LANDFILL MINING - FROM PROSPECTION TO ACTUAL MINING

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Abstract

This paper presents the concept of landfill mining as an integral building block in the transition to a circular economy. The (research) work that has been done so far with respect to landfill mining is summarized. The phases of resource classification, i.e. (pre-) prospection, exploration and evaluation, are typically run through to decide whether or not to start actual mining activities. In this paper these phases, together with their goals, key influencing factors and methods for decision making, are described for potential landfill mining projects. To conclude, the challenges and potentials of landfill mining are discussed, and some recommendations are derived.

Keywords: Landfill Mining, Resource Classification, UNFC

Introduction

Urban mining and landfill mining are integral building blocks in the transition to a circular economy (European Commission, 2014). Krook et al. (2012) define landfill mining as ‘‘a process for extracting minerals or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground’’. The alternative to mining a landfill is usually regulated aftercare, implying that the closed landfill is left untouched and landfill facilities are maintained, emissions treated, and monitoring is performed for many decades in the case of municipal solid waste (MSW) landfills (Laner et al., 2012).

Most of the early landfill-mining projects were driven by local pollution issues or by the need for new landfill capacities given the difficulty of getting permission to develop new landfills (e.g. van der Zee et al., 2004, Bockreis and Knapp, 2011, Hogland et al., 2004, Spencer, 1990, Burlakovs et al., 2017) rather than by the need to recover landfilled materials as secondary resources. Nowadays, in densely populated regions, such as Flanders, the key drivers of landfill mining are rising land prices and the need for new clean land, while the value of extractable materials can help to reduce costs (Winterstetter et al., 2018). In the EU there are between 150,000 to 500,000 landfills, with about 90% of them considered “non-sanitary” (Hogland, 2002). Although many of these historic landfills will require remediation measures to avoid future environmental and health problems, they can potentially make a substantial contribution towards meeting European material, energy and land needs (EURELCO, 2017). In countries like Germany, Austria or Belgium current waste streams are recycled to a large extent. But the untreated and unsorted waste streams that were disposed of in landfills until the late 1970s still contain a large amount of valuable resources. Franke et al. (2010) estimate that the potential energy content stored in German landfills in the form of wood, plastics, paper and cardboard amounts to approximately 7,700 PJ, corresponding to about 50% of Germany’s annual primary energy consumption. Furthermore, according to Mocker et al. (2009) 83 million t of iron and 13 million t of nonferrous metals have been disposed of in German landfills since 1975. Rettenberger (2009) calculated that in theory 50% of the annual German demand for aluminum scrap, 124% of the iron, as well as 142% of the copper could be covered by the materials deposited in the landfills.

This paper summarizes the (research) work that has been done so far with respect to landfill mining. The phases of resource classification, i.e. (pre-)prospection, exploration and evaluation, which have to be run through before starting actual mining activities, are described together with their goals, key influencing factors and methods for decision making. To conclude, the challenges and potentials of landfill mining are discussed, and some recommendations are derived.

Mine it or leave it?

Landfill mining exhibits significant similarities with conventional mining projects. In the primary resource sector, deciding on whether to start actual mining activities or not, typically the stages "(pre-)prospection", "exploration" and "evaluation" have to be run through (Winterstetter et al., 2015). After screening existing data bases and selecting a specific deposit to be mined, three key aspects – used in accordance with the three-dimensional primary resource classification framework UNFC (UNECE, 2010) – need to be considered (cf. Tab.1):

1) The knowledge on composition, contamination level, share of recoverable resources / land from a recovery project is expressed as the level of certainty on the G-Axis.
2) The technical and project feasibility of a mining operation (F-Axis) is indicated by the use of fully mature technologies and ongoing activities, including all required licenses.
3) In the evaluation phase the project's socioeconomic viability is analysed (E-Axis). Modifying factors such as legal, environmental, socioeconomic, political, marketing, transportation and technological factors are considered.

Pre-Prospection

The goal of the pre-prospection / mapping phase is to select a specific mining project by screening existing databases and reports on former landfill sites (cf. Table 1). In the case of missing databases, a macro scale Material Flow Analysis (MFA) (Brunner and Rechberger, 2004) can be helpful to get an overview of waste flows and stocks within a certain time period and - combined with information on local landfilling activities - to create an inventory of landfills in a certain region.

The Public Waste Agency of Flanders (OVAM) developed a screening tool FLAMINCO (Flanders Landfill Mining, Challenges and Opportunities) using seven criteria, namely landfill type, operation period, volume, current land use, distance to other landfills and transport ways as well as a landfill's specific environmental pollution potential (Behets et al., 2013, Wille, 2016). Based on those criteria, the specific mining conditions, i.e. the key drivers for landfill-mining, can be derived, such as remediation need (push) or resource / land recovery (pull), which constitute the preconditions for potential mining activities and define the setting for the following classification. OVAM is currently prospecting the resource and land recovery potential of further selected historic landfills. For this purpose, the estimated 2000 old landfills, out of which the majority is no longer operational, are continuously inventoried and integrated with the spatial model of Flanders to systematically provide information for their future management, as shown in Fig. 1 (Nagels and Wille, 2017).

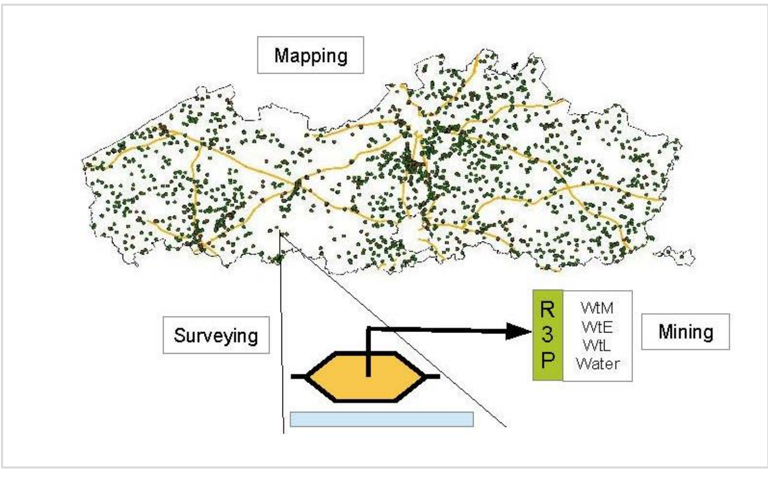
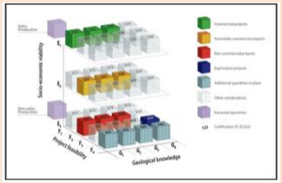


Fig. 1: Mapping of 2,000 historic landfills in Flanders for potential mining (Nagels and Wille, 2017)

Table 1: Decision-making process for potential landfill-mining projects based on Winterstetter et al. (2018).

Phases	1. Pre-Prospection	2. Prospection	3. Exploration	4. Evaluation
Goal	Screen & select a landfill to be mined	Identify the landfill's resource / land recovery potential & contamination level (G-Axis)	Deepen knowledge on the landfill's share of extractable materials / recoverable land / contamination level (G-Axis) Check technical & project feasibility (F-Axis)	Analyze socioeconomic viability of extraction & utilization (E-Axis)
Key Factors	**Mining condition** • **Pull:** Landfill can be mined (but does not have to) for land / resource recovery • **Push:** Remediation need	**Site specific parameters** • Type & Location • Volume • Composition	**Project specific parameters** • Technology maturity & different options of project set-ups for extraction & processing with specific recovery efficiencies • Project status (public perception, licenses etc.)	**Socioeconomic parameters** • Prices for secondary products (recovered resources / land/ new landfill space) • Costs • Avoided costs • Indirect financial effects • Non-monetary effects (environmental, societal)
	Systemic factors, such as • Political / governmental willingness • Legislation (EU, national, local) & enforcement • Institutional & organizational structures • Regional land price		• Regional infrastructure (e.g. WtE gate fees) • Markets for secondary products • Commodity prices world market • Background energy system	
Methods	Analysis & evaluation of reports / databases on historic landfills & their mining condition	Detailed investigation of a specific landfill (e.g. log book, sampling, waste analysis)	Micro scale MFA Technology assessment Policy framework analysis Stakeholder analysis	DCF* analysis & cut-off values for key parameters Net Present Values (NPV)** NPV > 0: Reserve NPV < 0: Resource or not?

				Social & environmental effects can or cannot be monetized
		Classification under UNFC 		

DCF = Discounted Cash Flow Analysis, **NPV = Net Present Value

Prospection & Exploration

After screening and selecting a landfill suitable for potential mining, the following two phases in the decision-making process, i.e. prospection and exploration, aim at gaining knowledge on the site and project specific parameters. First, information on the landfill's type, its location, size, depth, volume and rough composition shall be gained, allowing for first estimates on the resource potential (cf. Tab. 1). Then the landfill's share of extractable materials and recoverable land as well as its contamination level is examined and the technical and project feasibility is checked. Using Material Flow Analysis (MFA) (Cencic and Rechberger, 2008) allows the modelling of different options for extraction methods and processing technologies with their specific recovery efficiencies, as well as different project set-ups (Winterstetter et al., 2015).

In numerous pilot studies and research projects the main goal was to characterize a specific landfill's composition and to evaluate its recovery potential for resources, energy and landfill space, such as done by Hogland et al. (2004), Hull et al. (2005), Quaghebeur et al. (2012), Kaartinen et al. (2013), and Wagner and Raymond (2015). Some papers describe suitable technologies for the mining, processing and valorization of excavated materials, e.g. Bosmans et al. (2012), Danthurebandara et al. (2015a), and Wanka et al. (2017).

Tab. 2: The Remo MSW landfill's composition (Spooren et al., 2012)
Std. dev. abs.= absolute standard deviation, Wt % = Dry weight percentage

Reno MSW landfill's composition (Mean value ± std. dev. abs., wt-%)	
Plastics	20 ± 8
Textiles	7 ± 6
Paper / Cardboard	8 ± 6
Wood	7 ± 2
Metals	3 ± 1
Minerals / Stones	10 ± 4
Fines <10 mm	40 ± 7
Glass / Ceramics	1 ± 1
Unknown	4 ± 4

Tab. 2 shows the composition of the Remo MSW landfill in Belgium. Potential secondary products of a MSW landfill typically comprise refuse-derived fuel (RDF) made from the high calorific fractions paper, textiles, plastics and wood, which can be used in industrial processes or incinerated for energy recovery, with a calorific value of around 20 MJ/kg. Mechanical sorting allows for the recovery of inerts, stones and soil-type materials for construction purposes as well as ferrous and non-ferrous metals, typically Cu, Al, and Fe. Regained land or new landfill space often represents the most valuable secondary product (Burlakovs et al., 2017).

Evaluation

To analyze the socioeconomic viability of mining a landfill - as reflected on the E-Axis of UNFC - the Net Present Values (NPV) is calculated, as shown exemplarily for the Bornem landfill-mining project in Fig. 2. Socioeconomic parameters are investigated, such as prices for secondary products and recovered land, investment and operating costs, costs for external treatment and disposal, avoided costs as well as possibly monetized social and environmental externalities and indirect financial effects. Often they depend on the legal, institutional, organizational and societal structures in which a project is embedded. A positive NPV implies that a project is economically viable. Consequently, the evaluated materials can be classified as 'reserves' (UNFC score E1). If the NPV turns out to be negative, however, one has to judge whether there are reasonable prospects for economic extraction in the foreseeable future. Whether the deposit can be labelled a 'resource' (E2) or not (E3) can be decided by anticipating realistic changes of key economic parameters. The "cut-off values" of key parameters indicate when the project breaks even (NPV = 0) (cf. Fig. 3).

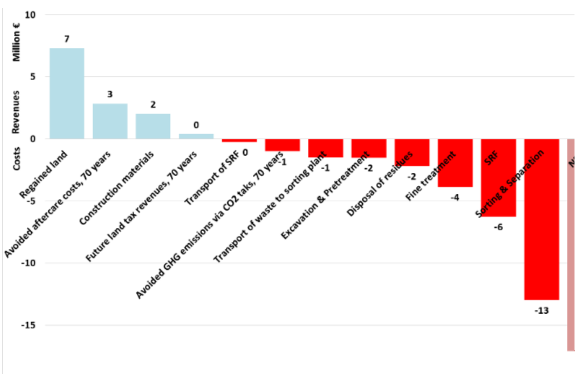


Fig. 2: Total costs and revenues of the Bornem landfill-mining project discounted with a discount rate of 3 % over 70 years (Winterstetter et al., 2018).

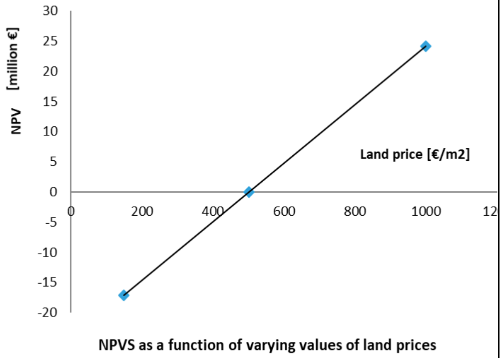


Fig. 3: NPVs shown as a function of varying land prices, currently 150 €/m2. The cut-off land price is reached at 502 €/m2 (Winterstetter et al., 2018).

A number of authors assess both the environmental and economic viability of landfill mining, such as Danthurebandara et al. (2015b), Frändegård et al. (2015), Van Passel et al. (2013), Laner et al. (2016), Diener et al. (2015), Winterstetter et al. (2015), Zhou et al. (2015), Kieckhäfer et al. (2017) and Gäth and Nispel (2012), to name just a few. Marella and Raga (2014) investigate the social and environmental benefits of landfill mining, focusing on avoided emissions to air, soil, and water, decreased resource import dependency and the increased value of surrounding land. Damigos et al. (2016) found that households in a rural area in Greece are willing to pay €50 per year for the removal of an old landfill.

Classification

Various attempts have been made to provide systematic guidelines and / or frameworks to evaluate landfill-mining projects. Lederer et al. (2014) evaluated different types of anthropogenic phosphorus stocks using the McKelvey box. Hermann et al. (2016) designed a comprehensive assessment method including monetary factors but also integrating non-monetary effects, such as the concerns of neighbors or environmental impacts based on a utility analysis. In their general guidelines on landfill mining, Krüger et al. (2016) recommend firstly identifying scenarios that are ecologically beneficial and then conducting an economic assessment.

Winterstetter et al. (2015) used UNFC to classify recovered materials from the historic Remo landfill site in Belgium and developed a first operative evaluation procedure including classification criteria, which was also applied by Krüse (2015) to the Hechingen landfill in Germany. Details can be found in Winterstetter (2016). Winterstetter et al. (2018) classify three potential landfill mining projects in Flanders with different levels of project maturity under UNFC to illustrate different settings for resource and land recovery (cf. Fig. 4). General decision making guidelines regarding the future management of old landfills are provided to decide whether a landfill site is to be mined or not, and under which framework conditions.

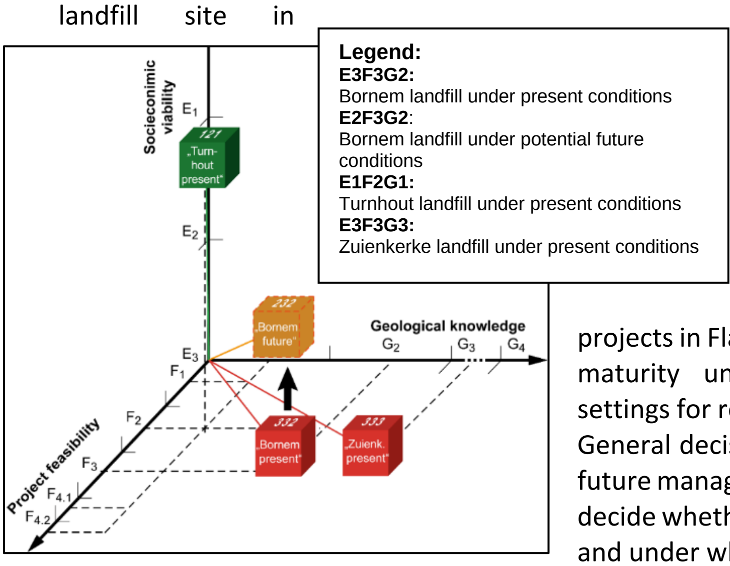


Fig. 4: Classification of the three landfill-mining projects under UNFC (Winterstetter et al., 2018).

Conclusions: Challenges and potentials of landfill mining

In the European Union there is a large number of historic landfills (150,000 – 500,000) with significant potential for raw materials to be recovered. It is necessary to develop sound inventories and a comprehensive long-term vision for the future management and restoration of these landfills, taking into account that many of them are situated in a (semi-)urban environment. A combined resource-recovery and remediation strategy, which will reduce future remediation costs, provides the double benefit of recovering materials and freeing-up valuable land in areas close to towns and cities. However, there are still a number of obstacles for the systematic mining of landfills.

An important barrier is a general **lack of empirical knowledge** from largescale real-life landfill-mining projects. To expose over-optimistic assumptions of ex-ante feasibility studies on landfill mining, Johansson et al. (2016) examined the market potential of excavated waste from a shredder landfill, sorted in an advanced recycling facility. While the metals could be sold, the other fractions (92%) were not accepted for incineration, as construction materials or not even for re-deposition. Krook et al. (2018) recommend using advanced approaches to model uncertainties related to landfill-mining projects.

Landfilled materials can be very heterogeneous, posing **technological challenges** when it comes to processing. To generate knowledge on the landfill's composition and the potentially extractable share of materials, data from samplings and test excavations together with data from logbooks on former landfilling activities (if existing) are relevant (e.g. Krook et al., 2012, Nispel, 2012). Hölzle (2017) provides advice on adapting the sample strategy to improve the prediction reliability of a landfill's composition. Efficiencies of recovery systems determine the extractable quantities of materials (Frändegård et al., 2015).They can vary widely, depending upon the techniques used, from simple shovel and sieves to sensor-based sorting technologies (Hölzle, 2010). An old landfill typically contains partially decomposed materials and a variety of non-recyclable fractions that can undermine the marketability of some of the landfilled materials (Prechthai et al., 2008, Wagner and Raymond, 2015, van der Zee et al., 2004, Johansson et al., 2016). Most of the landfill-mining projects performed so far focused on the recovery of the coarse material, while the fine fraction was re-landfilled without any treatment (Wanka et al., 2017). Developing cost-efficient separation and extraction methods to recover materials from the **fine fraction**, accounting for up to 50 % of an old landfill's body, is therefore of key importance (Bhatnagar et al., 2017, Quaghebeur et al., 2012).

Furthermore, it is vital to consider **site-specific conditions**. For instance, it must be decided whether to treat the combustible waste fraction on-site (and if so, what technology to use) or to export it to an already existing plant off-site (e.g. Ford et al., 2013). If there is a nearby incinerator willing to accept the waste at moderate gate fees, this solution might be more cost-efficient than building a new plant. In the case of smaller landfills to be mined, Fisher and Findlay (1995) suggest selecting a landfill as a hub site for other nearby landfills to host excavation and screening equipment, making use of economies of scales. Local residents' concerns often stem from increased noise, traffic volume and odor. It is therefore crucial to involve people and demonstrate the advantages of landfill mining (Craps and Sips, 2011).

The **role of governments and public authorities** is crucial for potential mining activities, especially in the pre-prospection phase, when it comes to mapping and collection of data on historic landfill sites, as done by OVAM. In Sweden, Johansson et al. (2017) found that materials contained in old landfills lack an institutional affiliation. Therefore they plead for common governmental structures for secondary resources and primary resources. As there is still **no legal framework for landfill mining**, individual permits and licenses are needed to advance a landfill mining project (e.g. Hermann et al., 2014, Ford et al., 2013).Due to technical and logistical complexities, potential landfill-mining projects are in many cases uneconomic, and only become viable through public interventions and subsidies.

Financial considerations can represent major barriers to landfill mining. An economic evaluation is a matter of specific stakeholder interests (e.g. Hermann et al., 2014, Winterstetter et al., 2015). In push situations, where a landfill has to be remediated, landfill mining can reduce costs for disposal and treatment (e.g. landfill gate fees). In pull situations, where a landfill can (but does not have to) be mined for land or resource recovery, legislation and policy can strongly influence the evaluation outcome, for instance by creating financial incentives (e.g. via subsidies or tax exemptions) or by imposing costly licensing procedures.
For a private investor, only direct financial effects are of interest, while non-monetary effects tend to be neglected unless they are monetized in form of subsidies (e.g. Bockreis and Knapp, 2011). Looking into mono-landfills, Wagner et al. (2015) demonstrate that ashfills can be profitably mined for metals without financial support from government. A public entity, in contrast to a private investor, is usually more interested in long-term effects, i.e. **societal and environmental aspects** (Graedel et al., 2012), such as the elimination of a source of local soil and ground and surface water pollution (e.g. Krook et al., 2012), the avoidance of long-term landfill emissions (e.g. Bernhard et al., 2011), the public's opinion (e.g. Ford et al., 2013), the creation of new jobs (e.g. Van Passel et al., 2013) and the potentially increasing value of surrounding land (e.g. Hölzle, 2010) after mining the landfill. Therefore, in addition to direct financial effects, non-monetary societal effects might also be monetized and included in the evaluation. Whether landfill mining increases or reduces climate impacts depends on the framework conditions. For a region more reliant on fossil fuels, combined with a landfill rich in organic waste and metals, and without a gas collection system, landfill mining would benefit the climate (Laner et al., 2016).

Each landfill-mining project has to be examined and evaluated on a case-by-case basis as a function of various possible project decisions, considering its local conditions and its systemic context. Winterstetter et al. (2018) conclude that classifying historic landfill sites under UNFC for potential mining helps to understand the **maturity of a project** and the developments or interventions needed to advance one project or another. This facilitates transparent communication and decision making for a number of different stakeholders. Uncertain and possibly missing data and information are prominently displayed on the three axes, such as the knowledge on composition and the recoverable share of materials, or the status of licensing procedures. Moreover, the **factor "time"** is acknowledged as key for progressively changing economic parameters such as policy, market environments and technological developments.

Conclusions:

Based on the results of the study, the following conclusions can be drawn:

- ► In the EU there is a large number of historic landfills with significant potential for raw materials to be recovered.
- ► An important barrier is a general lack of empirical knowledge from largescale real-life landfill-mining projects.
- ► Landfilled materials can be very heterogeneous, posing technological challenges when it comes to processing. Data from samplings and test excavations together with logbooks on former landfilling activities can help to generate knowledge on the landfill's composition and potentially extractable share of materials.
- ► Most of the landfill-mining projects performed so far focused on the recovery of the coarse material, while the fine fraction was re-landfilled without any treatment.
- ► The role of governments and public authorities is crucial, especially when it comes to mapping and providing data on historic landfill sites.
- ► Potential landfill-mining projects are in many cases subeconomic. In push situations, where a landfill has to be remediated, landfill mining can reduce costs for disposal and treatment (e.g. landfill gate fees). In pull situations, where a landfill can (but does not have to) be mined for land or resource recovery, legislation and policy can strongly influence the evaluation result, e.g. governmental subsidies can account for positive societal and environmental externalities.
- ► Classifying historic landfill sites under UNFC for potential mining helps to understand the maturity of a project and the developments or interventions needed to advance one project or another.

Recommentdation:

- ► Establish sound inventories and a comprehensive long-term vision for the future management and restoration of historic landfill sites.
- ► Devise a combined resource-recovery and remediation strategy to reduce future remediation costs and to provide the double benefit of recovering materials and freeing-up valuable land in areas close to towns and cities.
- ► Develop cost-efficient separation and extraction methods to recover materials from the fine fraction as a key priority..
- ► Evaluate each landfill-mining project on a case-by-case basis as a function of various possible project decisions, taking its local conditions and its systemic context into consideration. Advanced approaches to model uncertainties are key.
- ► Systematically classify historic landfill sites under UNFC to facilitate transparent communication and decision making for a number of different stakeholders for potential mining.

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