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Systematic assessment of critical factors for the economic performance of landfill mining in Europe: What drives the economy of landfill mining?

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A B S T R A C T

Landfill mining (LFM) is a strategy to mitigate environmental impacts associated with landfills, while simultaneously recovering dormant materials, energy carriers, and land resources. Although several case study assessments on the economy of LFM exist, a broader understanding of the driving factors is still lacking. This study aims at identifying generically important factors for the economy of LFM in Europe and understanding their role in developing economically feasible projects in view of different site, project and system-level conditions. Therefore, a set-based modeling approach is used to establish a large number (531,441) of LFM scenarios, evaluate their economic performance in terms of net present value (NPV), and analyze the relationships between input factors and economic outcome via global sensitivity analysis. The scenario results range from −139 Euro to +127 Euro/Mg of excavated waste, with 80% of the scenarios having negative NPVs. Variations in the costs for waste treatment and disposal and the avoided cost of alternative landfill management (i.e. if the landfill was not mined) have the strongest effect on the scenario NPVs, which illustrates the critical role of system level factors for LFM economy and the potential of policy intervention to incentivize LFM. Consequently, system conditions should guide site selection and project development, which is exemplified in the study for two extreme regional archetypes in terms of income and waste management standard. Future work should further explore the developed model to provide decision support on LFM strategies in consideration of alternative purposes, stakeholders, and objectives.

1. Introduction

Recent estimates state that Europe hosts several hundred thousands of landfills, of which the majority are old municipal solid waste (MSW) deposits lacking up-to-date sanitary technology (Van Vossen and Prent, 2011; Jones et al., 2018). Although these sites are associated with local to global environmental impacts, land-use restrictions and needs for aftercare and remediation (Johansson et al., 2012; Laner et al., 2012), Europe does not yet have any coherent strategy for their future management (Krook et la., 2018a). In several recent policy initiatives, including European Parliament seminars, policy briefs, and proposals to the amendment of the Landfill Directive, Landfill mining has been suggested as an alternative strategy to address unwanted implications of landfills while simultaneously recovering deposited materials, energy carriers and land resources (Jones et al., 2018). Although such an ambitious approach to landfill management displays a broader societal potential (Damigos et al., 2016; Krook et al., 2012; Jones et al., 2013) visions of a circular economy (European

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Commission, 2018), it also adds complexity to the implementation and evaluation of such projects (Van Passel et al., 2013; Burlakovs et al., 2017; Johansson et al., 2017). This complexity is further advocated by a general lack of real-life projects validating the feasibility of landfill mining as a mean to facilitate aftercare, reclaim valuable land or landfill void space and bring significant amounts of metals, minerals and energy carriers back to use in society (Krook et al., 2015). In this study, we focus on the essential issue of economic feasibility as the further development of the landfill mining area suffers from a deficit in knowledge about if, and if so, how, such projects could be executed cost-efficiently (Krook et al., 2015; Jones et al., 2018). In essence, our current understanding is restricted to a few case studies assessing the economic feasibility of mining a specific deposit by considering one or a limited number of possible project settings (Frändegård et al., 2013; Zhou et al., 2015; Wagner and Raymond, 2015; Wolfsberger et al., 2016; Winterstetter et al., 2018). Although these assessments provide valuable insights on some current challenges, they fail to address the importance of local landfill settings (Krook et al., 2018b) and only offer limited and case-specific guidance on how different technical set-ups (e.g. Danthurebandara et al., 2015; Kieckhäfer et al., 2017; Winterstetter et al., 2015) and policy and market conditions (Ford et al., 2013; Van Passel et al., 2013; Rosendal, 2015) influence economic performance. In order to facilitate selection of suitable landfills for mining and development of profitable projects, there is thus a need for more generic knowledge that goes beyond individual cases and develops a systemic understanding of the landfill mining economy (Krook et al., 2018b; Laner et al., 2016). This is especially so because the characteristics and importance of different site (e.g. landfill compositions, land values and obligations for aftercare), project (e.g. technologies for sorting, treatment and resource recovery) and system (e.g. policy instruments, regulatory frameworks and market structures) conditions could vary widely between projects and regions (Hogland et al., 2018; Hölzle, 2019).

Apart from a limited applicability of the findings, most previous assessments only provide superficial knowledge of what builds up the economy in the studied projects (Krook et al., 2018b). Typically, the provided results are limited to the net profitability and some main cost and revenue items, while the contributions and interrelations of the underlying conditions and settings that actually build up this performance remain unknown, or at least not reported (Esguerra et al. 2018). In particular, little emphasis has so far been laid upon the interactions of various conditions occurring on the site, project and system levels and how such interaction effects influence the landfill mining economy (cf. Saltelli et al., 2019; Ferretti et al., 2016; Saltelli and Annoni, 2010). Without such fine-grained knowledge, it is difficult to develop a sound understanding about the principles and critical factors of the landfill mining economy.

This study aims to enhance both the applicability and depth of current knowledge regarding what builds up the economic performance of landfill mining in different situations and settings. In doing so, we combine capital budgeting metrics, scenario modeling and global sensitivity analysis to perform a fine-grained assessment of how different site, project and system conditions interplay and jointly contribute to the net present value (NPV) of a large number of landfill mining scenarios. Altogether, these scenarios represent a wide range of possible landfill mining conditions and settings that could be encountered within Europe. In order to illustrate the usefulness of such generic and fine-grained knowledge on the economic principles of landfill mining, we apply it on two specific regional settings as a mean to facilitate selection of suitable landfills for mining and corresponding project set-ups. The spatial and temporal scope of the study involves MSW landfills in Europe with current regional variations in policy and regulatory frameworks, markets conditions and price settings as well as waste management and treatment practices.

In the following section, the selected factors and the methods used to analyze the results are described. In Section 3 results are presented with respect to the NPVs of the whole LFM projects as well as with regard to the present values of selected cost and revenue items. Critical factors are identified and discussed in general, for specific cost and revenue items, and also with respect to two specific regional settings (=archetypes). Finally, in Section 4, major findings on economically favorable and unfavorable conditions for landfill mining are highlighted and recommendations on how to improve the economic feasibility of landfill mining are provided.

2. Materials and methods

2.1. Modeling approach

The modeling approach to investigate the importance of different factors for the economy of landfill mining builds on (i) the combination of generic factor datasets to develop a large number of possible landfill mining scenarios, (ii) the economic assessment of each established scenario, and (iii) the analysis of relationships between factor variation and model results using global sensitivity analysis (see Fig. 1). The use of mathematically rigorous procedures to investigate the effect of different conditions and settings (i.e. specific factor realizations) on the economy of landfill mining projects enables a systematic identification of critical factors for the project economy in general as well as under specific conditions. The three steps of the modeling approach are illustrated in Fig. 1 and the main characteristics of each step are subsequently briefly outlined. Detailed explanations of the modeling steps including the description of the data and methods used are provided in the proceeding sections (Section 2.2–2.5). The basic structure of the modeling approach and the applied methods have been previously described by Laner et al. (2016), who developed the approach to perform a quantitative analysis of critical factors for the climate impact of landfill mining. The approach is grounded on global sensitivity analysis using variance based statistical methods (Saltelli et al., 2008; Saltelli and Annoni, 2010), which enables systematic determination of critical factors over the whole range of modeling results (see Section 2.4 for more details).

In step 1, a large number of scenarios is established using a combinatory procedure, which generates a scenario for each unique combination of factor datasets. Hence, in case of m factors with n alternative datasets each, the number of scenarios is n^m. In the present study, 12 factors on the site, project, and system level are identified, which influence the economy of a landfill mining project. Most of these factors have been reported to be of high relevance for the economy of landfill mining in previous case studies, while one factor is specifically defined to account for regional variation in excavation and sorting costs (F0). Each of the 12 factors is described by 3 alternative datasets, which are defined to reflect the possible range of circumstances and situations for landfill mining projects in Europe (see Section 2.2 for more details). In total, 531,441 (3^{12}) unique scenarios are generated. In step 2, an economic assessment is performed for each scenario to determine the overall project economy as well as the specific contributions of different cost and revenue items (=contribution analysis). Material and energy flow models are established for each scenario as a basis for the economic assessment, which is performed using discounted cash flow analysis. The net present value (NPV) is derived for each scenario to express the profitability of the whole landfill mining project. Furthermore, the present values (PV) of various cost and revenue items are also determined for each scenario to generate an understanding of what builds up the economic perfor-

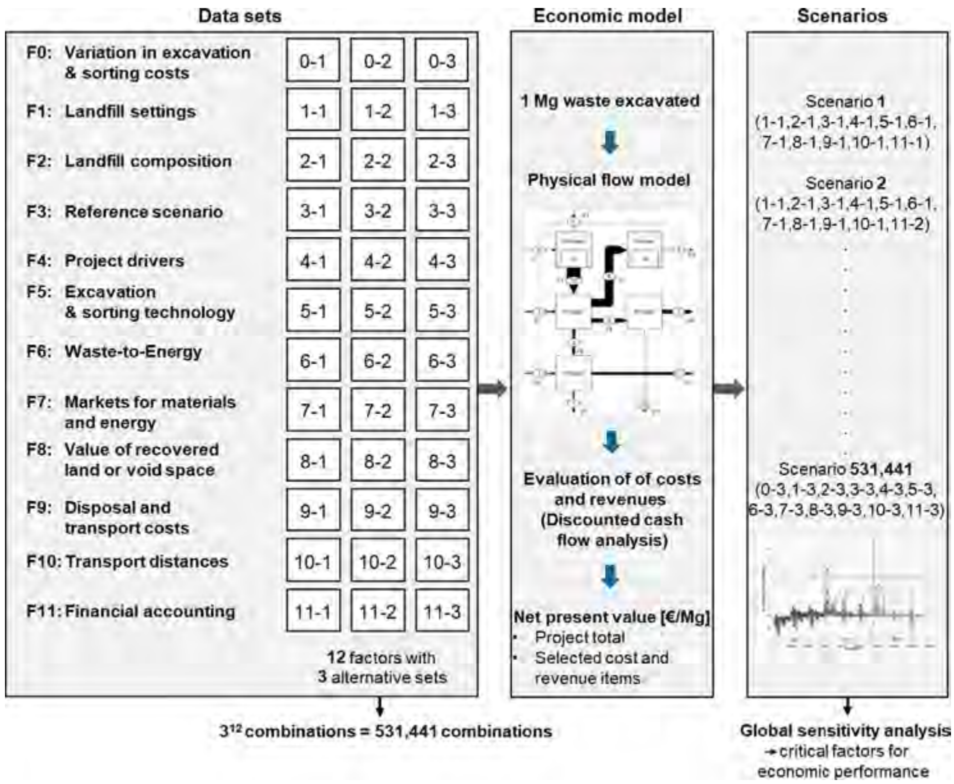

Fig. 1. Schematic illustration of the modeling approach to evaluate the importance of different factors for the economy of landfill mining.

mance of the scenario (see Section 2.3). Finally, in step 3, the effect of variation in the input factors (choice of dataset) on the scenario results is investigated in a systematic and quantitative way. Therefore, global sensitivity analysis is performed related to the project NPVs as model outcome and also with respect to the PVs of each cost and revenue item. The resulting sensitivity indices characterize the importance of each factor for the economy of landfill mining on different levels (NPV, PVs of selected items) and serve to identify drivers as well as particularly favorable or unfavorable conditions and settings for landfill mining (see Section 2.4 for details). Further analysis is done by constraining the dataset and analyzing a limited number of scenarios representing specific settings. These "regional archetypes" serve to gain a more detailed understanding of how boundary conditions influence overall project economy and therefore provide insight on the importance of site- and project-level factors under pre-defined system conditions (see Section 2.5 for details). The computations to generate the scenarios, do the economic assessment, and perform global sensitivity analysis are done in MATLAB®.

2.2. Selected factors and datasets

Each of the 12 factors in Table 1 is defined by three sets of parameters, which form the model input together with some fixed parameters. The different datasets were defined building on previous studies on landfill mining in Europe and related literature on landfilling, site remediation and waste treatment processes, as well as based on a specific data collection effort of the working group on landfill mining within the European Cooperation in Science and Technology Action – Mining the European Anthroposphere (COST Action MINEA, 2018). Within the latter, selected studies on the economy of LFM in different European countries were reviewed such as Austria (Hermann et al., 2016; Wolfsberger et al., 2016), Belgium (Danthurebandara et al., 2015; Van Passel et al., 2013; Winterstetter et al., 2015), Germany (Kieckhäfer et al., 2017), Netherlands (Van Vossen and Prent, 2011), and Scotland (Ford et al., 2013) and economic data on processes and price levels of relevance for landfill mining and landfill management in different European countries (i.e., Austria, Denmark, Estonia, Finland, Serbia, Sweden) was gathered and analyzed. The parameter values for the three datasets for each factor were then defined to reflect the ranges observed in the collected data from projects across Europe. The different datasets and the data sources are presented in the Supporting Information (SI) (see Tables S-1–S-13).

Three of the factors are site-specific and address the landfill settings (F1), the material composition of the landfill (F2), and the reference scenario (F3), which is the (hypothetical) management of the landfill alternative to mining. These factors are the foundation of any landfill mining project, as they determine the scale of the project, the potential for recoverable and hazardous materials, and alternative management costs (if mining does not take place). Landfill settings (F1) define the size of the landfill, site characteristics such as landfill geometry (e.g. average height and area) and the duration of the project (the annually excavated waste is a consequence of size and duration). The sizes and durations specified in the datasets are 100,000 Mg of waste and 2 years, 1,000,000 Mg of waste and 5 years, and 5,000,000 Mg and 10 years, respectively. The average landfill height increases from 8 m for small landfills to 10 m for medium and 15 m for large landfills (see Table S-2). The composition of the landfill (F2) is given in terms of 10 material categories. The different datasets display landfills from varying time eras involving different material compositions covering reported ranges from field studies on 18 MSW landfills in countries with different economic standards and waste management practices (cf. Laner et al. 2016) and are shown in the SI (see Table S-3). The reference scenario (F3) reflects different alternative management scenarios if the landfill was not mined. The datasets cover a range from basically no management required (i.e., aftercare is not

Table 1
Selected factors on the site, project or system level described by alternative datasets for the analysis of the economic performance of landfill mining. Each alternative set of a factor designates a possible realization in a landfill mining project in Europe.

No	Level	Description	Set 1	Set 2	Set 3
F0	System	Regional variations in excavation & sorting costs (investment, labor and maintenance)	Low cost-levels	Medium cost-levels	High cost-levels
F1	Site/ Project	Landfill settings	Small-scale landfill, short project duration	Medium-scale landfill, medium project duration	Large-scale landfill, long project duration
F2	Site	Landfill composition	Rich (organics & metals) MSW landfill	Average (organics & metals) MSW landfill	Poor (organics & metals) MSW landfill
F3	Site/ System	Reference scenario	“Do nothing” situation	Medium intensity aftercare	High intensity aftercare or remediation
F4	Project	Project drivers	Material recovery	Material recovery & land reclamation	Material recovery & void space recovery
F5	Project	Excavation & sorting technology	Mobile sorting (on-site)	Conventional tech. stationary sorting (off-site)	BAT stationary sorting (off-site)
F6	System	Waste-to-energy (WtE)	Low gate fee	Medium gate fee	High gate fee
F7	System	Markets for material and energy	Low-level prices	Medium-level prices	High-level prices
F8	Site/ System	Value of reclaimed land or landfill void space	Low value	Medium value	High value
F9	System	Waste treatment, disposal, and transport costs	Low costs	Medium costs	High costs
F10	System/ Site	Transport distances (off-site)	Short distances	Average distances	Long distances
F11	System	Financial accounting	Low risk, low discounting rate	Medium risk, medium discounting rate	High risk, high discounting rate

required or very low-effort) to medium intensity and duration of aftercare (i.e., gas and leachate treatment as well as maintenance costs) to high aftercare expenditures and duration (i.e., active stabilization is required or remediation obligations). The aftercare costs considered in the datasets of F3 (see Table S-4 of the SI) were derived from project data within the MINEA working group as well as from the literature (cf. Heyer et al., 2005; Stegmann et al., 2006). Apart from being site-specific, F3 has also a system-specific dimension, because aftercare regulations and related costs vary across countries in Europe (cf. Laner et al. 2012).

On the project level, deliberate choices can be made regarding the design, implementation, and operation of the landfill mining project. Relevant factors on this level are the project drivers (F4) and the technologies applied for waste excavation, as well as sorting and upgrading of the excavated materials (F5). The project drivers account for different motivations of landfill mining. Projects may only recover materials without valorizing land or void space, or they may be designed to valorize excavated materials and reclaim the land at the site or recover landfill void space increasing its landfilling capacity. In F5, three different processing schemes are specified in terms of their resource inputs and separation efficiencies ranging from a conventional mobile unit, a state-of-the-art stationary processing plant to a best-available-technology (BAT) separation facility. Separation efficiencies, as well as investment and operation costs, vary for the different technological setups. The data on the technical performance (i.e., separation efficiencies for different materials) are taken from Laner et al. (2016), and the economic data is derived from a German study by Kieckhäfer et al. (2017) on the economy of different sorting and processing schemes for landfill mining (cf. SI, Table S-6a-b).

The remaining factors relate to the system level, which means that they are external to the landfill mining project and cannot be significantly influenced by the authority of an individual actor. As systemic conditions differ from one region to another, the factors on the system level are also used to reflect regional differences in Europe. Therefore, these factors account for changes in conditions over time and space (e.g. markets for materials, energy, services) as well as over different types of actors and legal structures (e.g. public bodies vs. private investors). Factor F0 accounts for the fact that there is not only variation in the choice of technology for sorting and upgrading (F5, project level), but also with respect to the costs of implementing a specific technological setup. Therefore, F0 is defined as a scaling factor to reflect the variation in investment, labor, and maintenance costs related to excavation and sorting in European countries with different economic development levels (cf. SI, Table S-1). Waste-to-Energy (WtE, F6) is considered as a factor on the system level because a typical landfill mining project is dependent on the existing WtE infrastructure in the region, which is external to the project. This could be different for very large landfill mining projects, where internal WtE capacity is built up (such as described in Danthurebandara et al., 2015; Winterstetter et al., 2015), and costs and revenues of WtE are internal to the project. However, in most landfill mining projects, this will not be the case, which is why F6 is designated as a system-level factor. Therefore, factor variation is expressed by different gate fees from very low to high (cf. SI, Table S-7). Three of the other factors on the system level relate to market conditions with respect to different price levels for materials and energy (F7, see SI, Table S-8), reclaimed land and landfill void space (F8, see SI, Table S-9), and waste treatment, disposal, and transport (F9, see SI, Table S-10). Out of these three factors, F8 also has a strong site-specific aspect, because the value of land can be more dependent on the actual location (e.g. urban vs. rural area) than on the average price levels within a region. Therefore, the variation in the datasets of F8 covers differences of land values within a region (site level) and across regions (system level). Another system-level factor with a site-specific dimension is the transport distances (F10). However, typically, variation is mostly driven by system conditions in this case, because short transport distances occur when different plants and infrastructures are in relative proximity to each other, and large distances are to be expected in regions with lower population density and more remote infrastructures (see SI, Table S-11). Finally, the financial system is reflected by F11, which accounts for differences in inflation rates, interest rates, and depreciation rates (see SI, Table S-12). Inflation and interest rate give the effective discounting rate, and the depreciation rate accounts for the value loss of buildings and machinery initially purchased for the project. In general, low discounting and depreciation rates reflect stable conditions (political and financial) and are more common for public investors, whereas high discounting and depreciation rates reflect higher risks and are more common for private investors (cf. Winterstetter et al., 2015).

2.3. Economic assessment model

A schematic illustration of the economic model reflecting on its physical and economic dimension as well as the role of input factors is provided in Fig. 2. The physical landfill mining model is illustrated via material and energy flows (thin arrows) and processes (boxes). The economic dimension is indicated as an additional layer with differently colored areas to distinguish between costs, avoided costs, and revenues. In order to illustrate their role in the model, input factors are also related to the physical and economic dimension in Fig. 2. The balancing of material and energy flows for each landfill mining scenario forms the basis for the economic assessment. The fate of each material fraction of the excavated waste (given in F2) is modeled using transfer coefficients, which describe the partitioning of materials in the different processing steps (cf. Brunner and Rechberger, 2016). The process outputs are therefore a mix of different material fractions, and their properties (e.g. heating value, ash content, water content, etc.) are determined based on the characteristics of the constituting material fractions. In the physical flow model, landfilled waste materials are excavated and sorted (F5) and then directed to further treatment (F6), disposal (F9) or recycling (F7) or they are re-deposited, which is particularly the case for soil material and fines. Re-landfilling can take place at the landfill mining site, if only resource recovery (F4-1) or resource and landfill void space recovery (F4-3) is the driver, or at an external landfill, if resource recovery and land reclamation (F4-2) is the driver (cf. dotted arrows in Fig. 2). Costs of processing and transporting materials (internal costs, costs for external treatment and disposal, transport costs) are accounted for as well as (potential) avoided revenues from gas utilization in the reference case. Project revenues are generated from valorization of materials and land or void space as well as from avoided aftercare costs (management costs in the reference case). The net present value (NPV) of the overall project is calculated for one metric ton of excavated waste using discounted cash flow analysis according to Eq. (1). NPV refers to the cash flows over the period T, C_0 is the initial investment [Euro], C is the cash flow in a specific year [Euro/year], i is the inflation rate [%], d is the interest rate [%], and T is the last year of cash flow. Regarding the temporal scope, different project durations of 2–10 years were considered depending on the scale of landfill mining project (see Appendix A. Table S-2).

$$NPV = -C_0 + \frac{C_1 * (1+i)^1}{(1+d)^1} + \frac{C_2 * (1+i)^2}{(1+d)^2} + \cdots + \frac{C_T * (1+i)^T}{(1+d)^T} \quad (1)$$

Apart from the NPV of the whole project, the present value of individual cost and revenue items is calculated to enable a detailed

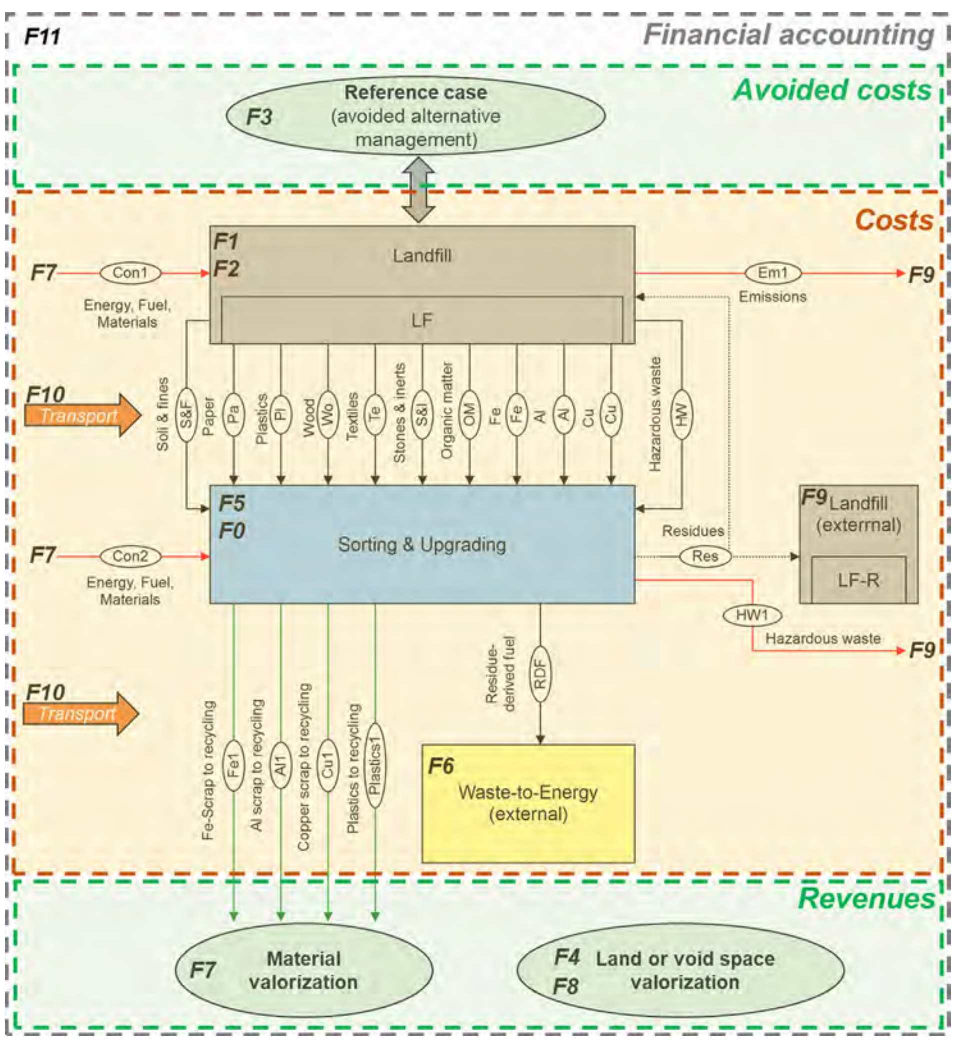

Fig. 2. Scheme of the economic assessment model for landfill mining based on the material flow structure of LFM. Elements of the model representing costs, avoided costs and revenues are highlighted as colored areas, and the varying factors considered in the model are indicated for the various processes and flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

analysis of the contribution of different processes to the economy of a landfill mining project and of the factors driving the cost and revenue items. Out of the nine items, four refer to costs, one refers to avoided costs, and four refer to revenues (see Table 2). Each item is given in Euro/Mg of excavated waste, and in total they sum up to the NPV of the overall project Eq. (2):

$$\mathrm{NPV} = \mathrm{CoI} + \mathrm{CoRI} + \mathrm{CoE} + \mathrm{CoT} + \mathrm{aCo} + \mathrm{ReMt} + \mathrm{ReVS} + \mathrm{ReMc} + \mathrm{ReL} \tag{2}$$

The presented factor datasets, material and energy flow scheme and economic model structure refer to a specific organizational scheme of a landfill mining project. As described above, excavation and sorting are fully internal to the project, and the internality or externality of fines re-landfilling depends on the project drivers. WtE is external to the project because new WtE plants are typically not built for a LFM project and significant overcapacities in existing plants, which are owned by the project operator, commonly do not exist. Hence, this business model structure is considered the most plausible under European conditions. Nevertheless, there may be alternative organizational structures, which are relevant to the economy of landfill mining and which might warrant detailed analyses. In the present study, the results of the default organizational scheme were compared to three other possible organizational schemes differing with regard to the internality or externality of WtE as well as re-landfilling of fines (see SI, Section B). Because the overall economic performance of these model versions was similar in terms of mean values and ranges of scenario outcomes (see SI, Figure S-1), this study focuses on the most plausible organizational scheme for landfill mining, enabling a highly fine-grained analysis of the factors that build up the economy of such projects.

2.4. Sensitivity analysis

In order to find out how the NPV of a landfill mining project and the present value of specific cost and revenue items change in response to variations of the studied factors, global sensitivity analysis is used. Global sensitivity analysis is the process of apportioning the variation in outputs to the variation in each input factor over their entire range of interest (Saltelli et al., 2008; Saltelli and Annoni, 2010). A sensitivity analysis is considered to be global when all the input factors are varied simultaneously and the sensitivity is evaluated over the entire range of each input factor. Therefore, the whole range of scenario results (531,441) is explored with respect to the variation in these factor datasets by apportioning the variance of the scenario results (output) to the variance of the twelve (input) factors (Saltelli et al., 2008). In the present analysis, factor variation is represented by the discrete choice of one out of three alternative sets and the effect of this choice is investigated for each factor and combinations of factors. The sensitivity of the output (project NPV or PV of specific cost/revenue items) with respect to varying specific factors is expressed by variance-based sensitivity indices (see Laner et al., 2016 for more details). The first order sensitivity index S_i is calculated according to Eq. (2) and represents the main effect contribution of an input factor to the output. In Eq. (3), F_i is the i^{th} factor, $F_{\sim i}$ are all factors but F_i, Y is the model output, and $E_{F\sim i}$ is the mean value of Y over all possible values of $F_{\sim i}$ while keeping F_i fixed. V_{Fi} is the variance of the mean values over the different sets of F_i, which is divided by the total (unconditioned) variance of the output (i.e., the variance observed for all scenario results).

$$S_i = \frac{V_{F_i}(E_{F_{\sim i}}(Y|F_i))}{V(Y)} \tag{3}$$

The total effect sensitivity index S_{Ti} measures the first and higher order effects (interactions) of factor F_i. In Eq. (4) the numerator is the first order effect of $F_{\sim i}$, so that V(Y) minus this term gives the contribution in the variance decomposition of all terms containing F_i (Saltelli and Annoni, 2010).

$$S_{T_i} = 1 - \frac{V_{F_{\sim i}}(E_{F_i}(Y|F_{\sim i}))}{V(Y)} \tag{4}$$

While the first order sensitivity index S_i measures the main effect of factor variation on the output variation, the total effect sensitivity index S_{Ti} provides the overall importance of a factor for the output variation including interactions with other factors. These interaction-related effects are expressed by the higher order sensitivity index S_{Hi}, which is given by S_{Ti} minus S_i. In this study, these sensitivity indices represent the quantitative measures to express the importance of specific factors (on their own and in combination with others) for the economy of landfill mining with respect to the overall project as well as regarding specific cost and revenue items.

2.5. Regional archetypal settings

In order to specifically analyze the effect of regional differences for the economy of landfill mining, two extreme archetypal settings are defined (low and high). Seven factors on the system level (F0, F3, F6, F7, F8, F9, F11), which can hardly be influenced by choices in the project implementation, are fixed to one of the three datasets, while the remaining factors (F1, F2, F4, F5, F10), which are under the influence of landfill practitioners, are allowed to vary. Thus, each archetypical setting is represented by a group of 243 scenarios (5 varying factors with three realizations each, $3^5 = 243$), which are then analyzed and compared for driving factors. One archetypal setting represents a region with low income levels and low waste management standards (setting: low), which is reflected by choosing the low alternative dataset for most fixed factors (F0-1, F3-1, F6-1, F7-1, F8-1, F9-1). Only for financial accounting the high dataset is chosen (F11-3), due to typically higher financial risks in less developed economies. The other archetypal setting relates to a region with high income levels and high waste management standards (setting: high), which is reflected by choosing the high alternative dataset for most fixed

Table 2
Division of results in terms of cost and revenue items (NPV, Euro/Mg).

Item	Name	Description
Excavation and sorting costs	CoI	Costs related to excavation and sorting (incl. landfill management during the mining project)
Internal re-landfilling costs	CoRI	Costs related to re-landfilling of fines if it takes place internally (in case of material recovery F4-1 & material recovery & void space recovery F4-3 as project drivers)
External waste treatment costs	CoE	Costs related to external waste treatment: WtE gate fees, hazardous waste disposal, re-landfilling of fines (in case of material recovery & land reclamation F4-2 as project drivers)
Transport costs	CoT	Costs related to transport to sorting plant, WtE plant, external waste treatment facilities, and markets for recycled materials
Avoided landfill management costs	aCo	Avoided costs due to the reference case (avoided aftercare/remediation costs)
Revenues from materials	ReMt	Revenues from the valorization of materials (plastics, construction aggregates, and scraps of steel, aluminum, and copper)
Revenues from void space	ReVS	Revenues from landfill void space recovery (in case of F4-3)
Revenues from machinery	ReMc	Revenues from residual value of used machinery (at the end of the project)
Revenues from land	ReL	Revenues from sale of land (in case of F4-2)

factors (F0-3, F3-3, F6-3, F7-3, F8-3, F9-3). In this case, the financial risks are expected to be low, which is why the low dataset is chosen for financial accounting (F11-1).

3. Results and discussion

3.1. Economic performance of landfill mining scenarios

3.1.1. Net present value of the whole landfill mining project

The results for the 531,441 landfill mining scenarios show a mean net deficit of −27 Euro/Mg and a large variation of possible outcomes, ranging from −139 to +127 Euro/Mg (Fig. 3). This implies that landfill mining is a challenging business venture with only 19% or 99,821 scenarios resulting in net profits. Most of these profitable scenarios (i.e., 92% or 92,165 scenarios) range within >0 to 50 Euro/Mg, while only few of the scenarios (i.e., 0.1% or 89 scenarios) have profits that are over 100 Euro/Mg.

The wide variation of results in this study covers that of previous assessments (−62 to +29 Euro/Mg) and is expectedly wider, due to considering a larger variation in site, project (Danthurebandara et al., 2015; Kieckhäfer et al., 2017; Winterstetter et al., 2015) and system conditions (Ford et al., 2013; Frändegård et al., 2015; Rosendal, 2015) as well as a larger number of influencing factors.

3.1.2. Present value of cost and revenue items

In order to better illustrate which main processes actually build up the economy of landfill mining, the scenario results (NPVs) are divided into selected cost and revenue items, and their present values are shown in Fig. 4.

In terms of the mean cost items, waste treatment and disposal costs, especially with respect to re-landfilling, and excavation and sorting costs dominate the negative contribution to the project economy, whereas costs for transport are less important. The expenditures for treatment and disposal include both internal and external costs. Internal costs for re-landfilling only occur in the case of resource recovery alone (F4-1) or in combination with void space recovery (F4-3) as project drivers. External costs for waste treatment and disposal consist of gate fees for WtE and hazardous waste disposal in all scenarios as well as external re-landfilling in the case of material recovery and land reclamation as project drivers (F4-2). The wide range of costs for waste treatment and disposal is mainly due to regional differences in technical operations, management practices and regulations and taxes for landfilling and incineration. Due to these differences in both project and system-level conditions, the general view in this study sets apart from previous case studies, which, in comparison, provide inconsistent conclusions regarding the relative importance of cost items.

In terms of the mean revenue items, avoided landfill management costs dominate the positive contribution to the project economy. The wide range for such indirect revenues reflects the possibility of largely different landfill management options, ranging from "do nothing" to high-intensity aftercare or remediation. This fact rarely has been acknowledged in previous case studies, for one thing, since they typically have involved landfills with no (Frändegård et al., 2015; Wolfsberger et al., 2016) or low obligations for aftercare (Danthurebandara et al., 2015; Kieckhäfer et al., 2017; Van Passel et al., 2013). Among the direct revenue items, the highest contribution is accounted to material sales including metals (steel, aluminum, and copper), plastics and secondary aggregates. This is closely followed by the joint revenues from reclaimed void space and land, and returns from the residual value of machinery. It should be noted, however, that revenues from void space and land are expected outputs of only one third of the scenarios due to the choice of project drivers (F4). Hence, in a scenario with land or void space recovery, the respective revenues are on average as high as revenues from materials or even higher. Also, the wide ranges observed for these revenue items are caused by varying market conditions related to material prices and the value of land and void space. These results highlight the importance of aiming for multiple resources recovery that are reclaimed land or landfill void space apart from materials.

Although this type of contribution analysis provides valuable knowledge on the main costs and revenue items, it fails to capture the underlying factors that drive each item's economic performance. These factors can be economic, such as regulatory costs and market prices, or physical (related to material flows), such as

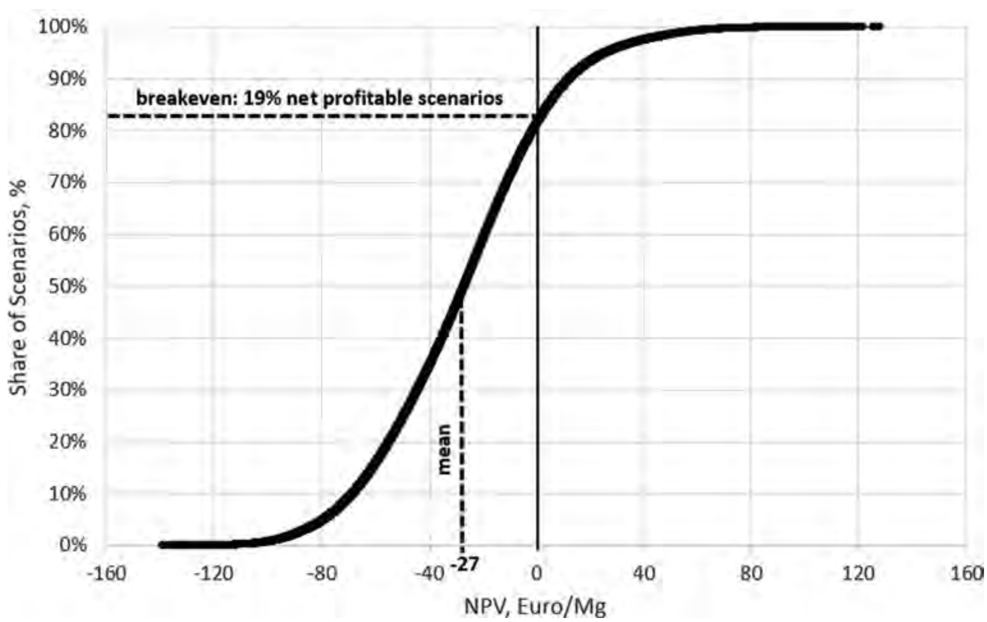

Fig. 3. Cumulative distribution of the 531,441 scenario results (in NPV). It shows a mean net deficit of −27 Euro/Mg and 19% are profitable scenarios (>0 Euro/Mg). Of the latter, 40% are at $0 < x \leq 10$ Euro/Mg, 33% at $10 < x \leq 25$ Euro/Mg, 20% at $25 < x \leq 50$ Euro/Mg, 8% at $50 < x \leq 100$ Euro/Mg, and 0.1% >100 Euro/Mg.

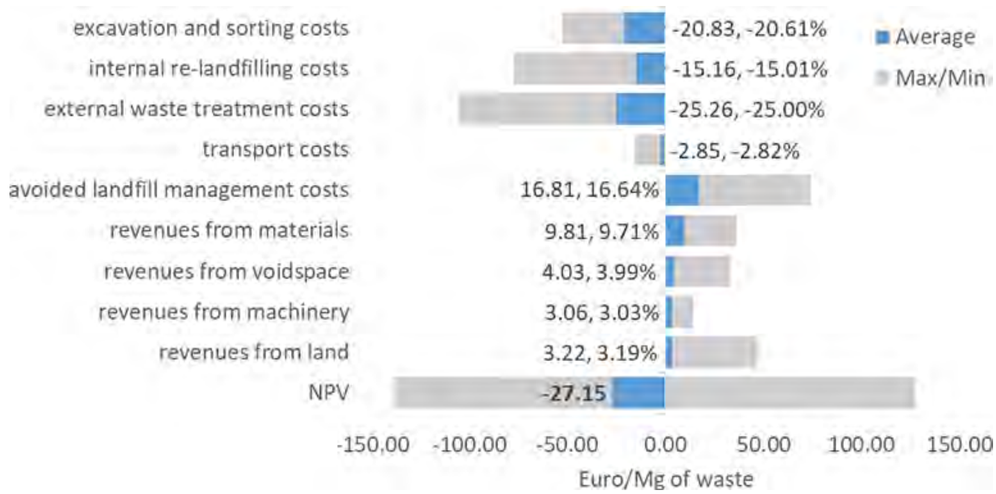

Fig. 4. Economic contribution analysis in terms of cost (–) and revenue (+) items. Mean (in blue) and maximum/ minimum values of each item are shown (in grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

waste composition and subsequent processing. Without such a detailed understanding, the development of strategies for improving the economy landfill mining remains difficult and might overlook critical challenges for obtaining cost efficiency.

3.2. Variance-based sensitivity analysis to identify critical factors

Variance-based sensitivity analysis serves to understand the reasons behind the variation in the results by assessing the criticality of individual economic or physical factors as well as their interactions. Here, this fine-grained approach for assessing what builds up the economy of landfill mining is applied to both the NPV of the overall scenario results and the specific cost and revenue items from the contribution analysis.

3.2.1. Sensitivity analysis related to the whole project (NPV)

Based on total-effect sensitivity (S_{Ti}), the studied factors can be grouped according to their criticality for the NPV of the landfill mining scenarios (see Table 3). The two most critical factors account for more than half of the total variation in the scenario results, which includes the costs for waste treatment, disposal, and transport (F9, 34%) and the reference scenario (F3, 21%). The former refers to the costs of disposal of hazardous wastes and various residues, expenditures for the treatment of landfill gas and leachate, and transport costs in general. The latter refers to the alternative landfill management costs, which are avoided costs if the landfill is mined (i.e., removed). The second pair of factors, which account for 22% of the variation in the scenario results, are the gate fees for WtE (F6, 12%) and the landfill settings (F1, 10%). F1 refers to landfill site characteristics such as the deposited tonnage and geometry, settings that among other things influence landfill mining capacity and project duration. Out of these four most critical factors, three address the system level such as regulatory and market settings influencing the intensity of required landfill management and aftercare (F3), gate fees and taxes for external WtE treatment (F6) and costs and taxes for re-landfilling of generated residues (F9). These three factors primarily affect the variation of scenario results in a first-order (S_i) manner. That is, the variation in scenario results is influenced by the variation in the datasets of the individual factors, and only to a minor extent due to combination effects with other factors (=higher-order effects, S_{Hi}). The dominance of first-order effects can be explained by the fact that F3, F6, and F9 address costs and prices, and thereby their variation has a direct influence on the scenario results. In contrast, landfill settings (F1) interacts with several other factors, influencing the physical flows of materials and valorization potentials throughout the entire landfill mining system. This means that apart from the landfill settings, the amount of materials to be processed, disposed of, further treated, and sold depends on the realization of other datasets such as landfill composition (F2), determining the gross

Table 3
Variance-based sensitivity indices quantifying the main or first-order effect (S_i), interaction or higher-order effect (S_{Hi}), and total-order effect (S_{Ti}) of factor variation with respect to the overall scenarios results (in NPV). The ranking is based on S_{Ti}.

Factors	S_i	S_{Hi}	S_{Ti}	Rank (S_{Ti})
F0 Regional variations in excavation & sorting costs	0.010	0.002	0.012	11
F1 Landfill settings	0.019	0.107	0.126	4
F2 Landfill composition	0.001	0.042	0.044	8
F3 Reference scenario	0.194	0.070	0.264	2
F4 Project drivers	0.025	0.038	0.063	6
F5 Excavation & sorting technology	0.017	0.057	0.074	5
F6 Waste-to-Energy	0.097	0.048	0.145	3
F7 Markets for materials and energy	0.008	0.004	0.013	10
F8 Value of recovered land or landfill void space	0.027	0.031	0.058	7
F9 Waste treatment, disposal, transport costs	0.380	0.037	0.417	1
F10 Transport distances	0.003	0.001	0.004	12
F11 Financial accounting	0.001	0.019	0.019	9
Total	0.784	0.456	1.240[a]	

[a] Note that double counting of factor interaction effects causes S_{Ti} to exceed 1.

amount of potentially recoverable materials, project drivers (F4), deciding what is recovered and whether the generated residues are re-deposited internally or externally, and finally the employed technology for excavation and sorting (F5), influencing the separation efficiency of materials and high-calorific fractions. Together with prices for reclaimed land or landfill void space (F8), these factors (i.e., F2, F4, F5, and F8) explain almost 20% of the total variation in the scenario results, where higher-order effects (S_{Hi}) dominate (cf. Table 3). In the case of F8, the higher-order effects depend on its relations to project drivers (F4), determining if either the value of land or void space is applicable. However, first-order effects are also crucial for F8, because price levels have a direct impact on the project economy. Lastly, the least significant group of factors only accounts for 4% of the variation in the results, including financial accounting (F11, 1.5%), market prices for material and energy (F7, 1%), variation in excavation and sorting costs (F0, 1%), and transport distances (F10, 0.3%).

The effects of dataset choices for the four most critical factors on the project economy are visualized in an ordered plot of scenario results in Fig. 5. Generally, the NPV of a landfill mining project decreases with higher waste treatment and disposal costs (F9) and higher gate fees for external WtE treatment (F6), while the opposite is the case for higher avoided costs for landfill management and aftercare (F3). Given that these three factors primarily involve first-order effects on the scenario results, determining favorable combinations of datasets, contributing to lower costs and higher revenues, is more or less straightforward. Of course, particularly bad conditions for landfill mining in terms of these factors exist, if aftercare costs are low in regions with high waste disposal and treatment costs and taxes.

For landfill settings (F1), however, which mainly has higher-order effects, determining a preferable dataset is less obvious. Instead, the graphical analysis reveals that the criticality of this factor is rather a matter of its interactions with the reference scenario (F3). For instance, the setting of small-scale landfills with short project durations (F1-1) is clearly preferable for scenarios with intensive aftercare or remediation (F3-3), while such settings are more or less insignificant in case of low-to-medium cost reference scenarios. The main reason for this combination effect is simply that performing intensive aftercare or remediation is more expensive in small-scale settings compared to large-scale (i.e., 0.1 instead of 0.05 Euro/Mg per year for gas treatment, 15 instead of 8 Euro/Mg for the costs for cover, and 0.7 instead of 0.4 Euro/Mg per year for maintenance and monitoring), thereby leading to higher avoided costs or indirect revenues. These economic-scale effects are reflected in this study by increasing average deposition heights for larger landfills, which results in a greater amount of waste being processed or managed per unit area from small-scale to large-scale landfill settings.

3.2.2. Sensitivity analysis for cost and revenue items

The criticality of different factors is also assessed for the present values of cost and revenue items, to provide a fine-grained analysis of drivers for each cost and revenue item building up the project economy (Fig. 6; for a more comprehensive description of the results in terms of first-order (S_i), higher-order (S_{Hi}) and total-order (S_{Ti}) effects, see SI, Table S-14).

Among the main cost items, internal re-landfilling costs for fines is mainly driven by the price settings for waste treatment, disposal, and transport (F9, 41%), which earlier was intuitively identified as a cost driver in the contribution analysis and systematically assessed as the most critical factor in the variance-based sensitivity analysis of the overall scenario results. However, the specific variance-based sensitivity analysis shows that an equally important factor for the internal re-landfilling costs is the project driver (F4, 41%), influencing the amounts of residues being internally and externally disposed of. In practice, this means that the cost for internal re-landfilling is not just a matter of local or

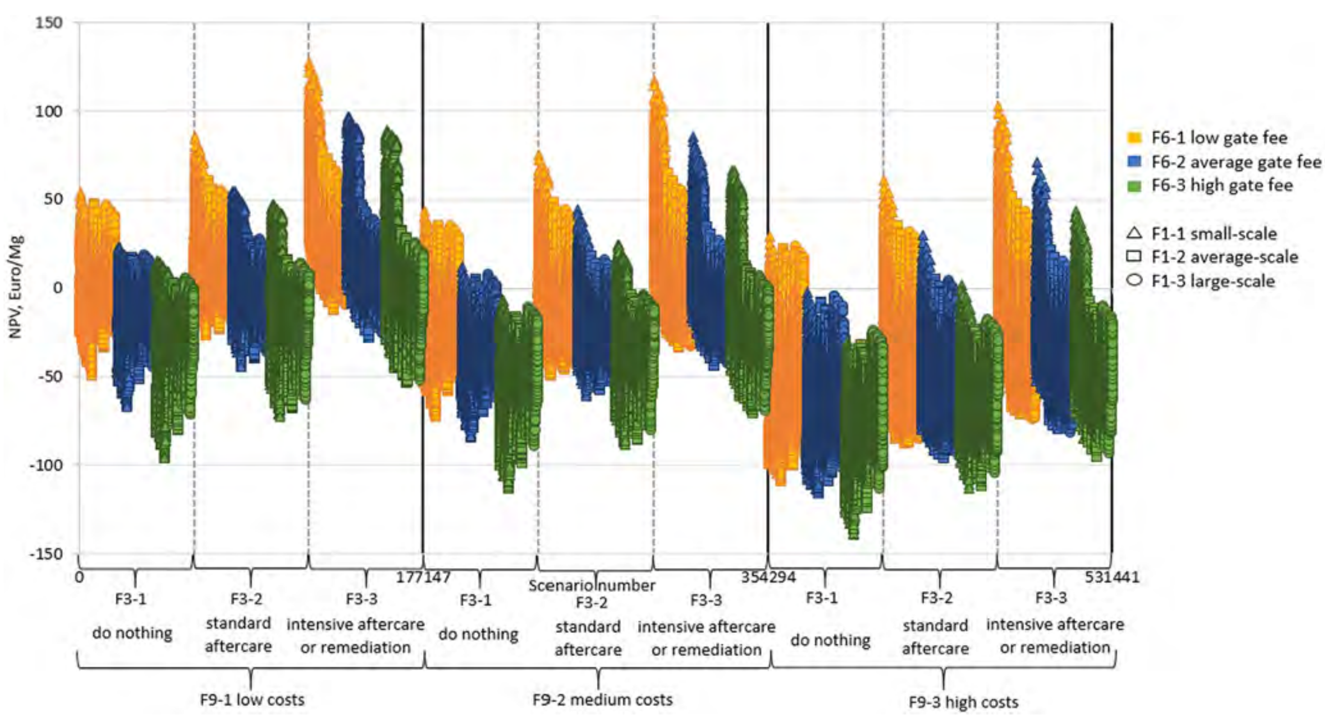

Fig. 5. Graphical analysis of the scenario results grouped according to the four most critical factors according to total sensitivity (STi) such as costs for waste treatment, disposal, and transport (F9), reference scenario (F3), costs of WtE technology (F6), and landfill settings (F1). Sample analysis: The highly profitable scenarios (yellow triangles in the upper left corner of the figure) involve low costs for treatment and disposal of wastes (F9-1), intensive aftercare or remediation in the reference scenario (F3-3), low gate fee for WtE (F6-1), and small-scale landfill with short project duration (F1-1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

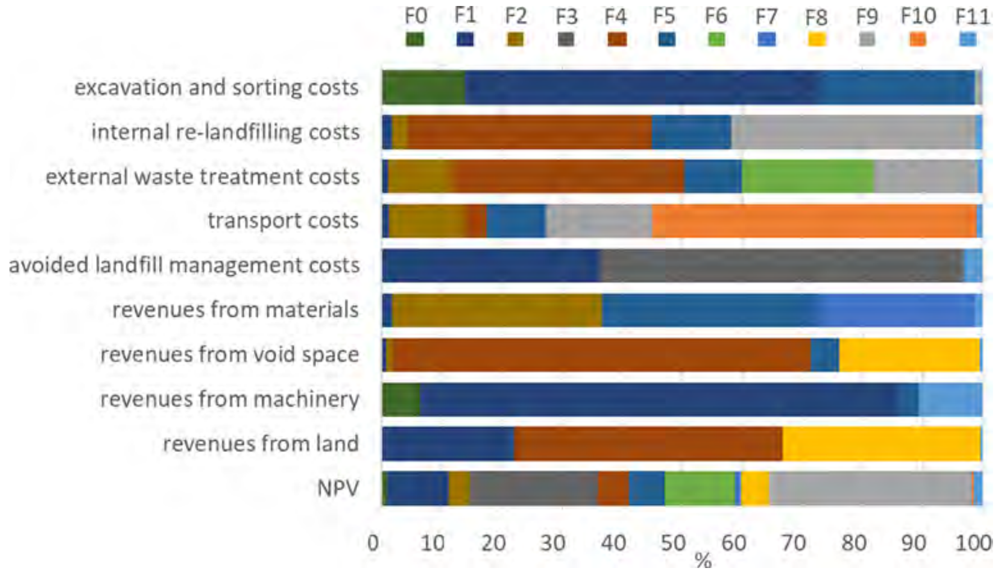

Fig. 6. The critical factors based on total-effect sensitivity (S_{Ti}) for each cost and revenue item.

regional price-settings but also the choice of project objectives as well as the employed excavation and sorting technology (F5, 13%). Consequent management costs for internally re-landfilled materials are directly dependent on the efficiency of sorting valuable fractions, i.e. higher efficiency lowers the amount of fractions which need to be re-landfilled. Similarly, the external costs for waste treatment are determined by several factors, primarily the project drivers (F4, 39%), gate fees for WtE (F6, 22%) and price settings for waste treatment, disposal, and transport (F9, 17%).

Concerning the main revenue items, avoided landfill management costs are driven by the type of aftercare scenario (F3, 61%) and landfill settings (F1, 36.3%), confirming their interplay as noted earlier in the graphical analysis (Fig. 5). In addition, information on relative criticality between these two factors is revealed. The revenue from materials is mostly driven by physical flow-related factors such as the choice of excavation & sorting technology (F5, 36%) and the landfill composition (F5, 35%), whereas the market prices for separated materials and high-calorific fractions are less important (F7, 26%). Thus, maximizing the revenues from materials is mainly a quest of selecting rich MSW landfills (F2-3) and employing efficient excavation and sorting technology (F5-3) in situations of high market prices (F7-3) that compensate for the higher treatment costs. Similarly, market price levels (F8) for reclaimed land (33%) and landfill void space (23%) are expected critical factors for the related revenues. However, the project drivers (F4), determining if land or void space is to be reclaimed, turn out as the most critical factor for both of these revenue items at 45% and 70%, respectively. Revenues from land are also driven by landfill settings (F1, 22%) because it influences the recoverable land area. Concurrently, revenue from void space is also affected by excavation and sorting technology (F5, 5%), which determines the amount of waste that will be re-landfilled—this is high in case of low separation efficiency, thus lowering the volume of the recovered void space. So aside from high market value for land and void space (F8-3), maximizing the respective revenues requires large-scale landfill settings (F1-3) and advanced excavation and sorting technology (F5-3).

3.3. Critical factors for regional archetype settings

In order to analyze the economy of landfill mining projects under specified boundary conditions (e.g. regional disparities), the importance of factors related to landfill selection and project implementation is subsequently investigated for two extreme archetype settings. These archetypes represent regions with low and high income levels and waste management standards, respectively. Most of the system-level and regionally determined factors are thus fixed while only the factors under the influence of landfill practitioners are varied, i.e., landfill settings (F1), landfill composition (F2), project drivers (F4), excavation and sorting technology (F5), and transport distances (F10). In other words, this archetype analysis targets the key questions of (1) how to select suitable landfill for mining and (2) which organizational and technical project setup is preferable in different site and regional settings.

For the low regional archetype (Fig. 7), the average scenario result is −13 Euro/Mg with a range of possible outcomes from −34 to +4 Euro/Mg. Only 6 out of the 243 scenarios are profitable (+0.07 to +4 Euro/Mg). These profitable scenarios are characterized by a large-scale landfill setting (F1-3), MSW landfills rich in recoverable resources (F2-1), advanced excavation and sorting technology (F5-3), and they aim at resource recovery and reclamation of landfill void space (F4-3). Only under these specific settings, the revenue items such as recovered materials and recovered landfill void space can compensate for the (low) costs of excavation and processing, WtE treatment, and disposal of residues. For the currently unprofitable scenarios, several observations for improved cost-efficiency can also be made. For instance, resource recovery alone (F4-1) is preferred over the combination with land reclamation (F4-2), because of low land values (F8-1) which cannot compensate for the additional costs caused by external re-landfilling of residues. For small-scale landfill settings with short project duration (F1-1), mobile sorting technology (F5-1) is preferred over advanced processing (F5-2, 3) due to higher costs than revenues from recovered materials given low market prices (F7-1), even if rich MSW landfills are mined (F2-1). Overall, the (very low) avoided costs for “do nothing” (F3-1) set a highly challenging condition for attaining a profitable scenario as it is typically the main source of (indirect) revenue.

For the high regional archetype (Fig. 8), the average scenario result is −37 Euro/Mg with a range from −79 to +30 Euro/Mg. Compared to the low regional archetype, this archetype involves more profitable scenarios (i.e., 34 scenarios ranging from +0.5 to +30 Euro/Mg) but also poses higher economic risks indicated by the wider range of possible outcomes. This situation is expected

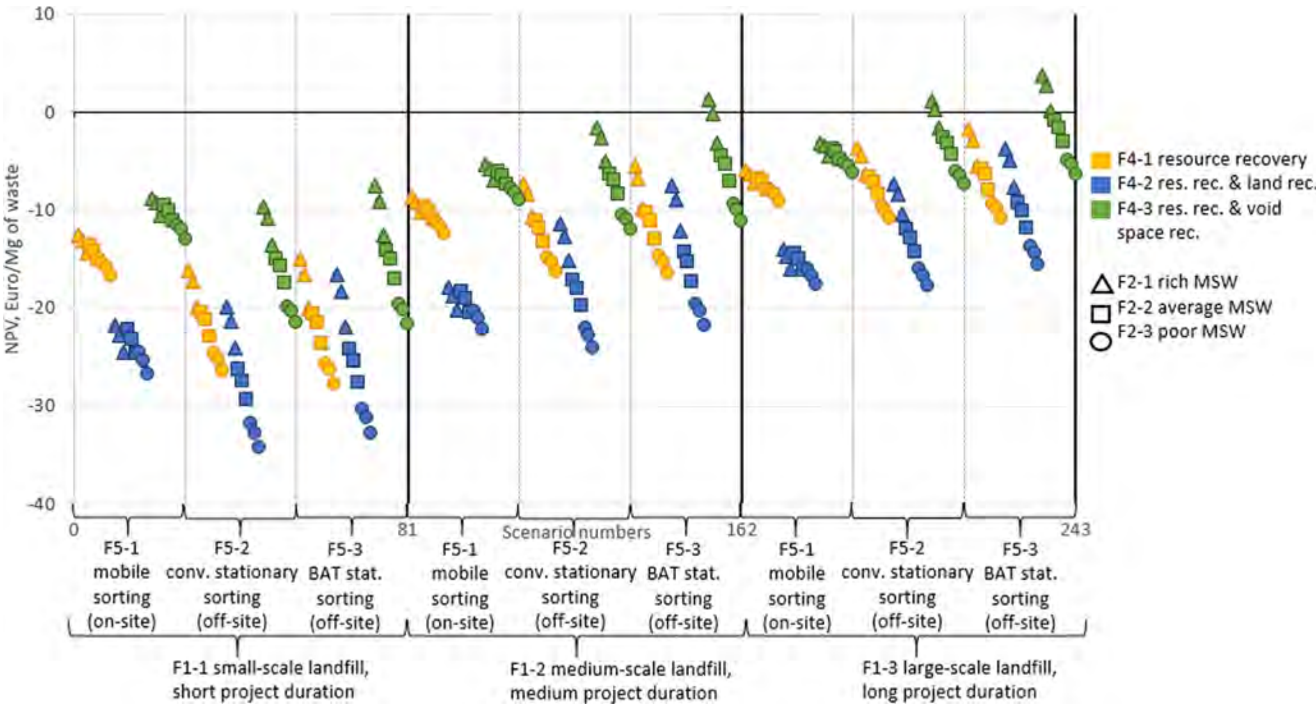

Fig. 7. Graphical analysis of European regional archetype with a low level of economic income and low waste management standards. The following factors are fixed to low datasets except for financial accounting (F11-3), as expected for less developed economies: variation in excavation & sorting costs (F0-1), reference scenario (F3-1), costs of WtE technology (F6-1), markets for material and energy (F7-1), prices of reclaimed land or landfill void space (F8-1), and costs for waste treatment, disposal, and transport (F9-1). The 243 scenario results are grouped according to the four most critical factors under the influence of landfill practitioners such as landfill settings (F1), excavation and sorting technology (F5), project drivers (F4), and landfill composition (F2).

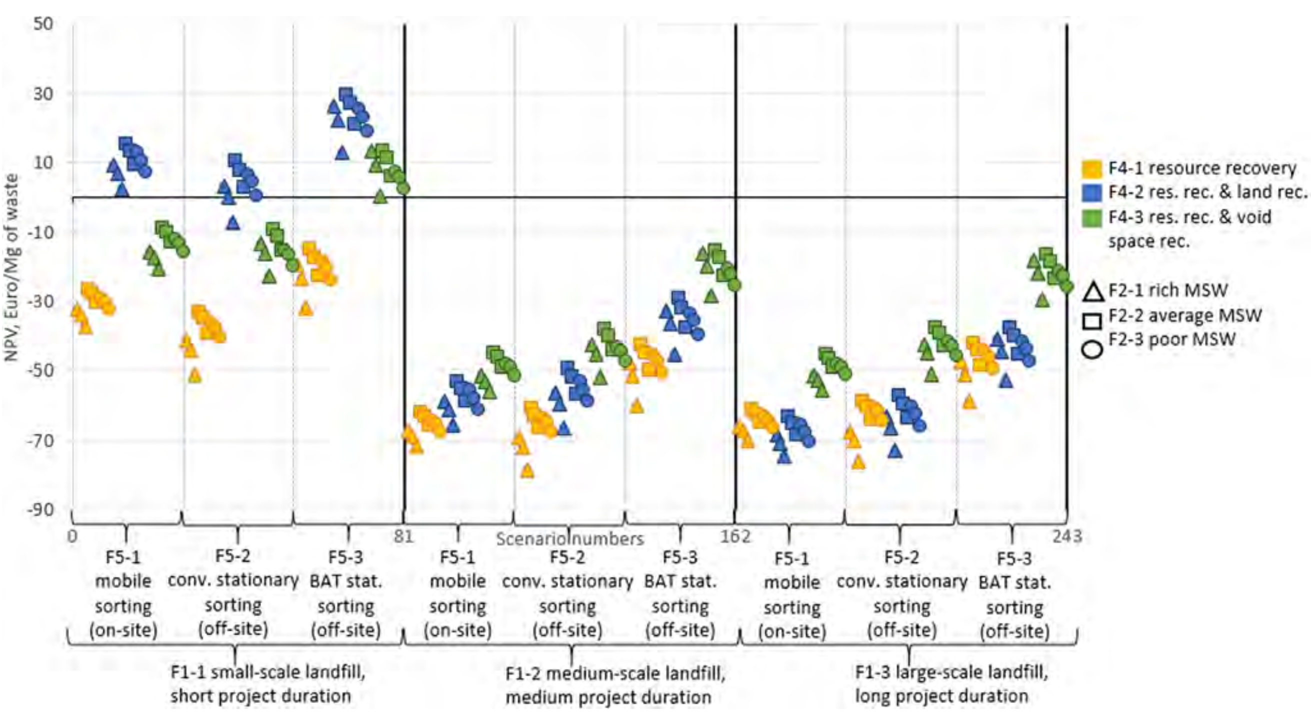

Fig. 8. Graphical analysis of European regional archetype with a high level of economic income and high waste management standards. The following factors are fixed to high datasets except for financial accounting (F11-1), as expected for more developed economies: variation in excavation & sorting costs (F0-3), reference scenario (F3-3), costs of WtE technology (F6-3), markets for material and energy (F7-3), prices of reclaimed land or landfill void space (F8-3), and costs for waste treatment, disposal, and transport (F9-3). The 243 scenario results are grouped according to the four most critical factors under the influence of landfill practitioners such as landfill settings (F1), excavation and sorting technology (F5), project drivers (F4), and landfill composition (F2).

from the set conditions for the most critical factors such as high costs for waste treatment, disposal, and transport (F9-3), high revenues for recovered materials, land and landfill void space (F8-3) and high avoided costs for intensive aftercare or remediation (F3-3), among others. The profitable scenarios involve small-scale landfill settings with short project duration (F1-1), employ highly advanced excavation and sorting technology (F5-3), and focus on resource recovery and land reclamation (F4-2). This indicates that revenues from reclaimed land with a high market value can compensate for high costs for excavation and processing, WtE treatment, and disposal of residues. Indifference in landfill composition (F2) is notable (indicated by almost converging shapes in Fig. 8), which implies that variations in revenues from recovered materials are insignificant relative to revenues from reclaimed land. Also, the preference for advanced excavation and sorting technology is due to less external costs for disposal of residues, more than the actual revenue for recovered materials. For medium and large-scale landfill settings (F1-2, 3), there is a major drop in the NPV and all scenarios, therefore, result in a clear economic deficit. It signifies the importance of the reference case because, for these larger landfills, significantly lower indirect revenues from avoided costs for landfill management are expected due to economic scale effects, as previously discussed. For the same reason, resource recovery and reclamation of landfill void space are also preferred for larger landfills. The prime reason for this is that in such settings a proportionally larger amount of residues is generated, making the costs for external disposal more expensive than internal re-deposition. The value of land (F4-2) can then not compensate for these higher external costs, hence the preference for internal re-deposition costs with void space recovery (F4-3).

From the analysis of regional archetypes, the importance of system-level conditions becomes apparent, especially with regard to costs for waste treatment, disposal, and transport (F9), and the reference scenario (F3). As discussed in previous sections, these factors are the most critical, driving the main cost (i.e., internal re-landfilling costs and external waste treatment costs) and revenue (i.e., avoided landfill management costs) items. Thus, they should be regarded as overarching boundary conditions that must guide landfill mining practitioners in their quest to select suitable landfills for mining and develop cost-efficient projects. In terms of landfill prospecting, selection of landfill settings is very important due to economic scale effects, in case of the high regional archetype. Landfills with low mass-to-area ratios (or low volume-to-area ratios) are preferred targets, because of potentially higher specific avoided landfill management costs. In such a setting, cost-efficient projects can often be achieved by minimizing costs for managing waste rather than maximizing revenues from materials. It follows that land reclamation is the preferred project driver under these conditions (high archetype and low mass/area-ratio) due to the high market value of land that can compensate for external re-landfilling costs. On the other hand, the opposite is true in case of the low regional archetype, because in this situation maximizing revenues from materials is more important than minimizing (already low) costs for managing waste. Hence, large-scale landfill settings with rich MSW composition contribute to a positive economy of landfill mining under these conditions. It follows that void space recovery is the preferred project driver over land reclamation because of low land value and that internal re-landfilling is slightly cheaper than external.

4. Conclusions

Through a set-based modeling approach, this study contributes with a systematic understanding of what builds up the economic performance of landfill mining in general and in a wide range of different European situations and settings. In contrast to previous case studies, the present analysis also generates knowledge on how different site, project and system conditions interplay and jointly contribute to the economic performance of landfill mining projects.

In general, landfill mining is a challenging business venture. Although the project NPVs of all the assessed landfill mining scenarios vary over a large range (−139 to +127 Euro/Mg), only a minor share of the projects is profitable (20% are >0 Euro/Mg). System conditions are most critical for the economy of a landfill mining project because such policy and market settings determine the magnitude of both main costs and revenues. On the one hand, expenditures for treatment and disposal of the exhumed materials are typically the most important cost factor. On the other hand, avoided landfill management costs (reference scenario) represent the potentially largest project revenue. This highlights the role of policy intervention to enable more economically favorable conditions for landfill mining projects. In particular, regulations aiming to lower re-deposition costs and taxes and to intensify aftercare requirements could be implemented. Furthermore, a key policy-related challenge involves measures to break up current market structures, in which the waste owner pays for subsequent recycling and recovery rather than obtain revenues for the separated materials and energy carriers.

On the level of projects and landfill settings, a major finding is that it is crucial for a positive economy of a landfill mining project to obtain multiple values by going beyond the often targeted revenues from material sales and include income from avoided management costs and recovered land resources (e.g. reclaimed land or landfill void space). The higher additional incomes or avoided costs for a specific project, the higher is the chance of economically feasible mining. Therefore, landfill mining prospection should pay attention to landfills with relatively low waste deposition heights (low mass-to-area ratio) in areas with land valorization potential (e.g. residential areas) and significant aftercare or remediation obligations. Because such relevant information is widely available from existing landfill surveys and databases, potentially attractive sites can be identified without extensive waste characterization efforts. However, apart from these general recommendations, the development and implementation of economically justified projects also depends on the specific situation (i.e. regional setting). For instance, whereas cost-efficient projects can mainly be achieved by minimizing expenditures for treatment and disposal of waste in case of high waste management costs, maximizing revenues by intensive sorting and upgrading of materials is more important than minimizing costs for managing waste in regions with low waste management costs. In the former case, material revenues are of minor importance for the project economy, whereas they are the main drivers in the latter case.

The modeling approach presented in this study can be applied to a wide range of emerging sustainable solutions and circular economy strategies, to go beyond a case study approach and guide future research, support strategic decision making as well as facilitate project implementation under a variety of boundary conditions and settings. With respect to the developed model, further analysis regarding alternative organizational project setups, business models, and policy impacts should be done to identify opportunities for better economic performance in specific situations from the perspective of different actors. Finally, model extension to integrate environmental and social dimensions in the assessment should be envisaged to provide a single tool for environmentally and economically informed decision-making on landfill mining.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2019.07.007.

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