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A DECISION SUPPORT TOOL FOR ENHANCED LANDFILL MINING

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ABSTRACT

Enhanced Landfill Mining has great potential to reduce the negative effects of landfills on both the environment and human health, to reclaim valuable land and provide a new source of raw materials. However, uncertainties in economic feasibility and environmental and social outcomes act as a bottleneck to its widespread uptake. Here, we present a decision support tool (DST) which aims to reduce these uncertainties by assisting site operators in assessing the economic, environmental and social consequences of a proposed project, while also evaluating the best technology train to use and the amount of rare earth elements (REE) present. Such a tool is the first of its kind and we propose its use as an initial assessment aid prior to more complex modelling of project feasibility in order to increase the uptake of enhanced landfill mining practices in the field of sustainable waste management.

1. INTRODUCTION

Enhanced Landfill Mining (ELFM) refers to the process of excavating waste materials that have previously been disposed of from landfills and valorising these historic waste streams as both materials (waste-to-material, WtM) and energy (waste-to-energy, WtE) (Jones et al., 2013).

Europe has an estimated 150,000 to 500,000 landfill sites with a predicted 90% pre-dating the EU Landfill Directive of 1999 (Jones et al., 2013). These older landfill often lack environmental protection technology and will soon require expensive remediation measures in order to avoid harm to human health and the environment. In addition, from previously following a linear economy model of take-make-dispose, "non-sanitary" landfills currently store an abundance of valuable materials as waste, including secondary raw materials (SRM), critical raw materials (CRM) and rare earth elements (REE), and therefore represent a huge untapped resource (Gutierrez-Gutierrez et al., 2015; Laner et al., 2016). Such resources are finite and under increasing demand due to the emergence of new economies (Wante and Umans, 2010). These resources are currently sourced primarily from outside of Europe, making Europe vulnerable to price fluctuations as a result of global demand (Lapko et al., 2016).

ELFM has the potential to drastically reduce remediation costs, provide new resources in the shape of SRM, CRM and REE from within the EU and reclaim valuable land (Gutierrez-Gutierrez et al., 2015; Laner et al., 2016). As a result, there has recently been an increased interest in the application of ELFM and the European Parliament has recently taken the decision to add ELFM to the Landfill Directive (EURELCO, 2017). However, due to uncertainty regarding the economic feasibility and social and environmental consequences of ELFM (Frändegård et al., 2013a; Danthurebandara et al., 2015), this concept is not presently broadly implemented by operators. To date, there is no tool available to assess clearly the economic feasibility of a proposed ELFM project, to evaluate the environmental and social impacts or to identify the best process to use.

This paper aims to present a Decision Support Tool (DST) that uses a step-wise approach to assess the best ELFM process, the expected economic output and the social and environmental impacts of ELFM. The DST was developed to deal with municipal solid waste (MSW) and commercial and industrial waste (C&I) and provides 5 waste composition mixes as default parameters taken from a literature review. The tool also gives the users the option to input their own waste composition, along with other input parameters. Furthermore, 9 processing scenarios were developed, considering the following technologies: soil flushing, excavation, screening, shredding, air separation, ballistic separation, magnetic separation, Eddy-current separation, and Advanced Thermal Treatment (ATT). For each scenario, on-site/off-site was considered and 3 options are proposed as follows: (i) all the treatments are done on-site (no transportation), (ii) the sorting is done on site but the refuse-derived fuel (RDF) is transported to an off-site Waste to Energy facility (transport WtE only), (iii) the excavated waste is only

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screened on site, then transported to a Waste Treatment Facility (WTF) for sorting, and the RDF transported again to a WtE facility for recovery (Transport WTF + WtE). The tool determines environmental, social and economic indicators for each scenario using multi-criteria analysis and the best scenario approach from a sustainability standpoint for landfill mining is identified. The tool also estimates the amount of REE present in landfill, determined by literature review.

2. METHODS

2.1 Determination of Typical Waste Composition

The typical waste fractions and composition of municipal solid waste (MSW) and construction and industrial waste (C&I) were determined based on six published case studies across Europe (Table 1).

A weighted average approach was then used to define the 5 waste compositions scenarios considered by default by the DST (Table 2). However, results obtained with this simple model approach should be taken with caution because the waste composition and fractions at site can vary significantly and either over or underestimate of the percentage of certain fractions. The DST is based on values taken from literature which will need to be updated over time as new data will become available to better reflect landfill waste composition processes.

2.2 Determination of ELFM Scenarios

The ELFM scenarios and technologies were based on a critical review of published articles and industry references. In our case, ELFM begins either by in-situ leaching/soil flushing and metal recovery or directly by waste excavation. The waste is then sorted with various techniques and the calorific fraction is recovered as RDF by ATT (Table 3).

TABLE 1: Typical waste composition of MSW and C&I landfill sites.

Case study	**Waste Composition**							**C&I**				
	1	**2**	**3**	**4**	**5**	**6**	**Average**	**5**	**6**	**2 (site 4)**	**2 (site 5)**	**Average**
Location	(site 4)	2	Belgium	Belgium	Germany	Belgium		Germany	Belgium	Belgium	Belgium	
<10 mm soil type	(site 5)	Average	44%	43%	46%	43%	46	27%	62%	70%	58%	60%
Plastic	8%	25%	17%	12%	9%	33%	17	33%	19%	7%	4%	15%
Paper/card	8%	14%	8%	2%	5%		7	-	-	1%	3%	2%
Wood	7%	4%	7%	9%	10%		7	-	-	2%	12%	8%
Textile	3%	3%	7%	4%	3%		4	-	-	2%	2%	2%
Glass	-	-	-	-	2%	-	2	-	-	-	-	-
Stones, inert	10%	2.5%	15%	10%	25%	10%	2	8%	8%	11%	10%	10%
Ferrous metals	4%	2%	3%	3%	3%	3%	3	2%	2%	2%	4%	3%
Non-ferrous metals (REE)	0.8%			-			0.8%	-	-	-	-	-
Hazardous	0.2%	-	-	-	-	-	0.2%	-				-
Organic waste	3%	-	-	-	-	-	3	-	-	-	-	-

[1] Frändegård et al. (2013b), [2] Quaghebeur et al (2013), [3] Jones et al (2013), [4] Danthurebandara et al (2015), [5] Wanka et al (2016), [6] Spooren et al (2012)

TABLE 2: Waste composition used in this study.

	MSW				
Waste Fraction	**100% MSW**	**75% MSW, 25% C&I**	**50% MSW, 50% C&I**	**25% MSW, 75% C&I**	**100% C&I**
<10mm Soil Type	45.9%	49.5%	53.1%	56.8%	60.4%
Plastics	17.2%	6.6%	15.9%	15.3%	14.6%
Paper/Cardboard	7.1%	5.9%	4.6%	3.4%	2.2%
Wood	7.4%	7.4%	7.5%	7.5%	7.5%
Textiles	4.0%	3.5%	3.0%	2.5%	2.0%
Glass	1.6%	1.2%	0.8%	0.4%	0.1%
Stones (inert)	10.4%	10.3%	10.3%	10.2%	10.2%
Ferrous Metals	2.8%	2.8%	2.9%	3.0%	3.1%
Non-ferrous Metals (REE)	0.8%	0.6%	0.4%	0.2%	0.0%
Hazardous	0.2%	0.2%	0.1%	0.1%	0.0%
Organic	2.7%	2.0%	1.3%	0.7%	0.0%
TOTAL	100%	100%	100%	100%	100%

TABLE 3: ELFM scenarios.

S	Technologies train process								
1	Soil flushing	-	-	-	-	-	-	-	-
2	Soil flushing	Excavation	Screening	Shredding	Ballistic separation	Ferrous metal separation	Non-ferrous metal separation	ATT (gasification)	-
3	Soil flushing	Excavation	Screening	Fines Ferrous metal separation	Shredding	Ballistic separation	Ferrous metal separation	Non-ferrous metal separation	ATT (gasification)
4	Soil flushing	Excavation	Screening	Shredding	Air separation	Ferrous metal separation	Non-ferrous metal separation	ATT (gasification)	-
5	Soil flushing	Excavation	Screening	Fines Ferrous metal separation	Shredding	Air separation	Ferrous metal separation	Non-ferrous metal separation	ATT (gasification)
6	Excavation	Screening	Shredding	Ballistic separation	Ferrous metal separation	Non-ferrous metal separation	ATT gasification)	-	-
7	Excavation	Screening	Fines Ferrous metal separation	Shredding	Ballistic separation	Ferrous metal separation	Non-ferrous metal separation	ATT (gasification)	-
8	Excavation	Screening	Shredding	Air separation	Ferrous metal separation	Non-ferrous metal separation	ATT (gasification)	-	-
9	Excavation	Screening	Fines Ferrous metal separation	Shredding	Air separation	Ferrous metal separation	Non-ferrous metal separation	ATT (gasification)	-

S = Scenario considered

For each scenario, 3 transportation options are considered (Figure 1):

1. No transportation (all treatments occur on-site)
2. Transportation for WtE only (on-site sorting, RDF transported to WtE facility)
3. Transportation for WTF and WtE (excavated waste screened on-site only, transportation to WtF for sorting and RDF transported to WtE facility)

2.3 Model Outputs

The DST assesses the impacts of the landfill mining scenarios based on three criteria: Environment, Society and Economy. The indicator set used were adapted from the SuRF-UK indicator set for sustainable remediation assessment (Table 4, CLAIRE, 2011). It is important to note that, at the outset of the assessment, an equal number of indicators (five) were identified under each of the environ-

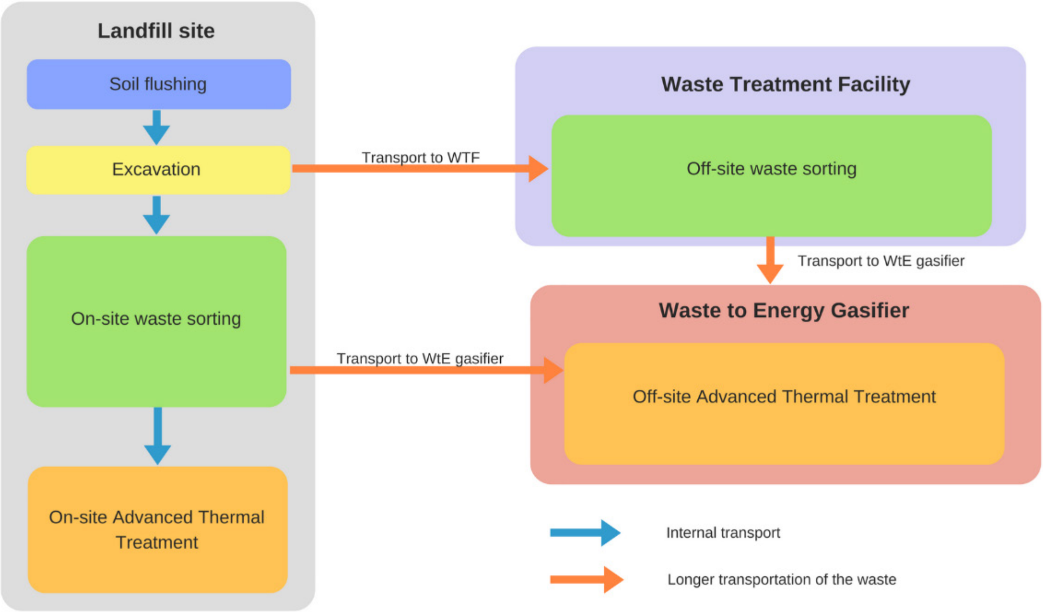


FIGURE 1: Transportation options.

TABLE 4: Sustainability indicator categories (adapted from CLAIRE, 2011).

Indicator	Environment	Social	Economic
1	Emission to air	Human health & Safety	Direct economic costs and benefits
2	Soil and ground conditions	Ethics & Equity	Indirect economic costs & benefits
3	Groundwater and surface water	Neighbourhoods & locality	Employment and employment capital
4	Ecology	Communities & community involvement	Induced economic costs & benefits
5	Resource Use and Waste Generation	Uncertainty and evidence	Project lifespan & flexibility

mental, social, and economic headlines (i.e., a total of 15 indicators across the sustainability assessment) (Table 4). This procedure ensured that, in the absence of individual indicator weighting, the three sustainability pillars were given equal weight (i.e., the outcome is not automatically biased by a disproportionate number of indicators in a single sustainability pillar). At higher levels of assessment, where stakeholder engagement and participatory processes seek to establish consensus on the relative weighting of the three components or their constituent indicators, it may be appropriate to apply weightings to the individual indicators to reflect the relative importance of different indicators to the stakeholders (CLAIRE, 2010).

The sustainability appraisal of the landfill mining options was carried out in a stepwise manner, starting with a simple qualitative assessment, followed by a semi-quantitaive muticriteria analysis (MCA) and a monetized cost-benefit assessment (CBA). The MCA approach was adopted using a spreadsheet tool (the DST). The benefits and impacts of undertaking LFM options were assessed based on the 15 SuRF-UK indicator categories (Table 4) and the relative importance of the five different indicator categories listed under each pillar of sustainability were weighted based on own judgement. Care was taken to ensure the total weights applied across the indicators under each of the environmental, social, and economic headings were equal, such that there was a balanced appraisal of the environmental, social, and economic factors.

2.3.1 Environmental Assessment

The assessment criteria used for the environmental indicators are summarised in Table 5.

Due to the difficulty to find quantitative information on the environmental impacts of the selected technologies, these were scored by comparing them with each other rather than by giving them absolute values. Thus, -3 was assigned to the technology with the highest positive impact and +3 was assigned to the technology with the highest negative impact (Table 6). Each technology was also compared to a do-nothing scenario and to each other (pairwise comparison approach).

The given score captures the impact of the technology in the worst possible case. For example, when assessing the impact of soil flushing on water contamination, Sapsford et al. (2016) mentioned an environmental concern of this technique regarding the fate of the extractant, being able to contaminate groundwater in case of poor conditions or management. In that regard, to capture the risk of pollution of groundwater, and as the impact of soil flushing on water contamination is believed to be the worst of all technologies, a score of +3 was given for soil flushing on the water contamination indicator. However, if the landfill has a liner, the risk of water contamination is lower, so the score should be reduced. Therefore, the tool applies a correction factor to take into account action or technology that can mitigate the negative impacts of landfill mining. The indicators that have a correction factor include GHG, NOx, SOx and water contamination. The correction factor on GHG and NOx-SOx describes the influence of the distance of transportation on the impacts of the scenario and was set as follows: 0.8 if less than 10 km; (0.005 x distance km) + 0.75 if between 10 and 50 km and 1 if over 50 km.

TABLE 5: Assessment criteria for the environmental impacts.

Assessment criteria for environmental Impact		Definition
Air	GHG	Release of greenhouse gas emissions; closely linked with energy consumption
	PM	Production and release of particulate matter into the air
	Odour	Production of odour
	NOx SOx	Production and release of nitrous and sulphurous oxides into the air
	VOCs	Production and release of volatile organic compounds into the atmosphere
Water	Water Contamination	Impact on contamination levels in water
Soil	Soil Contamination	Impact on contamination levels in soil
Ecology	Biota	Intrusion (e.g. light level changes, landscape changes, visual changes) on surrounding biota
	Noise	Amount of noise generated
Resource Use and Waste Generation	Waste Production	Amount of waste produced
	Metal Recovery	Amount of metal recovered
	Combustible Recovery	Amount of RDF recovered

TABLE 6: Scoring scale.

Score	Definition
3	High negative impact
2	Moderate negative impact
1	Low negative impact
0	No impact
-1	Low positive impact
-2	Moderate positive impact
-3	High positive impact

The water contamination correction factor depends on the presence or not of a membrane liner in the landfill; if the user selects "Yes", then the correction factor applied is 0.2, otherwise it is 1. It should be noted that the lack of information supporting the sensitivity of impact with the changes of input data prevented a fine definition of the correction factors. However, to provide user with a starting point, the use of these correction factors based on own judgment are provided to describe the reduction of impact as realistically as practicable. The performance of the 9 scenarios and their 3 options are calculated by adding the scores of the technologies they involved. As scenario 4 and 5 involve 10 technologies, the scale of the performance for each indicator ranges from -30 to +30. A score of -30 represents the highest beneficial impact on the indicator in comparison with the "do-nothing" scenario, while a score of +30 represents the highest negative impact.

2.3.2 Economic Assessment

Due to the difficulty in obtaining current estimates of costs for landfill mining from published case studies, some assumptions were made when choosing the economic indicators (Table 7). The costs and efficiencies of each technology were determined from a literature review (Sapsford et al., 2016, Danthurebandra et al., 2015, Ford et al., 2013, Wolfsberger et al., 2016) and were multiplied by the amount of input waste to calculate the amount of waste processed by each technology. Table 8 provides an overview of the capital cost and operating costs considered.

The efficiency of each technology considered is summarised in Table 9. The DST was developed to calculate an estimate of the revenue from mining a landfill, by taking into consideration the revenues produced by the sales of the recovered metals and the produced electricity, as well as the use of the remediated land. The prices for the recovery of materials and electricity considered in the DST are summarised in Table 10.

All revenues were summed to calculate the total revenue. The revenues were calculated as follows:

$$\text{RMR} = \text{revenue from ferrous metal} + \text{revenue from non-ferrous metal}$$

where: RMR is revenue from material recovery (WtM)
Revenue from ferrous metal = amount (tonne) ⋆ price (€/tonne) and revenue from non-ferrous metal = amount (tonne) ⋆ price (€/tonne). Prices obtained from Letsrecycle.com, 2017.

TABLE 7: Economic indicators and their associated assumptions.

Indicator	Definition	Assumptions
Net Income	Difference between revenues and costs	-
Revenue	Income from sale of recovered materials, sale of produced electricity and sale of reclaimed land	Heavy and hazardous fraction resulting from sorting and ATT have a net income of zero. Adjusted for inflation using inflation rates from 2005-December 2016 (OECD, 2017; Eurostat, 2017). All obtained currencies converted to Euros (€). Conversion rate for GBP (£) to Euros (€) and US Dollars ($) to Euros (€) 1.17 and 0.9416 respectively
Costs	Operational and capital costs of soil flushing, excavation, separation, sorting techniques and ATT. Also considers transportation costs	Adjusted for inflation using inflation rates from 2005-December 2016 (OECD, 2017; Eurostat, 2017). All obtained currencies converted to Euros (€). Conversion rate for GBP (£) to Euros (€) and US Dollars ($) to Euros (€) 1.17 and 0.9416 respectively

TABLE 8: Costs estimates used by the DST.

Technology	Capital cost (€/item)	Low operating costs (€/tonne)	High operating costs (€/tonne)	Reference
Soil flushing	-	10	228	Sapsford et al (2016)
Excavation	2.10 €/tonne	-	3.94	Danthurebandra et al 2015)
Visual separation	-	-	0.8	Ford (2013)
Ballistic separation	150,000	-	6.80	Wolfsberger 2016
Screening	200,000	-	2.91	Ford (2013)
Shredding	325,000	-	9.71	Ford (2013)
Air separation	292,500	-	14.56	Ford (2013)
Ferrous metal separation	45,000	-	2.91	Ford (2013)
Non-ferrous metal separation	65,000	-	5.83	Ford (2013)
Transportation	-	-	0.2	Schade et al., (2006)
ATT (gasification)	50 €/tonne	-	67	Danthurebandra et al (2015)

TABLE 9: Efficiency used for the DST for each technology considered.

% of material that goes to following processes	<10mm soil type	Plastic	Paper/ Card-board	Wood	Textile	Glass	Stones, inert	Ferrous metals	Non-ferrous metals	Hazard-ous	Organic waste	Reference
Excavation	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	
Ballistic separation Heavy fraction	5%	50%	20%	60%	20%	50	35%	95%	75%	80%	50%	Wolfsberger et al (2016)
Fine fraction	90%	10%	10%	20%	5%	50%	60%	3%	20%	15%	50%	Wolfsberger et al (2016)
Calorific fraction	5%	40%	70%	20%	75%	50%	5%	2%	5%	5%	0%	Wolfsberger et al (2016)
Screening	10%	80%	70%	75%	90%	10%	90%	50%	40%	15%	5%	Wolfsberger et al (2016)
Shredding	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	Assumption
Air separation	1%	99%	99%	1%	99%	1%	1%	1%	1%	1%	1%	http://www.nihot.co.uk/products/drum-separators/
Ferrous metal separation	98%	95%	100%	98%	99%	100%	98%	20%	100%	00%	100%	Wolfsberger et al (2016)
Non-ferrous metal separation	97%	98%	98%	98%	99%	100%	100%	97%	20%	100%	100%	Wolfsberger et al (2016)
Fines Ferrous metal separation	98%	95%	100%	98%	99%	100%	98%	20%	100%	100%	100%	Assumption
Soil flushing	100%	100%	100%	100%	100%	100%	100%	70%	70%	100%	100%	Assumption

TABLE 10: Revenues from metals and energy recovery and from land reclamation.

Revenue	Worst case	Best case	References
Electricity production	80 €/MWh	135 €/MWh	http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Electricity_prices_for_household_consumers,_second_half_2015
Ferrous metal recovery	130 €/ton	142 €/ton	Prices of scraps www.letsrecycle.com/prices/metals
Non-ferrous metal recovery	1827 €/ton	1913 €/ton	Prices of scraps www.letsrecycle.com/prices/metals
Land reclamation: Residential Industrial Agricultural Nature	 155 € 80 € 10 € 3 €		Danthurebandara et. al (2015)

$$RER = \text{amount of RDF (tonne)} * \text{calorific value (MJ/tonne)} * \text{ATT efficiency} * \text{conversion factor (MWh/MJ)} * \text{price of electricity (€/MWh)}$$

where: RER is revenues from energy recovery (WtE)
Prices obtained from http://ec.europa.eu/eurostat/statistics-explained/index.php/.

$$RLR = \text{land area (ha)} * \text{land value (€/ha)}$$

where: RLR is revenues from land reclamation. Land values obtained from Danthurebandara et al., 2015 for 4 different uses; residential, industrial, agricultural and nature. A land use for more landfill space was given a value of 0 €/ha, but can be changed by the users to consider avoided costs.

2.3.3 Social Assessment

The social indicators used were adapted from the SURF UK indicator set for sustainable remediation assessment (CLAIRE, 2011) and summarised in Table 4. A brief explanation of how they were considered in the tool is provided below.

- Community Involvement: measures the community involvement and acceptance of the project. This involvement depends on the consequences created that directly affect their life.
- Human Health: measures the impacts on the health of the site-workers and community members caused by the incidence of VOCs, noise, odour, dust and bioaerosols.
- Ethical considerations: measures the possibility of creating ethical disputes. For example, groundwater gets contaminated and a population is served from this source.
- Nuisance on neighbourhoods: measures the occurrence of nuisance factors (e.g. noise, light pollution, smells, litter and debris off site).
- Evidence of Sustainability and Level of Uncertainty:

measures the degree of environmental sustainability, as well as the levels of uncertainty related to the outcomes.

The social performance of the scenarios is calculated the same way as the environmental performance described previously. A correction factor was also applied for the human health and nuisance on neighbourhood indicators to take into account the influence of the number of close residents. Given the absence of supporting data, the correction factor were developed based on own judgement (Table 11).

2.4 Calculation of REE

REE estimates were calculated using a linear regression between percentage MSW and amount of REE. The data were taken from Morf et al. (2013) and Gutierrez-Gutierrez et al., (2015) (Table 12). REE value was calculated by multiplying the amount of REE with the market value from January 2017 to March 2017 (London Metal Exchange, 2017; Metalary, 2017).

3. MODEL OUTPUTS AND USER INTERFACE

The DST was created in Microsoft Excel. The following sections will explain the tool interface and outputs of the model.

3.1 Scenario Inputs

The scenario input tab is displayed in Figure 2. This tab is used to enter the input parameters. Users have the option to select either default values for waste composition, value of the remediated land or enter their own values (custom composition). The user can also select the best scenario calculation according to either best financial, environment or social outcomes.

3.2 Best Scenario Results and Scenario Comparison

The best scenario results tab displays the economic, environmental and social assessment results for the best scenario according to the user's criteria for selection (Figure 3). For the environmental and social assessments, the impact indicators are also displayed as a bar chart, where the baseline is the do-nothing scenario (Figure 4).

The scenario comparison tab compares the performance of all 9 ELFM scenarios against each other. This is displayed visually with radar charts, created by fixing the worst performer in each category (economic, environmental and social) to zero and the best performer in each category to 100; each scenario is placed along this scale of 0 to 100 (worst to best) by regressing the scale against actual values. Illustrative example is shown in Figure 5.

TABLE 11: Correction factor values used for the human health and nuisance on neighbourhood.

Number of residents living at less than 1km from the boundaries	Correction factor values
< 200	0.1
200 - 400	0.2
400 - 600	0.4
600 - 800	0.6
800 - 1000	0.8
> 1000	1

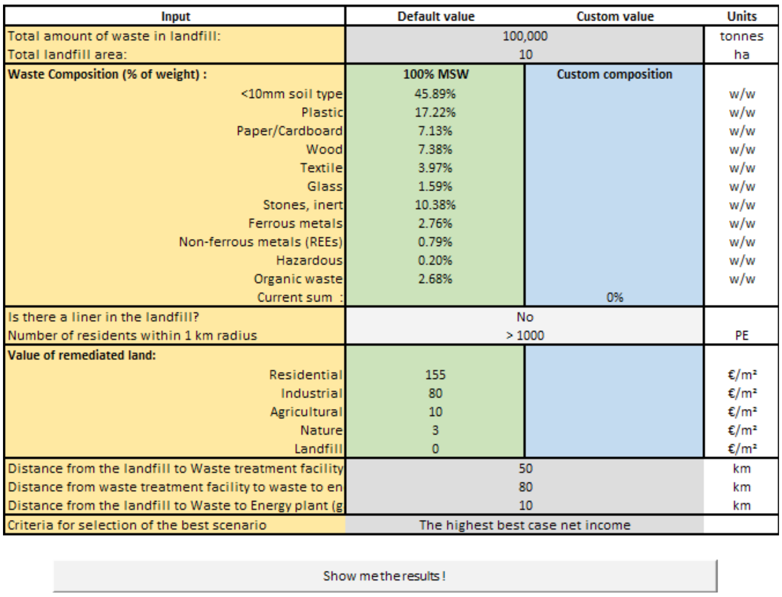
TABLE 12: Estimates of REE amount in landfill sites.

	Concentration mg/kg	Gutierrez et al (2015) 75% MSW 25% C&I	Morf et al (2013) 57,2% MSW 42,8% C&I
REEs	Sc	3.46	0.96
	Y	6.42	7.85
	La	9.36	9
	Ce	21.38	20.5
	Pr	2.39	1.9
	Nd	11.75	7.26
	Sm	2.06	
	Eu	0.59	
	Gd	2.07	0.75
	Tb	0.24	
	Dy	1.44	
	Ho	0.21	
	Er	0.65	
	Tm	0.08	
	Yb	0.52	
	Lu	0.07	
PGMs	Pt	0.02	0.059
	Pd	0.77	0.5
	Ru	21.90	0.0005
Other critical	Li	0.10	9
	In	7.71	0.29
	Sb	14.14	
	Co	1076.00	
Others	Cu	1076	2230
	Ag	2.26	5.3
	Au	0.18	0.4
	Al	17274	17000

4. MODEL TESTING AND VALIDATION

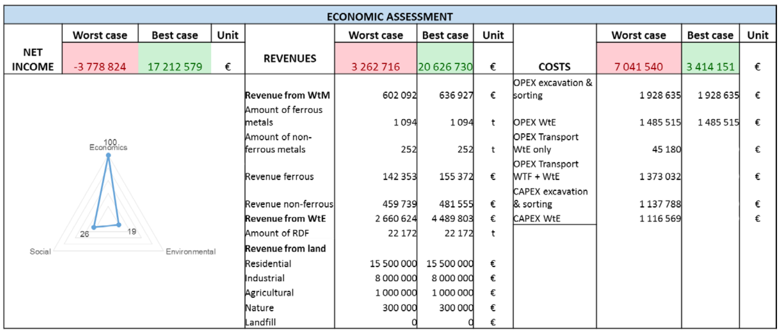
In order to test the tool and to further understand which factors affect landfill mining feasibility, 10 scenarios were simulated. The characteristics of each scenario are shown in Table 13. In all 10 cases, the same amount of waste and size of landfill were used. Five variations of the waste composition were considered to understand which materials make landfill mining more profitable. In addition, with each type of waste composition, parameters such as the presence of a geomembrane, number of residents and the distances to the energy and sorting facilities were varied in order to understand the variations of the social and environmental indicators. Given that the only parameter affecting the amount of REEs in the tool is the percentage of MSW, REEs calculation was only done for cases 1, 3, 5, 7 and 9. In this illustrative example the criteria for selection of the best scenario was "the highest best case net income".

The economic results are shown in Table 14. For all the different types of landfills used, the best suggested process approach is Scenario 8. This scenario allows the highest net income due to the high efficiency (99%) of the air separation process. This efficiency increases the amount of plastics, textiles and wood sorted, thus increasing the



Input	Default value	Custom value	Units
Total amount of waste in landfill:	100,000		tonnes
Total landfill area:	10		ha
Waste Composition (% of weight) :	**100% MSW**	**Custom composition**	
<10mm soil type	45.89%		w/w
Plastic	17.22%		w/w
Paper/Cardboard	7.13%		w/w
Wood	7.38%		w/w
Textile	3.97%		w/w
Glass	1.59%		w/w
Stones, inert	10.38%		w/w
Ferrous metals	2.76%		w/w
Non-ferrous metals (REEs)	0.79%		w/w
Hazardous	0.20%		w/w
Organic waste	2.68%		w/w
Current sum :		0%	
Is there a liner in the landfill?	No		
Number of residents within 1 km radius	> 1000		PE
Value of remediated land:			
Residential	155		€/m²
Industrial	80		€/m²
Agricultural	10		€/m²
Nature	3		€/m²
Landfill	0		€/m²
Distance from the landfill to Waste treatment facility	50		km
Distance from waste treatment facility to waste to en	80		km
Distance from the landfill to Waste to Energy plant (g	10		km
Criteria for selection of the best scenario	The highest best case net income		

FIGURE 2: Scenario inputs display.



ECONOMIC ASSESSMENT

	Worst case	Best case	Unit
NET INCOME	-3 778 824	17 212 579	€

REVENUES	Worst case	Best case	Unit
	3 262 716	20 626 730	€
Revenue from WtM	602 092	636 927	€
Amount of ferrous metals	1 094	1 094	t
Amount of non-ferrous metals	252	252	t
Revenue ferrous	142 353	155 372	€
Revenue non-ferrous	459 739	481 555	€
Revenue from WtE	2 660 624	4 489 803	€
Amount of RDF	22 172	22 172	t
Revenue from land			
Residential	15 500 000	15 500 000	€
Industrial	8 000 000	8 000 000	€
Agricultural	1 000 000	1 000 000	€
Nature	300 000	300 000	€
Landfill	0	0	€

COSTS	Worst case	Best case	Unit
	7 041 540	3 414 151	€
OPEX excavation & sorting	1 928 635	1 928 635	€
OPEX WtE	1 485 515	1 485 515	€
OPEX Transport WtE only	45 180		€
OPEX Transport WTF + WtE	1 373 032		€
CAPEX excavation & sorting	1 137 788		€
CAPEX WtE	1 116 569		€

FIGURE 3: Best scenario results.

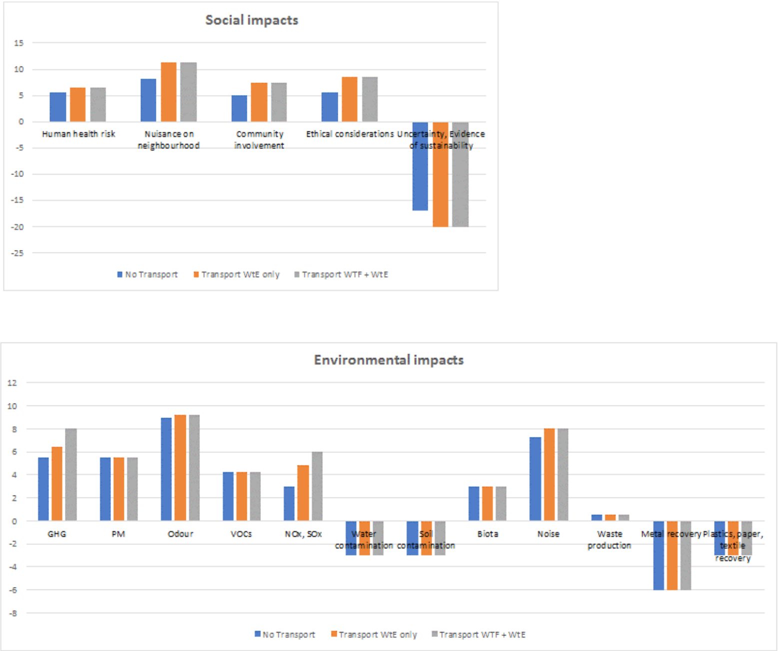


FIGURE 4: Bar charts showing social and environmental impacts.

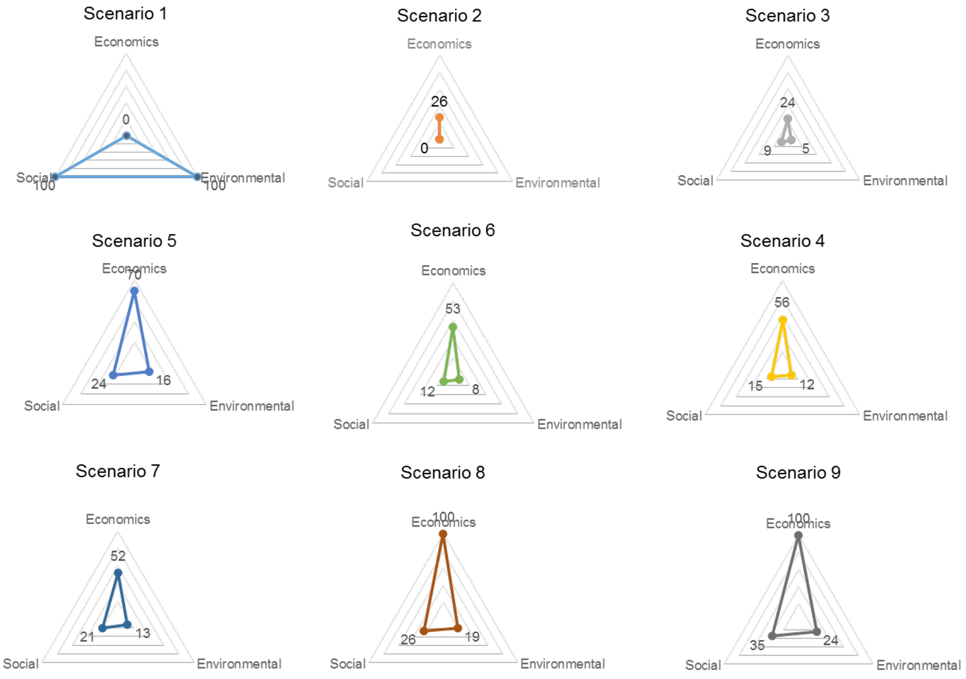


FIGURE 5: Radar charts for scenario comparison.

amount of electricity produced and sold. Even though the recovery of ferrous metals from the fines increases the total recovered amount of these materials, the extra cost of this process outweighs its revenues, thus decreasing the net income of the whole mining process. From these simulations, it can be seen that the higher the percentage of MSW in the landfill, the higher the net income. This is due to the fact that the higher the percentage of MSW, the higher the amount of non-ferrous metals, paper/cardboard and textile.

Social impacts such as human health risk and nuisance on neighbourhood increase with the number of people living in the areas surrounding the landfill. The presence of a geomembrane in the landfill increases the positive impact of landfill mining on the water contamination indicator. Also, the use of transportation increases the negative impacts on GHG emissions, SOx and NOx. For all the evaluated cases, the potential revenues from REEs are high, passing the 1.2 billion € threshold (data not shown). The elements with the highest values are: Sc, Pd, Au, Al and Cu. Even though the amount of Sc, Pd and Al is reduced as the percentage of MSW decreases, the quantity of Ag, Au, Cu and other elements increase, thus maintaining the high revenues. The high variations in the amount of REEs present in the different landfills can also be attributed to the fact that the correlation between REEs and percentage of MSW was done considering only two landfill sites.

To validate the model and the DST outputs, the DST was run for the REMO landfill as a case study. Input data

TABLE 13: Overview of the scenarios considered.

Case	Waste composition	Is there a liner in the landfill?	Number of residents within 1 km radius (PE)	Distance from the landfill to Waste treatment facility (km)	Distance from waste treatment facility to waste to energy plant (km)	Distance from the landfill to Waste to Energy plant (gasifier) (km)	Criteria for selection of the best scenario
1	100% MSW	Yes	0	0	0	0	Best net Income
2	100% MSW	No	1000	10	10	0	Best net Income
3	75% MSW 25% C&I	Yes	0	0	0	0	Best net Income
4	75% MSW 25% C&I	No	1000	10	10	0	Best net Income
5	50% MSW 50% C&I	Yes	0	0	0	0	Best net Income
6	50% MSW 50% C&I	No	1000	10	10	0	Best net Income
7	25% MSW 75% C&I	Yes	0	0	0	0	Best net Income
8	25% MSW 75% C&I	No	1000	10	10	0	Best net Income
9	100% C&I	Yes	0	0	0	0	Best net Income
10	100% C&I	No	1000	10	10	0	Best net Income

TABLE 14: Overview of the operating and capital costs for the 10 scenarios.

Scenarios		Costs (€)		OPEX excavation & sorting (€)		OPEX WtE (€)		OPEX Transport WTF + WtE (€)		CAPEX excavation & sorting (€)		CAPEX WtE (€)	
Case	**Waste composition**	**Worst scenario**	**Best scenario**	**Worst scenario**	**Best scenario**	**Worst scenario**	**Best scenario**	**Worst scenario**	**Best scenario**	**Worst scenario**	**Best scenario**	**Worst scenario**	**Best scenario**
1	100% MSW	716,819, 611	515,536, 732	291,223, 938	291,223, 938	224,312, 794	224,312, 794	-	-	32,680, 988	-	168,601, 891	-
2	100% MSW	754,191, 849	515,536, 732	291,223, 938	291,223, 938	224,312, 794	224,312, 794	37,044, 569	-	32,387, 030	-	168,563, 393	
3	75% MSW & 25% I&W	679,076, 429	491,499, 857	285,573, 737	285,573, 737	205,926, 120	205,926, 120	-	-	32,680, 988	-	154,895, 584	-
4	75% MSW & 25% I&W	715,894, 061	491,499, 857	285,573, 737	285,573, 737	205,926, 120	205,926, 120	36,817, 632	-	32,680, 988	-	154,895, 584	-
5	50% MSW & 50% I&W	641,333, 247	467,462, 983	279,923, 536	279,923, 536	187,539, 446	187,539, 446	-	-	32,680, 988	-	141,189, 276	-
6	50% MSW & 50% I&W	677,596, 273	467,462, 983	279,923, 536	279,923, 536	187,539, 446	187,539, 446	36,263, 026	-	32,680, 988	-	141,189, 276	-
7	25% MSW & 75% I&W	603,590, 065	443,426, 108	274,273, 336	274,273, 336	169,152, 772	169,152, 772	-	-	32,680, 988	-	127,482, 969	-
8	25% MSW & 75% I&W	639,298, 485	443,426, 108	274,273, 336	274,273, 336	169,152, 772	169,152, 772	35,708, 419	-	32,680, 988	-	127,482, 969	-
9	100% I&W	565,846, 883	419,389, 233	268,623, 135	268,623, 135	150,766, 098	150,766, 098	-	-	32,680, 988	-	113,776, 662	-
10	100% I&W	601,000, 696	419,389, 233	268,623, 135	268,623, 135	150,766, 098	150,766, 098	35,153, 813	-	32,680, 988	-	113,776, 662	-

was taken from (Van Passel et al., 2013) and a 50% MSW, 50% C&I waste scenario was used, congruent with waste sources described in the literature. The DST economic outputs are displayed in Table 15 alongside the economic assessment results from Van Passel et al. (2013).

While net income, WtE revenues and excavation, sorting and pre-treatment costs show little variance between the DST outputs and those published, values for WtM revenues and incineration costs vary greatly. This does not invalidate the DST outputs, but may be a product of model assumptions; for example (Van Passel et al., 2013) considered a scenario where a high capacity ATT plant is built, whereas the DST ATT plant is flexible in capacity depending on the amount of waste to be processed. In addition, some differences are likely to be a result of the economic models used; (Van Passel et al., 2013) used the more complex Net Present Value (NPV) model which considers monetary value change over time whereas the DST does not account for this.

5. CAUTIONARY NOTES

The DST provides a framework for the assessment of landfill mining projects. The DST is based on values taken from literature which need to be updated over time as new data will become available to better reflect landfill waste composition processes. No formal sensitivity analysis has been performed to test for interactions among the indicators due to a lack of field-scale data available whilst existing influences are present and are mentioned previously. Therefore, caution must be taken with different model settings as the results may not directly be comparable and recommendations for landfill mining scenarios are not necessarily supported by the authors. Several limitations such as error margin on the waste composition, technology process efficiency, technology cost, land value, weighting approach used which is based on a small panel of two academics and two professionals should be consider by the user when reviewing the tool results. Conservative estimates must be used in order to not overestimate or underestimate the sustainability criteria.

6. CONCLUSIONS

The DST is able to predict the economic, environmental and social outcomes of a ELFM project, along with an estimate of the amount of REE present and the best ELFM process and technology train to use. The DST has been designed to allow user input parameters, or for the user to select input parameters provided by the tool from literature review. The user is able to select the criteria for the best scenario and compare across different ELFM process scenarios. Overall, the DST is the first of its kind and acts as an initial assessment tool prior to more complex assessments and modelling. The DST will facilitate the uptake of ELFM practices by providing a feasibility assessment that is user-friendly for site operators.

The model validation shows that the DST modelling is congruent with literature in some economic outputs and differs in others. From this, we recommend future research into designing a similar DST that incorporates more complex models that account for value changes over time, such as NPV and full Life Cycle Analysis (LCA). In addition, parameters that are time dependent, such as market values, could, in future, be linked to continually updated databases to improve validity. Overall, the DST is an innovative and progressive tool that is successful in serving as a starting point for site operators to assess the feasibility of a proposed ELFM. The DST aids in reducing the uncertainty regarding the economic feasibility and social and environmental consequences of ELFM and will therefore encourage the uptake of ELFM projects.

TABLE 15: REMO simulation results.

Output	DST Value (€)	Van Passel et al. (2013) Value (€)	Variation
Net Income	2,123,650	1,933,825	10%
WtM Revenues	2,637,355	736,003	258%
WtE Revenues	8,785,195	6,831,834	29%
Excavation, Sorting and Pre-treatment Costs	2,875,956	3,373,913	-15%
Incineration Costs	6,304,862	2,260,409	179%

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