehicles (ELV), metallurgical slags, pyrite containing slags and dried sludge. (Quaghebeur et al., 2013). Quaghebeur et al.'s (2013) characterisation study for this landfill suggests that, for the plastics, paper/cardboard, wood and textile present in this site, thermal valorisation or feedstock recycling is the most suitable valorisation route since the level of contamination is too high to allow high-quality material recycling. Several other studies have also highlighted the usability of combustible MSW in advanced thermal treatment plants (Malkow, 2004; Zolezzi et al., 2004; Consonni et al., 2005; Al-Salem et al., 2009; Xiao et al., 2009). Hence, plastics, paper/cardboard, wood and textiles are considered in the present study as refuse derived fuel (RDF). The amount of such combustibles varies between 23% and 50% (w/w). The same study proposes that for metals, glass, ceramics, stones and other inerts in the landfill, material valorisation is possible when the materials can adequately be separated. The fine-grained (<10 mm) materials present in the REMO site vary between 40% and 60% (w/w). Furthermore, the characterisation study revealed that, especially for IW (mainly shredder from ELV), the fines fraction contains higher concentrations of heavy metals (Cu, Cr, Ni and Zn) and offers opportunities for metal extraction and recovery.

Possible ELFM activities related to the REMO landfill were identified according to the technological processes described in Fig. 1. Fig. 2 provides an overview of the processes that can take place in the case study landfill. After performing vegetation and top soil removal, the landfill is ready for excavation. There are two types of excavation: selective and unselective. The fraction subjected to selective excavation includes materials situated within the landfill at distinct layers of depth or locations. They are not mixed with the other materials. Stainless steel slag, pyrite ashes and industrial sludge were identified as the materials that required selective excavation. It should be determined whether these fractions are sold at a lower price, treated further or temporarily disposed of. Stainless steel slag contains on average 5 wt.% of stainless steel particles and recovery of this steel is economically interesting. However, crushing or grinding of the slag is necessary in order to recover this steel. The resulting fine-grained material is difficult to reuse due to the elevated leaching of chromium and molybdenum, as well as the swelling behaviour of the slag material (Spooren et al., 2013). Therefore, it is necessary to treat or stabilise the slag materials to lower the leachability of heavy metals prior to use as a construction material. As these stabilisation methods have not yet been well confirmed, the stainless steel slag fraction was considered to be disposed of temporarily, as shown in Fig. 2. Similar to stainless steel slag, pyrite ashes and industrial sludge present in the REMO landfill site contain heavy metals such as Cd, Cu and Zn, in amounts that are considerably above the limit values of the Flemish legislation for use of the materials in or as a construction material (Spooren et al., 2013). Temporary disposal was also applied to pyrite ash and industrial sludge fractions until proper valorisation routes have been identified. More details on implementation of temporary storage at the REMO landfill site can be found in Geysen (2013).

The fraction of waste obtained from unselective excavation (mixed waste fraction) is sent directly to the separation process. This process starts with pre-separation, which identifies the hazardous materials to be disposed of and fine grained materials that should not enter the advanced components of the separation process. After removing hazardous materials and fine-grained materials, the residual fraction is subjected to an advanced separation technology for further separation. The separation technology

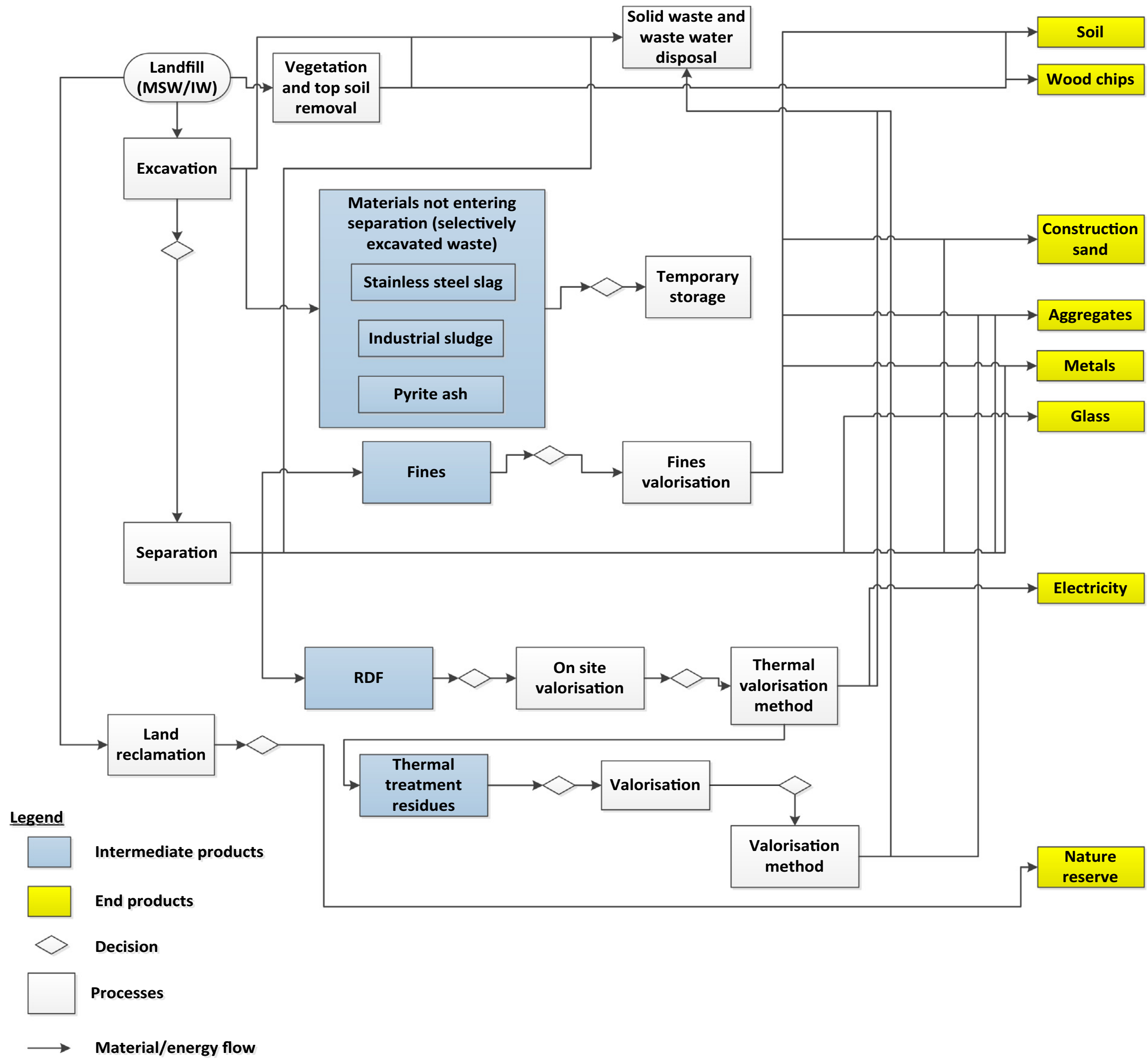


**Fig. 2.** Overview of the ELFM processes of REMO landfill.

depends on the characteristics of the excavated waste; that is, the moisture content, particle size distribution, etc. The detailed separation process applied to the case study landfill is not described further here due to confidentiality reasons. However, the considered separation process comprises air separation, dense media separation, magnetic separation and eddy current separation. The destination of the fines fraction resulting from the separation process was supposed to be further valorisation instead of selling for a lower price or temporary disposal. A decision was made to treat the RDF fraction thermally on-site. According to the concept of ELFM, the destination of the residues created during the thermal treatment should also be defined. For the case study landfill, these residues are intended to be further treated on site instead of selling or landfilling. All types of wastewater and solid waste generated during the treatment processes were directed to suitable treatment systems. As a final component of ELFM system, land reclamation was addressed by reclaiming the land as a nature reserve for the case study landfill site.

The variety of possible choices for several processes meant that a number of scenarios for the ELFM system of REMO landfill are possible. Each of these scenarios contains the processes of vegetation and top soil removal, waste excavation, separation, thermal treatment of RDF, valorisation of thermal treatment residues, valorisation of fines and land reclamation. The scenarios distinguish between (i) the waste type (MSW versus IW), (ii) the applied separation technology (depending on the characteristics of the excavated waste), (iii) the thermal treatment technology for RDF and (iv) the valorisation route of the thermal treatment residues. For the basic ELFM scenario discussed in this study, plasma gasification was chosen as the thermal treatment method. This decision was made based on Bosmans et al.'s (2013) recent study, which concluded that plasma gasification is a viable candidate for combined energy and material valorisation in the framework of ELFM. This method has high efficiency and the flexibility to valorise the resulting syngas in many ways, such as the production of electricity and/or heat, as a feedstock for chemical industry (hydrogen, methanol) or as a second-generation liquid fuel (Chapman et al., 2010, 2011; Ray et al., 2012; Taylor et al., 2013a,b). The present study only considered electricity production as the syngas valorisation route. Besides energy production, plasma gasification also delivers an environmentally stable vitrified residue called plasmastone, which can be converted into building materials. Although many methods have been identified recently for the valorisation of plasmastone (Iacobescu et al., 2013; Machiels et al., 2014), only the most obvious valorisation route, aggregate production (Chapman et al., 2011; Ray et al., 2012; Taylor et al., 2013a,b), was considered in the basic ELFM scenario. Plasma gasification was coupled with plasmastone valorisation and is denoted in the rest of this article as “thermal treatment”.

Apart from the basic ELFM scenario mentioned above, a “Do-nothing” scenario is used as reference scenario. The Do-nothing scenario supposes that no landfill mining activities are undertaken. Landfill gases and leachate are managed as mandated by the corresponding regulatory framework, applying common practices and ensuring adequate periodic maintenance and/or replacement of existing infrastructure. The landfill gas collection efficiency of REMO site is 50% and the collected gas is used for combined heat and power (CHP) generation. The gas production curve shows that this landfill enters its long-term landfill phases in which the methane production continuously decreases while the $CO_2$ concentration increases, as explained by Kjeldsen et al. (2002). Due to the drop of methane production, the CHP generation is only foreseen for the next five years (until 2019). The leachate collection and treatment systems are in place and comply with the Flemish and European legislation.

### 2.2. Environmental and economic assessment

#### 2.2.1. LCA methodology

The goal of this LCA study is to evaluate the environmental impacts of the valorisation of landfilled waste in the context of ELFM. The methodology is in accordance with the International Standards for LCA (ISO14040, 2006; ISO14044, 2006). SimaPro 7 was used as the LCA software tool for setting up the LCA model. Fig. 3 presents the general structure of the ELFM and Do-nothing scenarios and the system boundary of the assessment. The quality of the ELFM products that substitutes the virgin energy and material production are as follows. The metals recovered from separation, fines valorisation and thermal treatment processes are able to substitute the corresponding scrap metals. Sand, aggregates and soil recovered from fines valorisation processes and the aggregates obtained from valorisation of plasmastone have the quality of gravel that can be used in construction activities (Jones et al., 2013). The produced electricity from plasma gasification replaces the base load of electricity production in Belgium, being the Belgian electricity mix, which includes 53% nuclear energy, 40% conventional thermal energy (of which 25% is from natural gas, 11% from coal and 2% from oil, according to the ecoinvent database version 2.2), 2% hydro energy and 3% wind energy (Eurostat, 2012). Recovered land is converted into a nature reserve, as this is a specific feature of the Closing the Circle project in Belgium (De Vocht and Descamps, 2011). The input data was based on measured data, data obtained from published sources, calculated and estimated data (refer Appendix A). For the background processes, such as the production of electricity and raw materials, the life cycle inventory data with European averages was used, which has been published mainly in the ecoinvent database (version 2.2) present in the software. For the ELFM scenario, the functional unit was defined as the valorisation of a certain mass of landfilled waste. Based on this functional unit, the environmental impact was calculated for valorisation of (i) 1 tonne of MSW, (ii) 1 tonne of IW and (iii) total waste present in the landfill. In the third case, the environmental impact of ELFM was compared with that of the Do-nothing scenario. The environmental performance of the Do-nothing scenario was calculated as follows. In order to determine whether the ELFM is environmentally beneficial compared to the existing situation (the Do-nothing scenario), the residual impact of the landfill should be determined. The extrapolated landfill gas production curve revealed that production would last for the next 50 years in very low concentrations. Hence all inputs and outputs were calculated for 50 years in order to determine the respective environmental impact. The $CO_2$ emissions in this scenario were considered to be $CO_2$-neutral because of their biogenic origin. The data of the effluent of the leachate treatment plant of the REMO site was used to determine the emission to water for the considered 50 year period. This analysis does not consider the long-term releases that can occur after the considered period.

For the environmental impact assessment of this study, the ReCiPe endpoint method (Hierarchist version, H/A) was selected because it includes a variety of impact categories. These are: (i) climate change on human health, (ii) climate change on ecosystems, (iii) ozone depletion, (iv) terrestrial acidification, (v) freshwater eutrophication, (vi) human toxicity, (vii) photochemical oxidant formation, (viii) particulate matter formation, (ix) terrestrial ecotoxicity, (x) freshwater ecotoxicity, (xi) ionising radiation, (xii) agricultural land occupation, (xiii) urban land occupation, (xiv) natural land transformation, (xv) metal depletion, and (xvi) fossil fuel depletion (Goedkoop et al., 2013). The characterisation and normalisation stages of LCA were both considered when presenting the results. The results of the characterisation stage are presented in order to show the relative contribution of each waste type to each impact category. Next, normalisation is used to make the impacts on different impact categories are comparable with each other and to show the extent to which an impact category makes a significant contribution to the overall environmental problem (PRéConsultants, 2010). For this study, normalisation was performed on a European level. Finally, sensitivity analyses are performed for the most relevant parameters in order to determine the influence of a change in the inventory data on the results of the impact assessment.

#### 2.2.2. LCC methodology

The LCC model consists of a detailed cash flow with all relevant investment costs, operational costs and revenues for 20 years of period (refer Appendix A). When building up the cash flow for the ELFM of the REMO landfill, it was assumed that waste processing capacity during the first two years of the project life time would be 30%, after which the project would run at full capacity (100%). The net present value (NPV) was used as the major economic indicator in order to determine the major economic drivers of ELFM. For this assessment, a 15% discount factor was applied (Van Passel et al., 2013). To examine how the NPV varies when the values of uncertain assumptions are modified, a Monte Carlo simulation approach was used, as explained by Van Passel et al. (2013). This approach helps to identify the uncertainties of the input parameters as well as their importance.

## 3. Results and discussion

The results of the environmental analysis of waste valorisation, and of the respective sensitivity analysis, are presented and discussed in detail in Sections 3.1 and 3.2. Section 3.3 presents the economic performance.

### 3.1. Environmental performance of waste valorisation

This section discusses the individual environmental profiles of the basic scenarios for the two types of wastes (MSW and IW). This discussion provides an insight into the processes that contribute most to the environmental impact of ELFM. The environmental burdens are expressed as positive values and the benefits are indicated as negative values.

#### 3.1.1. Environmental performance of basic ELFM scenarios

Fig. 4 represents the environmental profiles of valorisation of the extremely mixed fraction (waste subjected to unselective excavation) of MSW and IW, respectively. The figure illustrates the

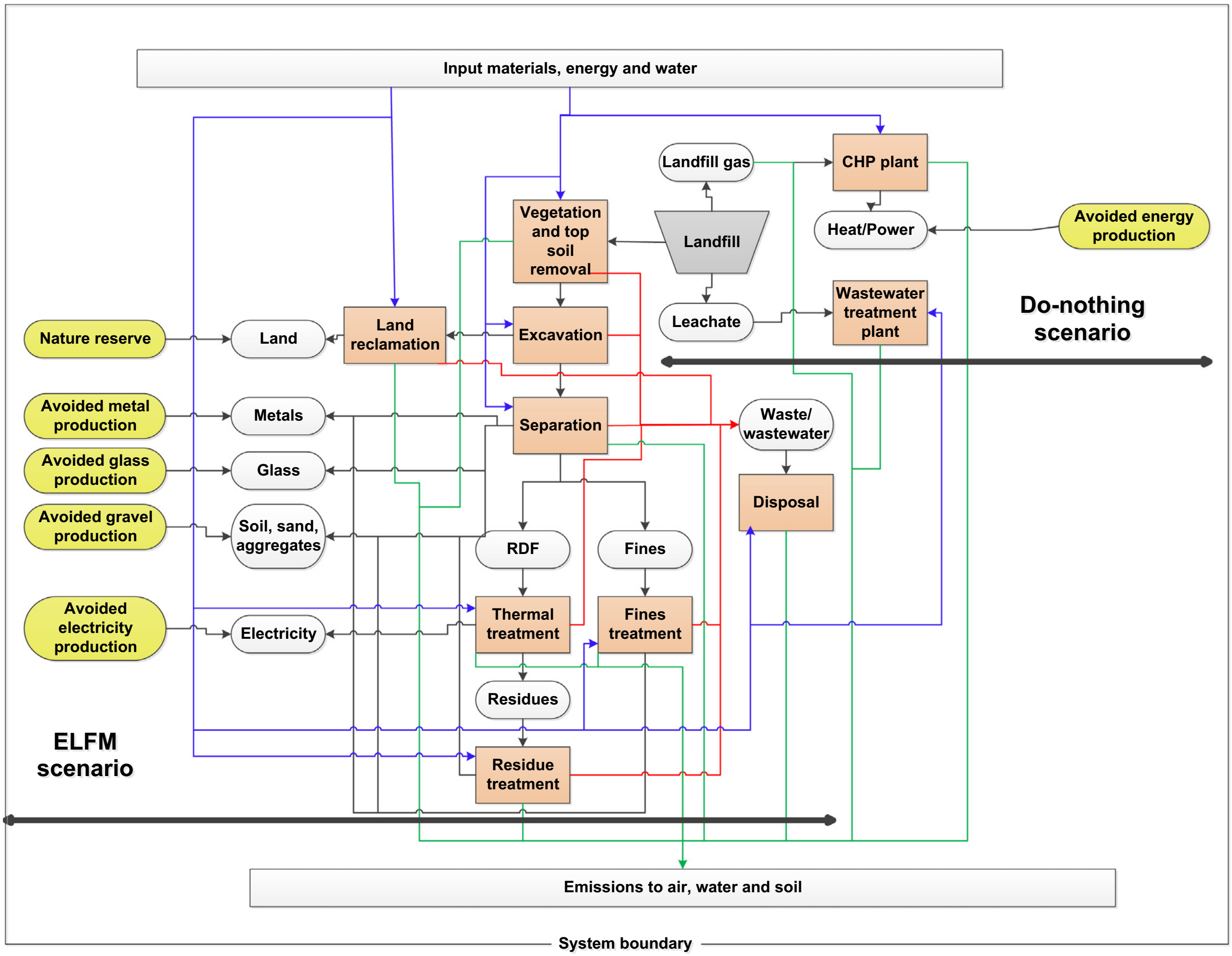


**Fig. 3.** System boundary of ELFM and Do-nothing scenarios.

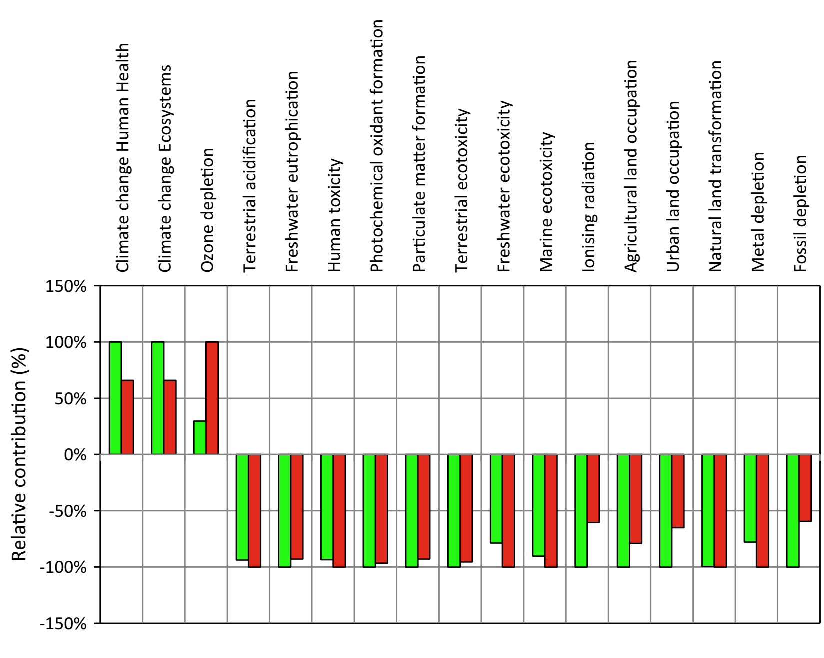


**Fig. 4.** Comparison between two types of wastes-net environmental impact of valorisation of 1 tonne of MSW/IW (basic scenario).

comparison of the valorisation of two types of wastes for the basic scenarios. The net impact (=burdens minus benefits) of the valorisation of 1 tonne of MSW and IW is shown for each impact category. It can be concluded from Fig. 4 that none of the waste types has the highest or the lowest environmental score for all impact categories considered in the context of ELFM. For example, valorisation of MSW is the most favourable in the fossil depletion, ionising radiation and urban land occupation impact categories. However, it also makes the highest contribution to climate change impact. On the other hand, valorisation of IW delivers the highest benefit in metal depletion. Its influence on the ozone depletion impact category is considerably higher than that of MSW valorisation. However, the valorisation of both types of waste yields burdens in only three impact categories: climate change on human health, climate change on eco systems, and ozone depletion.

Fig. 5 compares the different impact categories with each other according to the normalisation. The contribution to climate change, fossil depletion, metal depletion and natural land transformation is important for both waste types. In addition, the contribution to human toxicity and particular matter formation cannot be neglected. It is important to note the insignificance of the other impact categories. Based on Figs. 4 and 5 alone, however, we are not yet able to provide a straightforward explanation for the differences of impacts in each impact category. Therefore, the normalised environmental profiles that illustrate the contribution of the different stages or processes of ELFM to the total environmental impact are evaluated in more detail (Fig. 6). Only the significant impact categories are indicated in the figure.

From Fig. 6, it can be deduced that, in the valorisation of both waste types, the thermal treatment process dominates the most impact categories. In both waste types, thermal treatment process induces an environmental burden only on the climate change impact category. As illustrated in Danthurebandara et al. (2014) and UCL (2014), flue gas emissions and oxygen usage within the process generate this burden. Next to the burdens on climate change impact category, fossil depletion and metal depletion impact categories are significantly credited by the thermal treatment process due to the electricity production and metal recovery from the plasma convertor. These burdens and benefits caused by thermal treatment process are higher in the MSW valorisation than in the IW waste valorisation. These differences are directly linked with the RDF content in the landfill and the recovery efficiency of the separation technology. In this study, we applied the same RDF recovery efficiency (80%) for both MSW and IW. Thus, the differences in burdens and benefits of this case are mainly caused by the RDF content. The characterisation studies conducted for the case study landfill found that the RDF content per tonne of waste in the case study landfill is higher in MSW than in IW (Appendix A).

As suggested by Jones et al. (2013), the burden due to flue gas could be reduced considerably by using the flue gas (rich in $CO_2$) and low temperature waste heat in local horticulture. The $CO_2$ acts as a fertiliser for the plants, while the residual heat warms the greenhouses, avoiding the use of primary fossil fuels. Use of an alternative energy source for oxygen production can also further reduce the impact of plasma gasification. Further research is necessary to investigate the possibility of using air in plasma gasification instead of pure oxygen. The net electrical efficiency of the system and the calorific value of the RDF fraction play important roles in determining the credits due to avoided electricity production. Obtaining higher environmental benefits in the fossil depletion impact category seems to be possible as the net electrical efficiency of plasma gasification can be improved up to 30% or more (Taylor et al., 2013a,b). In addition, the existence of higher calorific values such as 20–26 MJ/kg is also possible for RDF (Arina and Orupe, 2012; Spooren et al., 2013). The environmental performance of plasma gasification can be further improved by using different plasmastone valorisation options. In this study, plasmastone is converted into aggregates. Nonetheless, the avoided environmental burden created by aggregate production is insignificant compared to the environmental impact of plasma gasification itself. Machiels et al. (2014) and Iacobescu et al. (2013) elucidated the possibility of developing binding materials from plasmastone that can be used as low-carbon alternatives for ordinary Portland cement (OPC) in construction applications. Application of those methods in plasmastone valorisation improves the environmental performance of plasma gasification (Danthurebandara et al., 2014).

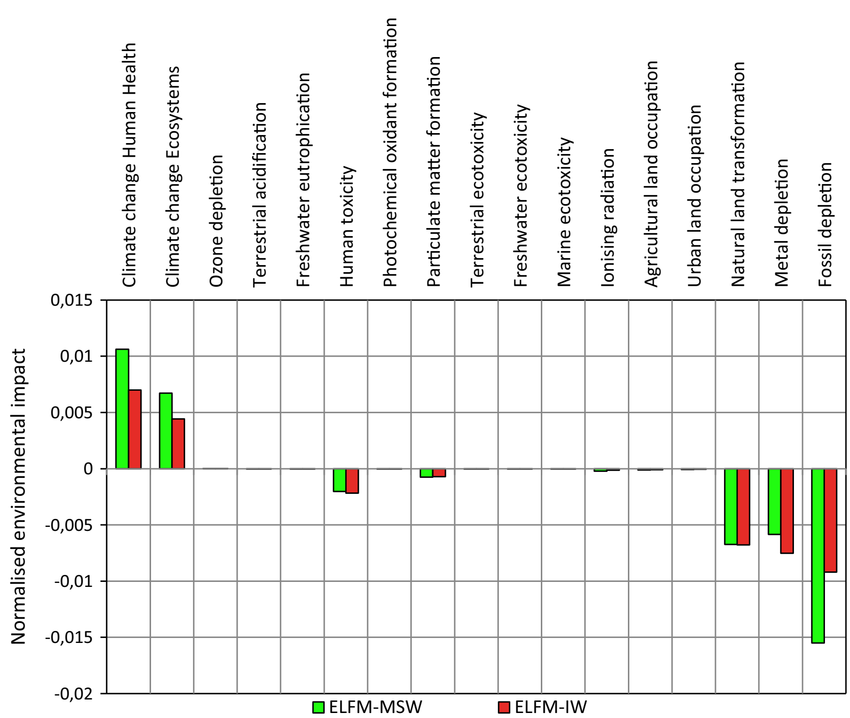


**Fig. 5.** Normalised environmental profile of valorisation of 1 tonne of MSW/IW (basic scenario).

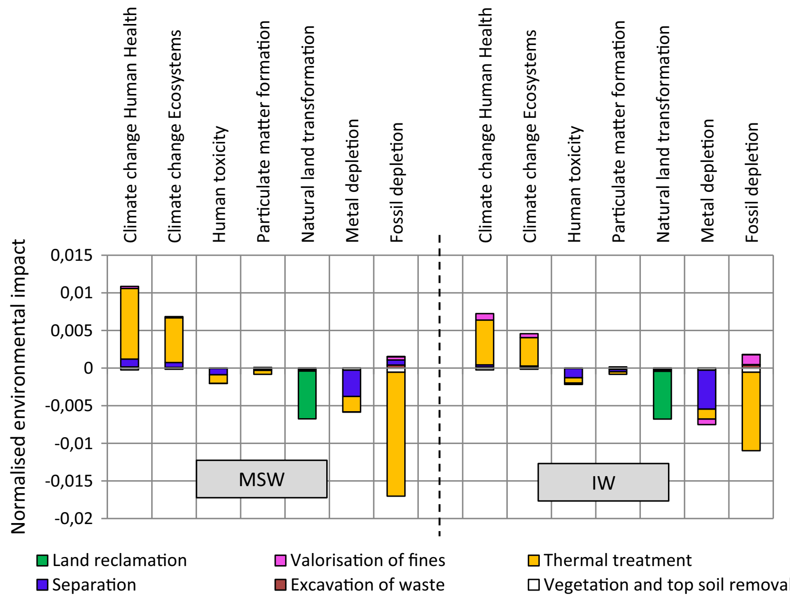


**Fig. 6.** Contribution of different ELFM processes-normalised environmental profile of valorisation of 1 tonne of MSW/IW (basic scenario).

Note, however, that these impacts of thermal treatment process have been derived from a comparison with the Belgian electricity generation mix, in which nuclear energy has a share of 53% (Eurostat, 2012). According to Ecoinvent, the environmental impact of the production of nuclear energy is lower than the other energy production methods. Hence, the replaced impact is also lower when the Belgian electricity mix is used as the substituted product of the thermal treatment process. The use of different energy mixes as the substituted product leads to significant changes in environmental impact of thermal treatment process. The environmental burden of thermal treatment processes increased by 65% for the electricity mix of France, in which includes 79% of nuclear energy. The environmental burden decreased by 87% for the electricity mix of the Netherlands, which consisted of only 4% of nuclear energy and 92% of conventional thermal energy. However, as the case study landfill is located in Belgium and all ELFM activities are carried out there too, it is reasonable to consider the Belgian electricity mix as the substituted product of thermal treatment processes of this study.

Next to the thermal treatment process, Fig. 6 shows that the separation process yields environmental benefits on metal depletion and human toxicity impact categories, mainly due to the metal recovery. The benefits from the recovery of stones and glass are very insignificant compared to the benefits due to metal recovery. The metal composition in the landfilled waste is imperative for the environmental profile of the process. Appendix A indicates that the ferrous metal content is higher in MSW than that in IW. In contrast, IW contains more non-ferrous metals than MSW does. According to the individual environmental profile of the separation process, non-ferrous metals give rise to a higher avoided environmental burden than ferrous metals. The above facts largely explain the higher benefit in metal depletion and human toxicity impact categories of the separation process in IW valorisation compared to MSW valorisation (Fig. 6).

Valorisation of fines affects the environmental profiles differently in MSW and IW. According to Fig. 6, the contribution of valorisation of fines is less important for MSW, while it becomes significant for IW. This difference is due to the different products that can be derived from the fines. Fines, in the case of IW, contain more metals than those of the MSW case. As Appendix A shows, 24% ferrous metals, 2% non-ferrous metals, 9% RDF, and 65% of other fraction that can be used as construction sand, soil or aggregates are present in IW fines. However, the metal percentage is very low in MSW fines and more than 80% of the total MSW fines have the quality of sand, soil and aggregates. Individual environmental profiles of fines valorisation show that the benefits due to recovery of sand, soil and aggregates are smaller, despite their high mass proportion, than the benefits due to metal recovery. This is the reason why fines valorisation becomes insignificant in MSW valorisation.

Vegetation and top soil removal can result in a partial (and temporary) loss of ecosystems. As Fig. 6 shows, however, the impact of that process is negligible compared to other activities. As explained by De Vocht and Descamps (2011), gradual restoration is possible after the landfill mining activities; this point is corroborated by the activity of land reclamation. As shown in Fig. 6, the contribution of the land reclamation to the total impact is only beneficial in the natural land transformation impact category and this benefit is very significant. The land area to be reclaimed is considered to be the same for MSW and IW in this study, providing the density of both waste types and the landfill depth are equal. Therefore, the impact of land reclamation is also the same in both cases.

#### *3.1.2. Environmental performance of ELFM versus Do-nothing scenario*

We have discussed the environmental impact of valorisation of 1 tonne of MSW and IW separately. When transforming ELFM from conceptual to implementation phase, it is necessary to know whether the ELFM is beneficial compared to the Do-nothing scenario. Fig. 7 shows the environmental impact of valorisation of total waste (MSW + IW) present in the landfill with their actual amounts. In addition, those impacts were compared with the impact of the Do-nothing scenario for the total amount of waste. Fig. 7 only shows the significant impact categories.

The net environmental impact of the valorisation of the total waste is very significant in all impact categories compared to the Do-nothing scenario. The impact of the Do-nothing scenario is negligible compared to the impact of ELFM scenarios, assuming that the landfill stays well controlled and maintained in the future. In the Do-nothing scenario, the burdens are mainly found in the impacts on climate change on human health and climate change on ecosystems. However, these burdens are much smaller. According to the gas production curve of the case study landfill, the REMO

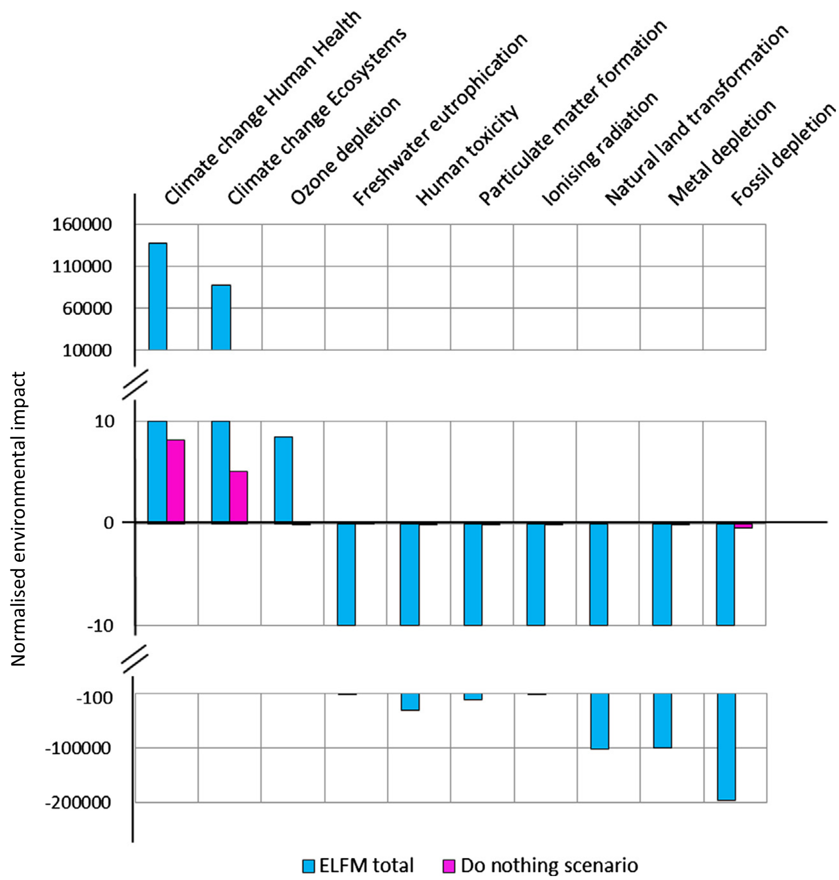


**Fig. 7.** Normalised environmental profile of valorisation of total waste present in the landfill compared to Do-nothing scenario.

landfill is in the stage at which the methane production continuously decreases. Methane leakage to the environment is comparatively lower in this phase. Hence, in this situation, the Do-nothing scenario does not produce higher burdens towards the environment. Although this scenario creates a benefit on fossil depletion due to methane recuperation, it is less pronounced than the benefit created by ELFM scenario (as shown in Fig. 7). This is because only a small amount of energy from methane is produced due to the lower methane production, and no material is recuperated at all.

The carbon footprint analysis performed by Van Passel et al. (2013) for the same landfill stated that the estimated $CO_2$ equivalent emission for the ELFM scenario is 5.3 million tonnes, compared to 6.3 million tonnes for the Do-nothing scenario; this suggests that ELFM is more beneficial. The present study is not fully comparable with the study of Van Passel et al. as the two studies used different methodologies. However, the impact on climate change impact category can be approximately compared as it is directly linked with the $CO_2$ equivalent emission. The present study contrasts with that of Van Passel et al. in that this impact is lower in the Do-nothing scenario than that in ELFM scenario. However, Van Passel et al. considered that the energy recovery from methane would last for approximately 15 years, which is not the case in the present study (energy recovery will take place for only five more years). Moreover, the authors considered the materials and energy to have been purchased on the market in the case of the Do-nothing scenario. Thus, the associated emissions of conventional market production methods were accounted for when estimating the emissions of the Do-nothing scenario. As this fact is not considered in this study (but as an avoided burden in the ELFM scenarios), it resulted in a lower impact in the Do-nothing scenario. Nevertheless, because of the lower environmental impact on climate change impact category, it should not be concluded that ELFM is not favourable compared to the Do-nothing scenario. As explained in the previous sections, all impact categories should be taken into account in decision making of ELFM from an environmental point of view.

### 3.2. Sensitivity analysis in environmental profiles

From the above analysis, it was identified that the separation, thermal treatment and IW fines valorisation processes are the most influencing processes in ELFM. Furthermore, metal recovery in the separation and IW fines valorisation processes, along with electricity production in the thermal treatment process, were recognised as the main factors that dominate the environmental profiles. Table 1 summarises the parameters for which the sensitivity analyses are performed. Table 2 illustrates the results of the sensitivity analysis. The table shows the type of the net impact: that is, benefit or burden of the basic scenario in each impact category. The other columns of the table indicate how this net impact deviates with the scenarios in the sensitivity analysis. Increments and decrements are denoted by (+) and (−) signs, respectively.

Table 2 shows that the climate change and fossil depletion impact categories are sensitive to the changes in RDF recovery efficiency, the calorific value of RDF and the electrical efficiency of thermal treatment process. A 10% increment in RDF recovery efficiency increases the burden on climate change impact category by 9–10%. However, the same change yields a 12% improvement in the benefit on fossil depletion impact category. The reason for this is that processing more RDF generates more flue gas, although it also produces more electricity. The benefit on fossil depletion

**Table 1**
Overview of the sensitivity analyses.

| Parameter | Scenario | Value |
|---|---|---|
| Metal recovery efficiency in separation process | Basic | 80% |
| | Best case | 90% |
| | Worst case | 70% |
| RDF recovery efficiency in separation process | Basic | 80% |
| | Best case | 90% |
| | Worst case | 70% |
| Calorific value of RDF | Basic | 20 MJ/kg |
| | Best case | 22 MJ/kg |
| | Worst case | 18 MJ/kg |
| Net electrical efficiency of plasma gasification system | Basic | 27% |
| | Best case | 30% |
| | Worst case | 24% |
| Metal recovery efficiency in IW fines valorisation process | Basic | 10% |
| | Sensitivity analysis | 30% |
| | Sensitivity analysis | 50% |
| | Sensitivity analysis | 70% |
| | Sensitivity analysis | 90% |

**Table 2**
Percentage changes in net impact of basic scenario, for the scenarios in the sensitivity analysis (coloured cells represent the IW valorisation).

| Impact categories | Climate change human health | Climate change ecosystems | Human toxicity | Particulate matter formation | Natural land transformation | Metal depletion | Fossil depletion |
|---|---|---|---|---|---|---|---|
| *Scenarios* | | | | | | | |
| Basic scenario[a] | Burden | Burden | Benefit | Benefit | Benefit | Benefit | Benefit |
| | Burden | Burden | Benefit | Benefit | Benefit | Benefit | Benefit |
| *Metal recovery efficiency of separation process* | | | | | | | |
| Best case (90%) | −1% | −1% | +5% | +5% | 0% | +7% | +1% |
| | −1% | −1% | +7% | +8% | 0% | +9% | +2% |
| Worst case (70%) | +1% | +1% | −5% | −5% | 0% | −7% | −1% |
| | +1% | +1% | −7% | −8% | 0% | −9% | −2% |
| *RDF recovery efficiency of separation process* | | | | | | | |
| Best case (90%) | +10% | +10% | +6% | +8% | 0% | +4% | +12% |
| | +9% | +9% | +3% | +5% | 0% | +2% | +12% |
| Worst case (70%) | −10% | −10% | −6% | −8% | 0% | −4% | −12% |
| | −8% | −8% | −3% | −5% | 0% | −2% | −11% |
| *Calorific value of RDF* | | | | | | | |
| Best case (22 MJ/kg) | −10% | −10% | +7% | +26% | 0% | +1% | +15% |
| | −9% | −9% | +4% | +18% | 0% | 0% | +16% |
| Worst case (18 MJ/kg) | +10% | +10% | −7% | −26% | 0% | −1% | −15% |
| | +9% | +9% | −4% | −18% | 0% | 0% | −16% |
| *Net electrical efficiency of plasma gasification system* | | | | | | | |
| Best case (30%) | −11% | −11% | +8% | +29% | 0% | +1% | +16% |
| | −10% | −10% | +4% | +20% | 0% | 0% | +17% |
| Worst case (24%) | +11% | +11% | −8% | −29% | 0% | −1% | −16% |
| | +10% | +10% | −4% | −20% | 0% | 0% | −17% |
| *Metal recovery efficiency of IW fines valorisation process* | | | | | | | |
| 30% | −4% | −4% | +16% | +23% | 0% | +20% | +6% |
| 50% | −7% | −7% | +33% | +46% | 0% | +39% | +12% |
| 70% | −11% | −11% | +49% | +68% | 0% | +59% | +18% |
| 90% | −15% | −15% | +66% | +91% | 0% | +78% | +25% |

[a] Basic scenario comprises 80% of metals and RDF recovery efficiency of the separation process, 20 MJ/kg calorific value of RDF, 27% net electrical efficiency of plasma gasification system and 10% metal recovery efficiency in IW fines valorisation process (Appendix A).

impact category increases by 15–17% when the calorific value of RDF and the net electrical efficiency of plasma gasification system are improved by 10%. These changes significantly affect the particulate matter formation impact category by increasing its benefit by 18–29%. The metal depletion impact category is clearly sensitive to changes in the metal recovery efficiency of the separation process and the IW fines valorisation process. The metal recovery efficiency of IW fines valorisation was set to 10% for the basic scenario with respect to the available valorisation technologies. Robust hydrometallurgical treatments are needed that can selectively recover valuable metals and produce a residue with improved environmental properties, so that it can be used as a secondary raw material (Spooren et al., 2013). Evidently, the environmental contribution escalates when higher metal recovery efficiencies are applied (Table 2). This improvement is especially pronounced in the metal depletion impact category. When applying different metal recovery efficiencies in this sensitivity analysis, the other process inputs, such as energy and chemicals, were kept constant

**Table 3**
Net present value sensitivity analysis using Monte Carlo simulations.

| Parameter | Minimum value | Maximum value | Variation in NPV (%) | | |
|---|---|---|---|---|---|
| | | | MSW valorisation | IW valorisation | Total waste valorisation |
| Net electrical efficiency of thermal treatment process (%) | 24 | 30 | 27.5 (+) | 27.7 (+) | 29.7 (+) |
| Calorific value of RDF (MJ/kg) | 18 | 22 | 18.8 (+) | 17.8 (+) | 14.0 (+) |
| Price of electricity (€/MW h) | 60 | 76 | 12.4 (+) | 13.4 (+) | 11.3 (+) |
| Price of green certificates (€/MW h) | 110 | 124 | 5.3 (+) | 4.7 (+) | 5.4 (+) |
| Green energy fraction (%) | 42 | 52 | 5.4 (+) | 4.2 (+) | 4.9 (+) |
| Investment cost of thermal treatment process (€/t RDF) | 45 | 55 | 26.2 (−) | 27.9 (−) | 29.4 (−) |
| Operational cost of thermal treatment process (€/t RDF) | 57 | 77 | 3.5 (−) | 3.9 (−) | 3.5 (−) |

as applied in the basic scenario. This enabled the environmental profiles to change according to the changes in energy and chemical inputs that need to be performed in order to obtain higher recovery efficiencies.

### 3.3. Economic performance of waste valorisation

Using the cash flow model described in the Section 2.2.2, the sensitivity of NPV to a wide range of parameters was investigated for MSW valorisation, IW valorisation and total waste (MSW + IW) valorisation. The following major parameters were considered: (i) key waste fractions, (ii) recovery efficiencies, (iii) the amount of different input materials to various processes, (iv) calorific value of RDF, (v) efficiencies of thermal treatment systems, (vi) investment and operational costs of the different valorisation processes, and (vii) the selling prices of the different products. Monte Carlo simulations show that the following parameters have an important impact on the economic performance for the basic scenarios: (i) net electrical efficiency of thermal treatment system, (ii) calorific value of RDF, (iii) price of electricity, (iv) price of green certificates, (v) green energy fraction (vi) investment cost of thermal treatment system, and (vii) operational costs of thermal treatment system. Table 3 illustrates the contribution of the different parameters in explaining the variation in NPV and their direction of influence obtained from Monte Carlo simulations using triangular distributions. Positive contributions indicate that an increase in the parameter is associated with an increase in the economic indicator. Negative contributions imply the opposite situation. NPVs are not included in the table due to confidentiality and only the most sensitive parameters are incorporated.

According to Table 3, all highly sensitive parameters belong to the thermal treatment process. The table highlights that the thermal treatment process dominates not only the environmental performance of ELFM but also the economic performance. This is the same in MSW valorisation or IW valorisation or total waste (MSW + IW) valorisation. The total variation in the NPV can be explained for 27–30% by the variation in net electrical efficiency of thermal treatment process. Higher efficiency logically results in a higher NPV. This shows that the efficiency of the thermal treatment process is of key importance for the economic feasibility of ELFM. Improvements in electrical efficiency may lead to higher investment costs. It appears that higher investment costs have a negative effect on NPV (26–30%). Therefore, these two parameters should be carefully controlled in order to reach the optimal profit of ELFM. The next important parameter is the calorific value of RDF. As the calorific value of the organics decreases over time due to degradation (Quaghebeur et al., 2013), starting ELFM activities before the landfill reaches its final stages of waste degradation makes it possible to treat waste with a high calorific value and obtain a higher energy output. Because plastics dominate the RDF fraction in the case study landfill and the landfill is already in its final stages of waste degradation, the calorific value cannot increase further. However, this finding could be considered in other future ELFM projects. Along with the calorific value, the price of electricity, the price of green certificates, the green energy fraction and the operational cost of thermal treatment process also contribute to the NPV considerably. The impact of other parameters, such as recovery efficiencies and prices of recovered materials, is negligible. Importantly, the LCA study identified that the metal recovery is highly beneficial in the metal depletion impact category, but its impact on the economic profile is insignificant. However, the range definitions of the various parameters strongly influence the final impact of the different parameters on the NPV. In this study, for most of the parameters, a 10% margin from the average value was set to the maximums and minimums of the range. For the cost parameters, such as green certificates and investment and operational costs, these ranges are defined after communication with the experts in the relevant industries. These results are in line with those obtained by Van Passel et al. (2013). Unlike that study, however, the present study includes all the possible activities that can be conceived within a ELFM project. However, the economic drivers identified by Van Passel et al. remain the same for this study as well, despite the large range of parameters considered. As explained in the previous study, technology (efficiency, investment cost), markets (electricity price) and regulations (price of green certificates, green energy fraction) determine the economic performance of ELFM to a large extent.

## 4. Conclusions

This paper has presented a full LCA and LCC of ELFM based on the REMO landfill as a case study. The results show that the total environmental impact of ELFM depends on the type and composition of the waste and the chosen process technologies. Apart from that, the net environmental impact of ELFM depends heavily on the quality and the quantity of the output products. In this research, we assumed that all metals recovered from the landfill have the quality of the secondary metals. This leads to large energy savings and helps avoid many kinds of environmental pollution caused by the replacement of primary material. The recovered soil, sand and aggregates, with the quality level of gravel, avoid a large area of arable land that has to be converted for gravel extraction. The produced electricity substitutes the Belgian electricity mix, which contains 40% of conventional thermal energy. In this respect, it is necessary to perform ELFM with the maximum product quality.

We conclude that the waste types and different processes of ELFM behave differently on the considered impact categories. None of the waste types or processes has the highest or lowest environmental score for all impact categories. On the other hand, ELFM does not yield only the benefits on all impact categories. In this case study, the impact categories related to climate change are always influenced adversely by ELFM, while human toxicity, particulate matter formation, natural land transformation, metal depletion and fossil depletion impact categories are positively affected.

The environmental impact (both benefits and burdens) of valorisation of total waste (IW + MSW) in all impact categories is highly significant compared to the Do-nothing scenario. However, the level of this impact differs depending on the type and phase or average age of the landfill. This suggests that the actual situation of the landfill is important in decision making in ELFM.

We found that the thermal treatment (plasma gasification) is the process that has the greatest influence, both from an environmental and an economic point of view. Therefore, it is necessary to explore the possibility of using other possible thermal treatment technologies as well. Essentially plasma gasification must be benchmarked against conventional incineration, a commonly used thermal treatment method in waste processing, with the purpose of proving that plasma gasification is one of the efficient technologies for achieving the goals of ELFM concept. In addition, it is important to know how the by-products of plasma gasification (plasmastone) contribute to the performance of ELFM. Apart from use of plasmastone in aggregate production, its higher added value applications should also be analysed in order to investigate how the environmental and economic impacts of ELFM vary along the different product qualities.

Importantly, this study shows that the impact of some parameters and processes are negligible from an economic perspective, but become key drivers from an environmental point of view, and vice versa. Examples include the higher influence of metal recovery in environmental profiles and the insignificant impact of metal prices in economic profiles. The study further confirms that the technology, regulations and markets have a clear impact on the economic feasibility of ELFM. Finally, it can be concluded that the environmental and economic profiles of ELFM vary from case to case depending on landfill characteristics, compositions, technologies used and products of ELFM. In fact, the results obtained for this case study landfill suggest a cluster of parameters that need to be considered in future ELFM projects in order to minimise their environmental burden and to maximise the economic return.

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## Appendix A. Case study input data

**Appendix A** (*continued*)

| Parameters | | | Sources |
|---|---|---|---|
| Total amount of waste (million tonnes) | | | |
| MSW | 8.2 | | Case study |
| IW | 6.9 | | Case study |
| Time length (years) | 20 | | Case study |
| IRR (%) | 15 | | Van Passel et al. (2013) |
| Depreciation rate (%) | 5 | | Case study |
| *Waste composition* | | | |
| | MSW | IW | |
| Wastes for selective excavation (%) | 0.0 | 26.5 | Case study |
| Metallurgical slags (%) | | 10.0 | Case study |
| Pyrite ashes (%) | | 1.5 | Case study |
| Industrial sludge (%) | | 15.0 | Case study |
| Wastes for unselective excavation (%) | 100.0 | 73.5 | Case study |
| Fines (%) | 43.0 | 62.0 | Spooren et al. (2013) |
| RDF (%)[a] | 33.0 | 19.0 | Spooren et al. (2013) |
| Metals (%)[b] | 2.8 | 2.4 | Spooren et al. (2013) |
| Rocks, glass, slag (%)[c] | 10.0 | 8.3 | Spooren et al. (2013) |
| Undefined (%) | 11.2 | 8.3 | Spooren et al. (2013) |
| *Vegetation and top soil removal* | | | |
| Vegetation density (t/m$^2$) | 0.01 | | Case study |
| Spraying rate of water to minimise dust (t/m$^2$) | 0,01 | | Case study |
| Electricity consumption of wood choppers (kW h/t wood) | 20 | | Industrial reference |
| Diesel consumption of excavators (kg/t top soil) | 0.281 | | Ecoinvent database (version 2.2) |
| Investment cost (€/m$^2$) | 0.48 | | Industrial reference |
| Operational cost (€/m$^2$) | 0.90 | | Industrial reference |
| *Waste excavation* | | | |
| Diesel consumption of excavators (kg/t waste) | 0.281 | | Ecoinvent database (version 2.2) |
| Investment cost (€/t waste) | 1.6 | | Industrial reference |
| Operational cost (€/t waste) | 3.0 | | Industrial reference |
| *Separation* | | | |
| Recovery efficiencies (%) | MSW | IW | |
| Fines | 80 | 80 | Case study |
| RDF | 80 | 80 | Case study |
| Metals | 80 | 80 | Case study |
| Glass | 80 | 80 | Case study |
| Stones | 80 | 80 | Case study |
| Electricity consumption (kWh/ t waste) | 35 | | Case study |
| Water consumption (t/t waste) | 0.25 | | Case study |
| Investment cost (€/t waste) | 6 | | Industrial reference |
| Operational cost (€/t waste) | 11 | | Industrial reference |
| *Thermal treatment (plasma gasification)* | | | |
| Calorific value of RDF (MJ/kg RDF) | | 20 | Case study |
| Start-up energy (kWh/t RDF) | | 269 | Chapman et al. (2010), Bosmans et al. (2013), Taylor et al. (2013a,b) |
| Net electrical efficiency (%) | | 27 | Chapman et al. (2010), Bosmans et al. (2013), Taylor et al. (2013a,b) |
| Plasmastone generation (t/t RDF) | | 0.17 | Industrial reference |
| APC residues (t/t RDF) | | 0.024 | Industrial reference |
| Metal recuperation (t/t RDF) | | 0.01 | Industrial reference |
| Auxiliary materials | | | Danthurebandara et al. (2014), industrial feedback |

(*continued on next page*)

**Appendix A** (*continued*)

| Parameters | | | Sources |
|---|---|---|---|
| Oxygen (t/t RDF) | | 0.55 | |
| $NaHCO_3$ (kg/t RDF) | | 4 | |
| Activated carbon (kg/t RDF) | | 0.2 | |
| NaOH (kg/t RDF) | | 0.8 | |
| $H_2O_2$ (kg/t RDF) | | 0.4 | |
| Urea (kg/t RDF) | | 1.2 | |
| Emission | | | Danthurebandara et al. (2014), industrial feedback |
| Carbon dioxide (kg/t RDF) | | | |
| Biogenic[d] | | 689 | |
| Fossil | | 776 | |
| Carbon monoxide (kg/t RDF) | | 0.02 | |
| Particulates (kg/t RDF) | | 0.2 | |
| Nitrogen oxides (kg/t RDF) | | 0.42 | |
| Sulphur dioxide (kg/t RDF) | | 0.08 | |
| Hydrogen chloride (kg/t RDF) | | 0.02 | |
| Green energy factor (%) | | 47 | Van passel et al. (2013) |
| Investment cost (€/t RDF) | | 50 | Industrial reference |
| Operational cost (€/t RDF) | | 67 | Industrial reference |
| *Fines treatment* | | | |
| | MSW | IW | |
| Fines for direct use (%) | 10 | 10 | Case study |
| Fines need a treatment (%) | 90 | 90 | Case study |
| Composition of fines need a treatment | | | |
| Ferrous metals (%) | 3 | 24 | Spooren et al. (2013) |
| Non-ferrous metals (%) | 0 | 2 | Spooren et al. (2013) |
| RDF (%) | 14 | 9 | Spooren et al. (2013) |
| Rest (aggregates) (%) | 83 | 65 | Spooren et al. (2013) |
| Recovery efficiencies (%) | | | |
| Ferrous metals | 10 | 10 | Case study |
| Non-ferrous metals | 10 | 10 | Case study |
| RDF | 90 | 90 | Case study |
| Rest (aggregates) | 90 | 90 | Case study |
| Electricity consumption (kW h/t fines) | 35 | 70 | Industrial reference |
| Investment cost (€/t fines) | | 3 | Industrial reference |
| Operational cost (€/t fines) | | 2 | Industrial reference |
| *Land reclamation* | | | |
| Investment cost (€/$m^2$) | | 0.48 | Industrial reference |
| Operational cost (€/$m^2$) | | 0.9 | Industrial reference |
| *Solid waste disposal* | | | |
| APC residue disposal (€/t) | 96 | | ETC/SCP (2012), industrial reference |
| Other waste disposal (€/t) | 10 | | ETC/SCP (2012), industrial reference |
| *Wastewater treatment plant* | | | |
| Investment cost (€/t wastewater) | 5 | | Industrial reference |
| Operational cost (€/t wastewater) | 3 | | Industrial reference |

**Appendix A** (*continued*)

| Parameters | | | Sources |
|---|---|---|---|
| *Temporary storage* | | | |
| Investment cost (€/t waste) | 5 | | Industrial reference |
| Operational cost (€/t waste) | 4 | | Industrial reference |
| *Materials and energy prices* | | | |
| Soil for refilling purposes (top soil) (€/t) | | 5 | Industrial reference |
| Ferrous metals (€/t) | | 200 | Eurofer Scrap price |
| Non-ferrous metals (€/t) | | 1000 | Van Passel et al. (2013), industrial feedback |
| Glass (€/t) | | 6 | Industrial reference |
| Aggregates (€/t) | | 10 | Industrial reference |
| Electricity (€/MW h) | | 68 | Van Passel et al. (2013); Eurostat (2014) |
| Green certificates (€/MW h) | | 117 | Van Passel et al. (2013) |
| Land (€/$m^2$) | | 3 | Van Passel et al. (2013), industrial feedback |

[a] MSW RDF contains 5.7% paper and cardboard, 35% plastic and rubber, 13% textile, 26% wood, 2% mineral, 0.9% glass, 0.07% metals and 18% fines (Spooren et al., 2013). The composition of IW RDF is not reported.
[b] MSW metals contain 2.2% ferrous metals and 0.6% non-ferrous metals. IW metals contain 1.5% ferrous metals and 0.9% non-ferrous metals.
[c] Rocks, glass and slag fraction contains 4% glass and 4% stones in MSW. In IW these values are 3% for both glass and stones.
[d] Calculated by considering 47% of renewable fraction.

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