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Landfill mining: Development of a cost simulation model

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Abstract

Landfill mining permits recovering secondary raw materials from landfills. Whether this purpose is economically feasible, however, is a matter of various aspects. One is the amount of recoverable secondary raw material (like metals) that can be exploited with a profit. Other influences are the costs for excavation, for processing the waste at the landfill site and for paying charges on the secondary disposal of waste. Depending on the objectives of a landfill mining project (like the recovery of a ferrous and/or a calorific fraction) these expenses and revenues are difficult to assess in advance. This situation complicates any previous assessment of the economic feasibility and is the reason why many landfills that might be suitable for landfill mining are continuingly operated as active landfills, generating aftercare costs and leaving potential hazards to later generations. This article presents a newly developed simulation model for landfill mining projects. It permits identifying the quantities and qualities of output flows that can be recovered by mining and by mobile on-site processing of the waste based on treatment equipment selected by the landfill operator. Thus, charges for disposal and expected revenues from secondary raw materials can be assessed. Furthermore, investment, personnel, operation, servicing and insurance costs are assessed and displayed, based on the selected mobile processing procedure and its throughput, among other things. For clarity, the simulation model is described in this article using the example of a real Austrian sanitary landfill.

Keywords

Landfill mining, cost estimation, cost simulation model, feasibility, evaluation of waste quantities, estimation of waste quality

Introduction

More than 60 landfill mining projects have been carried out worldwide to date (BMBWFT, 1995; Bockreis and Knapp, 2011; Nispel, 2012). The past arguments for such projects have mostly been the recovery of landfill space, the rehabilitation of contaminated sites or the protection of the environment (especially groundwater) (Bockreis and Knapp, 2011; Zhao et al., 2007). Recovering secondary raw materials has rarely been an incentive to initiate the mining of a landfill. However, according to the European Commission (2008), which demands a change from waste management to a circular and resource economy by the prevention of waste or preparing it for re-use and recycling, resource efficiency must be improved. Thus, primary raw materials can be conserved and Europe`s dependence on imports reduced. As a result, landfill sites gain the attention of industry and science with regard to their potential in secondary raw materials. In this context, various research projects have been recently conducted in Europe (e.g. Tielemans and Laevers, 2010; Umans, 2011; Wanka et al., 2014). Landfill mining (LFM) helps recover secondary raw materials, like ferrous and non-ferrous metals or calorific fractions (such as plastics or wood), from deposited waste. These materials can be supplied to material recovery or to energy production, saving primary resources. The key to economic success of a LFM project is the costs accruing for mining the waste and for disposing of unusable waste, beside the amount of potential secondary raw material and the revenues gained from it. Since mined landfill waste is often heterogeneous and might be highly contaminated, feeding potential secondary raw materials directly to available recycling or production processes is often impossible. To comply with the European Commission (2008) and keep the share of re-deposited material as low as possible, the mined waste ought to be processed. At least impurities, like stones that can adversely affect the utilisation, should be removed. This generates more costs for the landfill operator. The total expense of a LFM project is, hence, often difficult to be qualified, owing to the following factors (Krüse, 2015).

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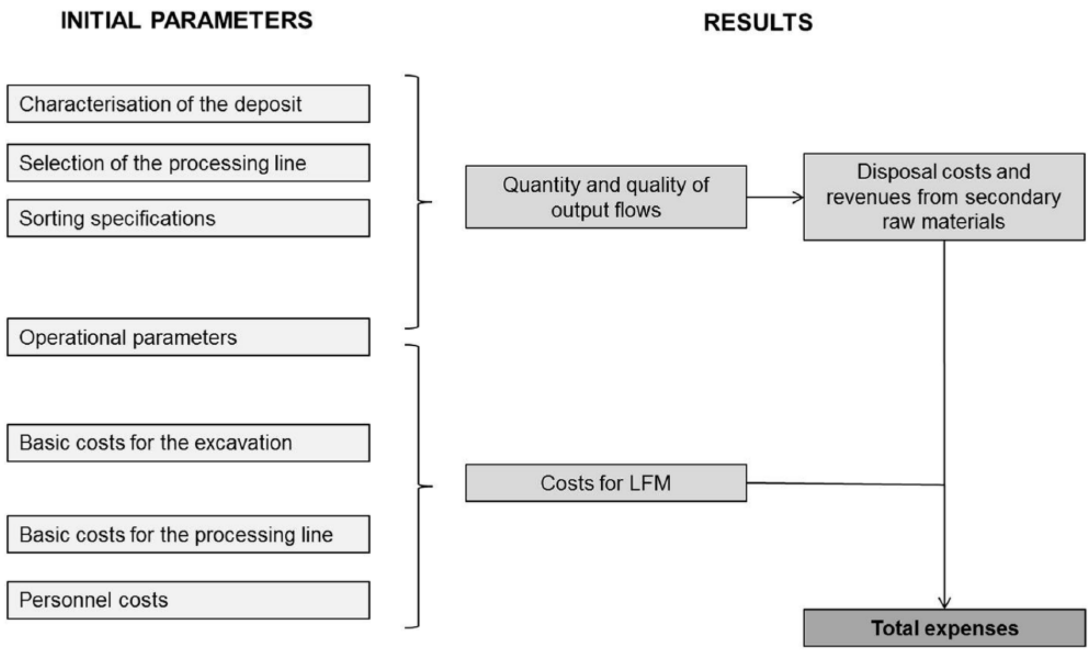

Figure 1. Required initial parameters and results.
LFM: landfill mining.

- The actual composition of a landfill body (determining the shares of usable and re-deposited materials, providing information about the presence of potentially hazardous waste).
- The efficiency of processing technologies that separate potential secondary raw material from landfill waste.
- The quality and the resulting marketing options of secondary raw material recovered from landfill waste.

Since the investment costs are often an essential argument for or against LFM, the required statement of cost ought to be as detailed as possible. To provide operators with a way to simulate the mining of their landfill, an Excel-based software model was developed in cooperation with communal and industrial partners to help estimate, among other things, secondary raw material revenues (marketing potential) and disposal costs resulting from LFM. Researches and model developments of this kind have already been carried out by scientists of the Justus Liebig University, Gießen (Germany). In this context, the excavated deposit has been classified by various waste fractions (like ferrous, non-ferrous, plastics or other), based on results of sorting and analysing that has been obtained, in parts, from references and from research operations at several German landfill sites, according to Nispel and Gäth (2014). With disposal or utilisation lines given for each fraction, the costs required for disposal and the expected revenues from secondary raw materials could be determined that way. Costs for processing the waste, however, have only been approximated in this model. The quality of the resulting potential secondary raw materials has not been assessed at all. By contrast, the model presented in this article does not only allow examination of disposal costs and raw material revenues, it also includes the computation and detailed breakdown of investment, personnel, operational, servicing and insurance costs in relation to the operator's chosen objective of the LFM (like separation of the fine-grain fraction, recovery of the metal fraction, etc.) and the throughput of a selected mobile processing line. The efficiency of mobile processing technologies in separating secondary raw materials, based on experience values, is considered by precisely specifying the processing line (see section Material and methods). Moreover, the chemical composition of the resulting output flows is assessed and useful recovery paths or disposal strategies are indicated.

The total result established by the model is the annual investment (sum of excavation, processing and disposal costs including revenues from secondary raw materials) that can be automatically converted into the total investment costs of the LFM period at the model's computation stage. These computations are based on the initial parameters entered in the model, see Figure 1.

The amount and quality of each output flow, which are automatically computed by the simulation model, derive from the initial parameters 'characterisation of the deposit', 'selection of the processing line', 'sorting specifications' and 'operational parameters'. Hence, revenues for potential secondary raw materials, as well as resulting disposal costs for non-reusable materials, can be deduced. The parameters 'operational parameters', 'basic costs for the excavation', 'basic costs for the processing line' and 'personnel costs' are used to compute the expenses for excavation and processing. The total costs derive from the total expenses of the LFM (excavation and processing) and the costs of disposal after deducing the secondary raw material revenues. Note that the parameter 'operational parameters' influences both, the quantity and quality of waste, as well as the costs for LFM.

A detailed description of the initial parameters is included in the section 'Material and methods'. For clarity, they are demonstrated by the example of a selected Austrian sanitary landfill (LFS 2). A detailed description of the landfill site is available in

Table 1. Composition of the landfill LFS 2 (based on stored data).

Fraction	Amount (%w/w)	Bulk density (kg m^{-3})
Ferrous	1.4	450
Non-ferrous	0.6	250
Paper, paperboard and cardboard (PPC)	2.2	150
Plastics	18.5	50
Glass	0.4	750
Composites	2.9	200
Minerals, inert	4.4	700
Wood	3.1	160
Textiles	5.1	120
Other	2.0	140
Fine-grain (<12 mm)	59.2	1410
Problematic substances	0.1	160
Total	100.0	909

Wolfsberger et al. (2014). With regard to LFS 2, its operator expects only a low potential of secondary raw materials. As a result, the objective of the simulated LFM can be described as follows: Processing should separate the fine-grain fraction, any impurities and the heavy fraction (essentially minerals and inert) to facilitate the delivery of the remaining waste flow to an incineration plant (energetic utilisation). However, ferrous and non-ferrous metals should be recovered and reused as much as possible (material recovery). The fine-grain fraction, impurities and the heavy fraction should be re-deposited at another sanitary landfill.

Materials and methods

The newly developed simulation model for evaluating the costs of mining a landfill will be presented as follows. The individual stages of the model and the initial parameters required are described based on the example of LFS 2, taking the objective of the LFM of LFS 2 into account.

Characterisation of the deposit

This parameter comprises data on the composition of the deposited waste. It includes results obtained from analysing sorted excavated waste and chemical descriptions of the fractions emerging from the sorting procedure. These data permit dividing the deposit in fractions while the input quality (chemical composition) of the waste is defined. If those data have been collected during a preliminary investigation of the actual landfill, these locally derived results can be entered in the model. If no such information is available, the model allows the use of previously stored data of Austrian sanitary landfills that have been derived from investigations of a landfill filled with untreated municipal solid waste (MSW) and another landfill site with MSW that has undergone mechanical biological treatment (MBT). These investigations have been performed during a research project by the Chair of Waste Processing Technology and Waste Management (AVAW) of the Montanuniversitaet Leoben and they have been implemented in the model. Selected results of these investigations and more about the chemical analyses have been published in Wolfsberger et al. (2015). Stored data of the landfill filled with MBT waste have been selected for simulating LFS 2, as MBT has always been applied on this site. Therefore, the landfill material of LFS 2 can be characterised as shown in Tables 1 and 2.

Selection of the processing line

The characterisation is followed by choosing the desired processing line that should be installed right on site. There are several processing aggregates to select from, like crusher, drum screen, magnetic separator or non-ferrous metal separator. The aggregates should be selected with the objective of the LFM in mind. If only the fine-grain fraction is to be removed from the waste flow, for example, then fragmenting the waste and sieving it may be sufficient. But if ferrous and non-ferrous metals and a calorific fraction are also supposed to be recovered, magnetic and eddy current separators or maybe ballistic separators will also have to be employed.

The processing line shown in Figure 2 has been selected for this simulation to meet the objectives of LFS 2's operator. In this context, to recover ferrous metals from the fine-grain fraction, a second magnetic separator was added to the processing equipment according to the specifications of the operator.

The waste is excavated with a clamshell excavator. Terrain loaders are used to transport the excavated waste to the mobile processing plant and to remove the resulting output flows within the landfill area. In addition, the landfill should be ventilated with the Smell Well system (The IUT Group, 2015) before any excavation commences. Ventilation reduces odour and gas emission while waste is dried before processing. Loss of water can be reasonably assumed at a level of 10% w/w or higher (Göschl R, Personal communication, 24 July 2015). A consultation with the landfill operator suggested it should be assumed for the purposes of this simulation that all mobile applications and the required conveyors would be bought and not rented.

Sorting specifications

The choice of processing equipment determines which sorting specifications should be entered in the model for every process

Table 2. Input quality of the waste of landfill LFS 2, based on stored chemical analysis data of individual fractions.

	Unit	Ferrous	Non-ferrous	PPC	Plastics	Glass	Composites	M/I	Wood	Textiles	Other	Fine-grain	Problematic substance
Net calorific value	kJ kg_{OS}^{-1}	–	–	13,250	15,600	0[d]	16,400[d]**	0[d]	15,225	13,600	10,500	4250	–
Water content	%	5.2	6.6	59	43	1[d]	8[d]	2[d]	57	53	50	38	–
Ash content	%	92.0[a]	92[a]	34	50	95[c]	–	99[c]	27	42	–	74	–
Ignition loss	%	8.8	8.8	64	48	3[c]	80[d]	1[c]	69	55	51.7	20	0[c]
TOC	%	4.1	4.1	32	31	0.6[d]	47.9[d]	1.0[d]	36	31	22.5	13	–
Antimony	mg kg_{DM}^{-1}	0.3	91	11	34	0[c]	17	53.04[c]	8	33	13	34	0[c]
Arsenic	mg kg_{DM}^{-1}	2.1	25	13	28	0.29[c]	1[c]	16.1[c]	11	29	15.0	36	0[c]
Lead	mg kg_{DM}^{-1}	9.2	2300	603	1083	104.5[c]	136[c]	2294[c]	283	570	710	2020	17,000[c]
Cadmium	mg kg_{DM}^{-1}	0.2	1.3	5	24	0.5[c]	2[c]	41.7[c]	4	8	6.50	10	0.4[c]
Chrome	mg kg_{DM}^{-1}	5 828	1400	370	383	81.55[c]	63[c]	92.4[c]	66	970	290	298	3230[c]
Cobalt	mg kg_{DM}^{-1}	73.9	23	17	20	0.1[c]	3[c]	24.86[c]	6	15	290	26	0[c]
Nickel	mg kg_{DM}^{-1}	1513	1100	55	178	0.23[c]	16[c]	76.04[c]	43	93	100	158	0[c]
Mercury	mg kg_{DM}^{-1}	0.1	1.25	2	2	0.11[c]	0.41[c]	1[c]	1	93	0.950	4	100[c]
Thallium	mg kg_{DM}^{-1}	0.1	1.25	0.32	1	0[c]	0.5[c]	0[c]	0	0	0.25	0	–
Chlorine	mg kg_{DM}^{-1}	0[b]	180	3450	10,100	150[c]	8350[c]	256[c]	1575	2950	4760	2148	27,125[c]
Sulphur	mg kg_{DM}^{-1}	87.2	1470	11,275	12,250	0.09[c]	2760[c]	0[c]	6025	15 875	5780	8 550	0.54[c]
Magnesium	mg kg_{DM}^{-1}	568.5	790	9645	10,675	11,020[d]	1940[d]	11,350[d]	7890	10,408	3400	10,828	–
Calcium	mg kg_{DM}^{-1}	200[b]	13,800	25,975	46,075	66,730[d]	25,010[d]	82,500[d]	30,825	40,075	30,400	73,350	–
Potassium	mg kg_{DM}^{-1}	0[b]	420	3860	7753	4870[4]	2100[d]	14,540[d]	2973	4308	5870	7108	–
Sodium	mg kg_{DM}^{-1}	0[b]	540	5003	6775	55,290[d]	4060[d]	4330[d]	5065	4395	5160	12,170	–

All values adopted from examinations of the mentioned research project of the AVAW chair unless otherwise stated.
[a]Ash content based on the ignition loss according to Wolfsberger (2013).
[b]Schenk (2014).
[c]IUT (Ingenieurgemeinschaft Innovative Umwelttechnik GmbH) Personal communication, 23 September 2014.
[d]BLU (2003).
**Values converted to original substance based on the water content (rounded up).
M/I: minerals/inert; TOC: total organic carbon; PPC: paper, paperboard and cardboard.

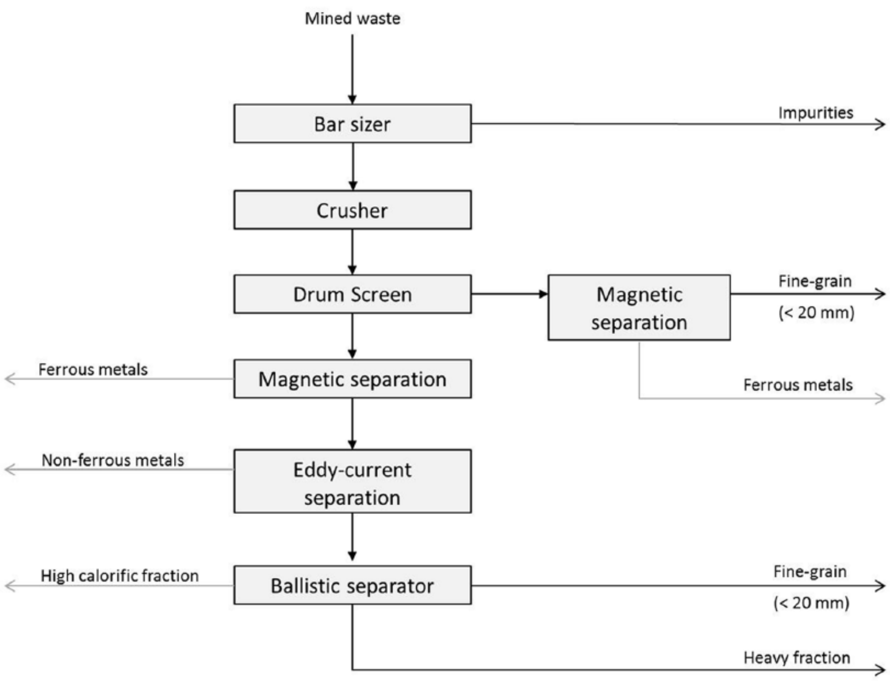

Figure 2. Processing line selected for waste of LFS 2.

stage. The specifications help divide the input material of each processing step into different output flows. The sorting specifications of every process step are preset in the model; deriving from past experience with processing MSW. Hence, these data do not need to be collected by the landfill operator, but are compellingly adopted as soon as a specific type of equipment is chosen. The sorting specifications given in Table 3 apply to the respective processing equipment for the selected processing of waste from

Table 3. Sorting specifications for the selected processing line for the LFM of LFS 2.

Fraction	Bar sizer		Drum screen		Ferrous separator		Non-ferrous separator		Ballistic separator		
	Content in the impurity (%w/w)	Content in the rest (%w/w)	Content in the fine grain (%w/w)	Content in the screen overflow (%w/w)	Content in the ferrous (%w/w)	Content in the rest (%w/w)	Content in the non-ferrous (%w/w)	Content in the rest (%w/w)	Content in the HF (%w/w)	Content in the fine grain (%w/w)	Content in CF (%w/w)
Ferrous	5	95	50	50	80	20	3	97	95	3	2
Non-ferrous	0	100	60	40	0	100	80	20	75	20	5
PPC	5	95	30	70	0	100	2	98	20	10	70
Plastics	6	94	20	80	5	95	2	98	50	10	40
Glass	0	100	90	10	0	100	0	100	50	50	0
Composites	1	99	25	75	2	98	0	100	50	10	40
Minerals	10	90	10	90	2	98	0	100	35	60	5
Wood	7	93	25	75	2	98	2	98	60	20	20
Textiles	0	100	10	90	1	99	1	99	20	5	75
Other	0	100	30	70	0	100	0	100	45	5	50
Fine fraction (<20 mm)	0	100	90	10	2	98	3	97	5	90	5
Problematic substances	5	95	85	15	0	100	0	100	80	15	5

HF: heavy fraction; CF: calorific fraction; PPC: paper, paperboard and cardboard.

Bar sizer						
	Input bar sizer		Sorting speifications bar sizer		Output flows bar sizer	
Fraction	[%]	[Mg*a^{-1}]	IMPURITY [%]	Residue [%]	IMPURITY [Mg*a^{-1}]	Residue [Mg*a^{-1}]
Ferrous	1%	2 430	5%	95%	121	2 308
Non-ferrous	1%	1 089	0%	100%	0	1 089
PPC	2%	3 658	5%	95%	183	3 475
Plastics	19%	31,523	6%	94%	1 891	29,632
Glass	0%	715	0%	100%	0	715
Composite	3%	4 877	1%	99%	49	4 829
Minerls/Inert	4%	7 505	10%	90%	750	6 754
Wood	3%	5 284	7%	93%	370	4 914
Textiles	5%	8 742	0%	100%	0	8 742
Other	2%	3 338	0%	100%	0	3 338
Fine grain	59%	100,701	0%	100%	0	100,701
Problematic substances	0%	238	5%	95%	12	226
Total	100%	170,100			3 377	166,723
				Total	170,100	

Figure 3. Output flows from the bar sizer.

landfill LFS 2 (Figure 2). For clarity, the meaning of the sorting specifications is explained as follows: Figure 2 shows that the input material of the bar sizer is the excavated landfill material, composed as shown in Table 1. Assume that the bar sizer releases 6% of the supplied plastics in the impurities fraction. The other 94% are processed in the line and fed to the drum screen. About 20% of those 94% are removed with the fine-grain fraction, about 80% remain in the screen overflow and are fed to the next processing aggregate. All other waste fractions are accordingly distributed.

Separating the input material also allows computing the chemical composition or quality of every output flow according to the characterisation of every waste fraction shown in Table 2. This is illustrated in equation 1, applying the net calorific value.

$$NCV_{O1} = \frac{NCV_{WF1} * w_{WF1} + NCV_{WF2} * w_{WF2} + usw.}{w_{Total}} \tag{1}$$

where NCV is the net calorific value (kJ kg$_{OS}^{-1}$), O is the output flow (e.g. impurities from bar sizer), WF is the waste fraction (as ferrous, plastics, PPC) and w is the total mass of the output flow (kg).

In this manner, the results shown in Figures 3 and 4 may be derived for the output flows of the bar sizer (impurities and residue).

The indicated chemical composition helps find suitable ways of how to utilise or dispose of the relevant output flow. In case of LFS 2, the operator defined established utilisation and disposal lines (see objective of the simulated LFM). Figure 4, therefore, merely illustrates the calculations (according to equation (1)).

CHEMICAL COMPOSITION OF THE OUTPUT FLOWS			
Parameter	Unit	IMPURITY	Residue
Moisture	%	34	38
Net calorific value	kJ*kg OS^{-1}	11,360	7 463
Antimony	mg*kg DM^{-1}	32	32
Arsenic	mg*kg DM^{-1}	21	30
Lead	mg*kg DM^{-1}	1 182	375
Cadmium	mg*kg DM^{-1}	23	13
Chrome	mg*kg DM^{-1}	484	414
Cobalt	mg*kg DM^{-1}	21	29
Nickel	mg*kg DM^{-1}	179	168
Mercury	mg*kg DM^{-1}	2 065	7 966
Chlorine	mg*kg DM^{-1}	6 290	3 751
Sulphur	mg*kg DM^{-1}	8 175	8 793
Ash content	[%]	58	64
Ignition loss	[%]	40	31
Total organic carbon	[%]	24	19
Thallium	mg*kg DM^{-1}	0.36	0.42
Magnesium	mg*kg DM^{-1}	9 937	10,061
Calcium	mg*kg DM^{-1}	49,294	61,098
Sodium	mg*kg DM^{-1}	5 641	9 676
Potassium	mg*kg DM^{-1}	8 139	6 856

Figure 4. Chemical composition of the output flows from the bar sizer.

Table 4. Agreed operational parameters for a LFM of LFS 2.

Operation times (with setup, maintenance, cleaning and dead times)	
Shifts per day	2
Hours per shift	7.5
Days per week	5
Weeks per year	48
Availability of the plant (net time of treatment) in %	75
Throughput of the plant in tonnes per hour	70
General information	
Volume to be mined in m^3	466,092
Compressed density in t m^{-3}	1.5
Computed amount to be mined in tonnes	699,138
Computed time for LFM in years	3.7

LFM: landfill mining.

Operational parameters

Data about the operation of the plant have to be entered in this section of the calculation model, including intended input per hour, the operation time of the plant including setup, maintenance, cleaning and dead times, and data on the total amount of waste to be mined. Entering this information permits computing the time required for the LFM (in years). The operational parameters shown in Table 4 have been defined for the simulated LFM of LFS 2 after consultation with the landfill operator.

An annual net time of treatment of 2700 h and an annual throughput of 189,000 t of excavated waste are the results of the entered operational parameters. Since the landfill should be ventilated before mining, a loss of weight (of water) by 10% can be expected according to experience, so that 170,100 t are actually supplied to mobile processing per year. LFM of landfill LFS 2 takes 3.7 years.

Basic costs for the excavation and basic costs for the processing line

In a further step, basic costs, which have to be considered for excavating and processing, are entered in the model.

Basis costs for the excavation. Excavation costs comprise costs for a preliminary examination, for approvals, surface preparation (e.g. removing a surface cover) and capital costs, meaning costs for required engineering (erecting fencing, recovering and safeguarding hazardous waste, installing electrical installations), system engineering for the ventilation, fire prevention or purchasing (or renting) mobile units needed for excavation (like a terrain loader, excavator, dumper, etc.). Again, preset costs (from experience) included in the model may be adopted or specific local conditions taken into account.

The simulation of LFS 2, for example, does not need development site preparation, fencing or installing foundations, because this infrastructure is already available on site. Historical recordings also allow excluding hazardous waste, which is why

Table 5. Basic costs for excavating waste of LFS 2.

Cost factor	Unit	Value	Number
Basic costs for removing waste			
Removing the surface cover	€ m^{-3}	3	–
Ventilation by Smell Well	€ m^{-3}	2.5	–
Terrain loader	€ $Item^{-1}$	160,000	3
Clamshell excavator	€ $Item^{-1}$	180,000	1
Basic costs of the processing line			
Power access	€ m^{-1}	10	–
Measures for reducing dust and odour emission	All-inclusive	30,000	–
Bar sizer	€ $Item^{-1}$	110,000	1
Crusher	€ $Item^{-1}$	325,000	1
Drum Screen	€ $Item^{-1}$	200,000	1
Ferrous separator	€ $Item^{-1}$	45,000	2
Non-ferrous separator	€ $Item^{-1}$	65,000	1
Ballistic separator	€ $Item^{-1}$	150,000	1
Roll belt conveyor – basic equipment	€ $Item^{-1}$	5000	5
Roll belt conveyor – additional length	€ m^{-1}	1000	–
Container	€ $Item^{-1}$	5000	8
General			
Planning costs	% of the capital costs	8	–
Maintenance costs for system engineering	% of the capital costs *a^{-1}	0.8	–
Maintenance costs of the mobile units	% of the capital costs *a^{-1}	4	–
Insurance costs	% of the capital costs	0.45	–
Commissioning	% of the capital costs	1	–
Interest	% of the capital costs *a^{-1}	4	–

Capital costs refer to the capital investment for equipment.

recovery, safeguarding and disposal are not considered. The basic costs for excavation, defined in consultation with the landfill operator, are given in Table 5. About 100,000 m^3 of surface cover must be removed before excavation of waste. The ventilation should be installed for the whole landfill body (466,092 m^3).

Basic costs of the processing line. The basic costs for the selected processing line consist of the following elements.

- Overhead costs.
- Operation and maintenance costs.
- Insurance costs.
- Planning and commissioning costs.
- Depreciation costs.
- Interest costs.

Overhead costs. Overhead costs comprise costs for purchasing (or renting) the processing devices and costs for reducing dust and odour, for electrical installations (like emergency-off systems) and for conveyor technology. They have been defined after consultation with the landfill operator, see Table 5. Power access was assumed to have a total length of 500 m. Ten continuous metres of roll belt conveyors were purchased in addition to the basic equipment.

Operation and maintenance costs. Operation and maintenance costs for the equipment have to be included in addition to the above-mentioned cost factors. Operating costs are based on the fuel consumption of the mobile units. To determine the total consumption of diesel-operated aggregates, their nominal consumption, their power factor (based on experience) and the actual use of the devices (their availability) during the LFM (Table 6) are entered into equation (2). These data are preset in the model, but can be customised by the landfill operator any time.

$$FC = NC * PF * A * N \quad (2)$$

where FC is the Fuel consumption (L a^{-1}), NC is the nominal consumption (L a^{-1}), PF is the power factor (%), A is the availability (%) and N is the number of units or metres (conveyors).

The operating expenses are derived subsequently from multiplying the fuel consumption with the selected fuel price of 1.2 € L^{-1}. The determination of operating costs for equipment needed for excavation (terrain loader, excavator; Table 6) is also implemented as described.

As shown in Table 6, the motors of conveyors, ferrous separators, ballistic separators, bar sizers and non-ferrous separators are electrically powered so that the operating costs have to be computed by converting their power consumption (kWh a^{-1}) into the fuel consumption (L a^{-1}) according to:

$$FC = RP * PF * A * N * \frac{1}{11,4 * 0,85 * 0,4} \quad (3)$$

where 11.4 is the power of 1 kg of diesel (kWh) (Kuchling, 2011), 0.85 is the density of diesel (kg/l) (Kuchling, 2011), 0.4 is the efficiency of the energy conversion (%) (Paschotta, 2015), and *RP* is the rated power (kW $item^{-1}$).

Table 6. Fuel consumption of the mobile units.

Diesel-operated equipment					
Aggregate	Nominal consumption ($L\,h^{-1}$)	Power factor (%)	Availability (%)	Power consumption ($kWh\,a^{-1}$)	Fuel consumption ($L\,a^{-1}$)
Terrain loader	12	100	60	–	58,320
Clamshell excavator	12	100	80	–	25,920
Crusher	50	100	80	–	108,000
Drum Screen	8	100	95	–	20,520
Electrically powered equipment					
	Rated power (kW)	Power factor (%)	Availability (%)	Power consumption ($kWh\,a^{-1}$)	Fuel consumption ($L\,a^{-1}$)
Roll belt conveyor	0.3	60	100	24,300	6269
Ferrous separator	8	60	100	25,920	6687
Non-ferrous separator	12.6	100	95	32,319	8338
Ballistic separator	5.5	60	95	8465	2184
Bar sizer	6.6	60	80	8554	2207

Nominal consumption/rated power per item or metre (conveyor equipment).

The maintenance costs are computed from the respective purchase value of the mobile unit (including terrain loader and excavator). The percentage preset for the simulation can be taken from Table 5.

Insurance costs. The landfill operator of LFS 2 specified that the mobile processing line (without containers) shall be insured and that 0.45% of the purchase costs have to be assumed for that.

Planning and commissioning costs. In addition, planning and commissioning costs are included in the model. The planning costs are considered as a percentage of the total purchase value of all mobile units (including terrain loader and excavator). The commissioning costs are, like the insurance costs, derived from the purchase values of the mobile processing line.

Depreciation costs. The model computes the costs due per year; as a result, the purchase values of units and machinery have to be fitted to the time the LFM will take. A depreciation term of 5 years (linear depreciation) has been assumed for the terrain loaders and the clamshell excavator. The resulting annual expense of a terrain loader is €32,000, for example. After LFM has finished – for landfill LFS 2, this has been the case after approximately 4 years – the remaining value of a terrain loader is accordingly €32,000. The units of the mobile processing line (bar sizer, crusher, drum screen, ferrous and non-ferrous separators and ballistic separator) have been allocated to a depreciation period of 7 years. The containers are written off over a period of 3 years, the power access of the equipment and the dust and odour emission reduction systems are written off over the whole time of LFM (4 years, rounded value). The conveyors are written off over a period of 5 years.

Interest costs. The actual execution and financing of a LFM project may require taking a loan; loan repayment rates are therefore included in the model. They are computed with an RMZ (periodical payment) function (Excel), which is based on the annuity method described in equation 4:

$$Annuity = PV * \frac{i*(1+i)^n}{(1+i)^n - 1} \tag{4}$$

where PV is the purchase value of unit (€), i is the interest rate (%) and n is the term (a).

The term n applies to the respective depreciation period of the equipment needed for the excavation and processing of the waste, including processing devices, terrain loaders, excavators, containers, power access of the equipment and the dust and odour emission reduction systems (see section ‘Depreciation costs’). The annual payment of interest is subsequently derived from the difference of the computed annuity according to equation (4) and the annually depreciation of the respective unit.

According to a consultation with the landfill operator, the simulated LFM of LFS 2 should best assume a loan with an annual repayment rate of 4% of the purchase costs (see ‘Interest’, in Table 5).

Personnel costs

The personnel costs expected may be estimated based on the processing line and the operation parameters chosen. The model has data integrated in this context for managers, administrative assistants, shift managers, technicians and service staff, drivers (terrain loader, excavator, disposal vehicle) and assistants and staff for weighing and reception. The landfill operator can very easily customise these data when required. Concerning the simulated LFM of LFS 2, the personnel costs shown in Table 7 and the proportionate cost allocation have been established.

Table 7. Personnel costs for LFM of landfill LFS 2.

	Personnel costs (€ a^{-1})	Proportional cost allocation (%)	Number
Manager	55,000	20	1
Administrative staff (secretariat, human resource department, etc.)	40,000	20	1
Shift manager	40,000	100	2
Scales/reception	35,000	50	1
Technicians, service staff	35,000	20	1
Drivers	32,000	100	4
Assistants (sorter, cleaning staff, etc.)	32,000	100	1
Social costs for staff (% of the personnel costs *a^{-1})*		0.25	

*Expenses for, e.g. personal protection equipment, corporate parties, etc.

Results and discussion

Based on the previous inputs, the automated computation processes the:

- annual costs for mining and operating the facility (like personnel, investment, operational, servicing, depreciation, interest and insurance costs);
- annually expected output quantities and its quality (chemical composition);
- disposal costs due every year; and
- annual revenues from selling potential secondary raw materials.

Based on the annually expected costs and revenues, it is possible to compute the total expenses of the LFM project, the total revenues and the remaining value of the purchased processing equipment at the end of the calculated LFM period.

The ascertained costs and revenues of the simulated LFM of LFS 2 are shown in Tables 8 and 9.

The chemical composition of the output flows, calculated by the model, is shown in Figure 5. Note again that this depiction only illustrates the calculation, results and methods of utilisation or disposal ways had not been derived because they had been predefined by the landfill operator.

Chemical analysis shows, however, that the calorific fraction is little different from the separated heavy fraction. This can be explained as follows: The setting of a ballistic separator is always selected in a way so that the resulting calorific fraction contains high-quality material. As a result, some %w/w of the calorific fraction are delivered in the heavy fraction, causing the results of both fractions to look alike. This was also observed when MSW had been processed in the course of a large-scale technical experiment by the IUT (Ingenieurgemeinschaft Innovative Umwelttechnik GmbH).

Tables 8 and 9 show the annual total expense (sum of the annual expenditure and the disposal costs) at €8,246,486; 83% of which are made up of disposal costs. These costs (including transport) and the secondary raw material revenues were derived from the costs or revenues per tonne shown in Table 9, referring to the disposal or utilisation line defined by the landfill operator. Note that the disposal costs per tonne shown in Table 9 do not include the contaminated site reconstruction tax (ALSAG). In Austria, this tax helps safeguard the financing of reconstructing contaminated sites and has had to be paid for various treatments of waste since 1989, like depositing on sanitary landfills (29.8 € t^{-1}) or incineration (8 € t^{-1}), in addition to the customary disposal costs. Because this tax has been paid for the major part of the waste present on LFS 2 when it had been landfilled, it was supposed that it would not have to be paid again for any incineration or secondary dumping after LFM. It was, therefore, not included in the calculations.

Secondary raw material revenues of ca. €544,000 per year can be achieved by material utilisation of the ferrous and non-ferrous fractions. After LFM, the processing aggregates are still worth ca. €550,000, which can be registered as revenues when they are sold.

Hence, a LFM period of 3.7 years requires total expenses of approximately €30,512,000 (see Table 10) or 44 € t^{-1} or 65 € m^{-3}. If the total expenses (sum of disposal costs and costs for mining and processing) are compared with the attainable total revenues, the remaining expense is ca. €27,951,100 (see Figure 6) or 40 € t^{-1} or 60 € m^{-3}. Specific LFM costs of 30–40 € m^{-3} (without transport; Rettenberger, 2010), 54 € m^{-3} (without transport; Schulte, 2011) and 43–110 € t^{-1} (including transport; Bölte and Geiping, 2011) have been mentioned in literature.

Conclusion

The newly developed model, presented in this article, enables the easy calculation of costs and revenues of an intended LFM, based on defined initial parameters. In addition, the chemical composition and, as a consequence, the quality of the output flows of a selected mobile processing line can be assessed. Suitable utilisation or disposal paths can then be suggested for every output flow. The results obtained from simulating an Austrian sanitary landfill (60 € m^{-3} or 40 € t^{-1}) match the values found in literature well. Hence, the developed simulation model can significantly support a landfill operator who would like to assess the costs of mining a specific landfill. Since the simulation can be customised any time to match different settings of tasks and objectives, the landfill operator can also develop various scenarios to find the best approach.

Table 8. Annual costs for excavating and processing (without disposal) and the remaining value of the processing aggregates (for a LFM period of 3.7 years).

Cost factor	Number (item)	Total investment costs (€)	Depreciation (€ a^{-1})	Operating costs (€ a^{-1})	Loan repayment (€ a^{-1})	Annual expenditure (€ a^{-1})	Remaining value of the aggregates after LFM (€)
Basic costs for the excavation							
Excavation or removal of the surface cover layer	All inclusive	300,000	–	–	–	81,081	–
Smell well	All inclusive	1,165,230	–	–	–	314,927	–
Terrain loader	3	480,000	96,000	89,184	11,821	197,005	96,000
Clamshell excavator	1	180,000	36,000	38,304	4433	78,737	36,000
Planning costs	All inclusive	52,800	–	–	–	14,274	–
Basic costs of the processing line (with terrain loader and excavator)							
Bar sizer	1	110,000	15,714	7048	2613	25,375	47,143
Drum screen	1	200,000	28,571	32,624	4751	65,946	85,714
Crusher	1	325,000	46,429	142,600	7719	196,748	139,286
Ferrous separator	2	90,000	12,857	11,624	2138	26,619	38,571
Non-ferrous separator	1	65,000	9286	12,606	1544	23,436	27,857
Ballistic separator	1	150,000	21,429	8621	3562	33,612	64,286
Roll belt conveyor	5	75,000	15,000	10,523	1847	27,370	15,000
Container	8	40,000	13,333	0	1081	14,414	0
Insurance	All inclusive	4568	–	–	–	1235	–
Commissioning	All inclusive	10,150	–	–	–	2743	–
Planning	All inclusive	81,200	–	–	–	21,946	–
Power access	All inclusive	5000	1250	40	127	1417	0
Dust and odour emission reduction	All inclusive	30,000	7500	240	765	8505	0
Personnel costs							
Managers	1	40,700	–	–	–	11,000	–
Administrative staff	1	29,600	–	–	–	8000	–
Shift managers	2	296,000	–	–	–	80,000	–
Scales/reception	1	64,750	–	–	–	17,500	–
Technicians/service staff	1	25,900	–	–	–	7000	–
Drivers	4	473,600	–	–	–	128,000	–
Assistants	1	118,400	–	–	–	32,000	–
Social costs for staff	All inclusive	2622	–	–	–	709	
Total						**1,419,599**	**549,857**

Operating costs include maintenance costs.
LFM: landfill mining.

Table 9. Annually expected disposal costs and secondary raw material revenues.

Fraction	Amount (t a^{-1})	Disposal and utilisation methods	Disposal costs*		Revenues	
			(€ t^{-1})	(€ a^{-1})	(€ t^{-1})	(€ a^{-1})
Ferrous	5760	Material	–	–	65	374,400
Non-ferrous	1301	Material	–	–	130	169,130
Calorific fraction	20,193	Energy	82	1,655,826	–	–
Fine-grain	120,261	Secondary dumping	36.2	4,353,448	–	–
Heavy fraction	19,209	Secondary dumping	36.2	695,366	–	–
Impurities	3 377	Secondary dumping	36.2	122,247	–	–
Total	**170,100**			**6,826,887**		**543,530**

*Without ALSAG (polluted areas reconstruction contribution).

It has been shown that the computation of disposal costs and secondary raw material revenues, as well as the quality assessment of the output flows (chemical composition), depend on the composition of the deposit, entered initially, and the sorting specifications preset in the model. Hence, these are important initial parameters of the simulation model. With Table 2 showing that in some cases, no chemical analysis values for excavated materials had been found (as for example with problematic substances) or values had

CHEMICAL COMPOSITION OF THE OUTPUT FLOWS							
Parameter	Unit	IMPURITY	FINE GRAIN	FERROUS	NON-FERROUS	CALORIFIC FRACTION	HEAVY FRACTION
Moisture	%	34	36	28	34	45	41
Net Calorific value	kJ*kg OS^{-1}	11,360	5 262	6 240	8 502	14,283	14,360
Antimony	mg*kg DM^{-1}	32	34	23	46	28	27
Arsenic	mg*kg DM^{-1}	21	33	21	27	24	22
Lead	mg*kg DM^{-1}	1 182	237	354	1 061	752	801
Cadmium	mg*kg DM^{-1}	23	12	11	12	14	16
Chrome	mg*kg DM^{-1}	484	314	2 090	680	507	418
Cobalt	mg*kg DM^{-1}	21	27	39	21	32	31
Nickel	mg*kg DM^{-1}	179	156	590	409	122	148
Mercury	mg*kg DM^{-1}	2 065	5	3	8	28	9
Chlorine	mg*kg DM^{-1}	6 290	2 686	3 567	4 417	6 569	7 474
Sulphur	mg*kg DM^{-1}	8 175	8 198	6 559	8 283	11,768	10,046
Ash content	[%]	58	71	72	65	39	40
Ignition loss	[%]	40	23	26	33	54	53
Total organic carbon	[%]	24	15	16	20	32	32
Thallium	mg*kg DM^{-1}	0.36	0	0	1	0	0
Magnesium	mg*kg DM^{-1}	9 937	10,522	7 306	7 809	9 330	8 905
Calcium	mg*kg DM^{-1}	49,294	68,971	41,053	41,587	40,386	40,990
Sodium	mg*kg DM^{-1}	5 641	11,102	6 321	6 022	5 717	6 176
Potassium	mg*kg DM^{-1}	8 139	7 271	4 972	4 992	5 740	6 121

Figure 5. Chemical composition of the output flows of the simulated LFM of landfill LFS 2.

Table 10. Comparing costs and revenues (period of LFM: 3.7 years).

Cost and revenue position	Annual costs (€ a^{-1})	Annual revenues (€ a^{-1})	Total costs (€)	Total revenues (€)
Costs for excavating and processing	1,419,599	–	5,252,516	–
Disposal	6,826,887	–	25,259,482	–
Secondary raw material revenues	–	543,530	–	2,011,061
Remaining value of the aggregates	–	–	–	549,857
Total	8,246,486	543,530	30,511,998	2,560,918
Difference	**7,702,956**		**27,951,080**	

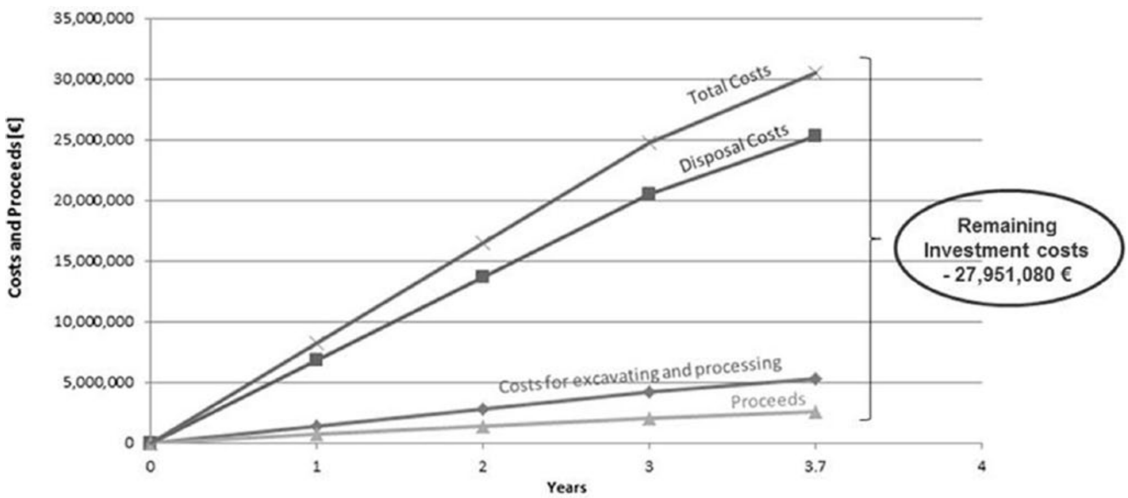

Figure 6. Remaining expenses after deducing the revenues (for secondary raw materials and remaining values of the aggregates) for the simulated LFM of LFS 2.

been derived from analyses of common MSW (like lead in composites), more research into this subject is needed.

The condition of the waste (dry, wet, high or low organic content, etc.) and its influence on the results of processing is not considered in the discussed simulation model yet. This factor would have to be integrated in the model by entering sorting specifications. No experience values are available for landfill waste, though, requiring further research in this context as well.

Table 10 and Figure 6 show that the costs of LFM cannot be covered by secondary raw material revenues or by selling the processing aggregates. There are many other arguments for an LFM project beside the recovery of secondary raw materials, however. Hermann et al. (2014) have discussed them thoroughly, referring to gaining space for deposits, achieving revenues by reusing the surface or socio-economic benefits (like the interests of neighbours). The presented simulation model would have to be expanded to cover such opportunities for gaining revenues additionally.

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