Assessing the economic potential of landfill mining: Review and recommendations

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Abstract

As landfill mining (LFM) gains public attention, systematic assessment of its economic potential is deemed necessary. The aim of this review is to critically analyze the usefulness and validity of previous economic assessments of LFM. Following the life cycle costing (LCC) framework, (i) the employed methods based on goal and scope, technical parameters and data inventory, and modelling choices were contrasted with respect to (ii) the synthesized main findings based on net profitability and economic performance drivers. Results showed that the selected studies (n=15) are mostly case study-specific and concluded that LFM has a weak economic potential, hinting at the importance of favorable market and regulation settings. However, several method issues are apparent as costs and revenues are accounted at different levels of aggregation, scope and scale—from process to sub-process level, from private to societal economics, and from laboratory to pilot-scale, respectively. Moreover, despite the inherent large uncertainties, more than half of the studies did not perform any uncertainty or sensitivity analyses posing validity issues. Consequently, this also limits the usefulness of results as individual case studies and as a collective, towards a generic understanding of LFM economics. Irrespective of case study-specific or generic aims, this review recommends that future assessments should be learning-oriented. That is, uncovering granular information about what builds up the net profitability of LFM, to be able to systematically determine promising paths for the development of cost-efficient projects.

Keywords

Economic assessment, life cycle costing, landfill mining, landfill management

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1. Introduction

The shift from a linear to a circular economy has influenced the perception of landfills as final waste deposits. Apart from minimizing waste flows through circular design, production, and use (Ellen MacArthur Foundation, 2013), keeping resources in the loop also extends through considering landfills as anthropogenic stocks (Cossu and Williams, 2015; Johansson et al., 2012; Jones et al., 2013; Krook and Baas, 2013). The potential of extracting these previously deposited resources is increasingly gaining public attention (Financial Times, 2018; World Economic Forum, 2017) and is commonly referred to as landfill mining (LFM).

Although LFM has been in practice for over 50 years, the motivation for performing it has changed over time (Hogland et al., 2010). As a concept, it has gradually progressed from an initial focus on local landfill management issues and pollution risks, to an increasing emphasis also on the recovery of deposited materials and energy resources (Krook et al., 2012). The most recent concept of LFM even targets a zero-waste approach by including innovative resource recovery technologies, as well as extending the typical process chain (i.e. excavation, separation, and thermal treatment) with more downstream residue valorization processes (Danthurebandara et al., 2015a; Hernández Parrodi et al., 2018; Jones et al., 2013). Furthermore, the motivation for such projects has been suggested to go beyond traditional economic and environmental impacts by also considering revitalization of ecosystem services (e.g. land-use services) and broader sustainability perspectives (Burlakovs et al., 2017). Although these changes in the LFM concept try to capture a wider societal potential, there is also an inevitable increase in complexity when it comes to both its realization and sustainability consequences.

At present, however, the recovery of materials and energy resources from landfills remains at the niche level or at a laboratory to pilot scale level (Johansson et al., 2012). This gives a hint on the compelling challenges for realizing such projects. Beyond the technological challenges, the implementation of LFM is also subject to the complex web of political, organizational, environmental, and economic considerations (Hermann et al., 2016; Johansson et al., 2017; Krook et al., 2015; Van Der Zee et al., 2004), which is common to emerging concepts (Hekkert et al., 2007). In Europe, although LFM failed to be integrated into the recent amendment of the EU Landfill Directive (1999/31/EC), its implementation is neither prohibited (European Parliament, 2018). In fact, several LFM research projects are being funded (European ELFM Consortium, 2019), especially in the view of landfills as secondary sources for critical metals (Løvik et al., 2018). Moreover, going beyond research and envisioning a full-scale and widespread LFM implementation, development of sustainable projects should be assured to attract the support of various stakeholders (Hermann et al., 2014; Krook et al., 2018a; Van Der Zee et al., 2004).

To enable structured assessments of various systems (e.g. products, services, projects and policies), different systems analysis tools (Ahlroth et al., 2011; Finnveden and Moberg, 2005) have been widely used addressing separated or integrated sustainability aspects (Guinée, 2016; Heijungs et al., 2013). These assessments can serve multiple purposes (Finnveden and Moberg, 2005; ISO, 2006a; Swarr et al., 2011). A common objective of such studies is to obtain an accurate result on the net performance of certain systems to support decisions on capital investments or for marketing reasons. In contrast to such decision-oriented purposes, systems analysis tools can also be used to obtain a more in-depth understanding of what builds up the net performance of the system in question. Such learning-oriented purposes are often used to identify strategies and measures to further improve the performance of various systems through optimization and design development. These are particularly useful in guiding the development of emerging concepts through early assessments, or so-called ex-ante assessments (Cucurachi et al., 2018; Fleischer et al., 2005; Wender et al., 2014).

Although most decisions related to real-life projects rely on the economic potential (Martinez-Sanchez et al., 2015), studies accounting for environmental impacts are more common within the field of waste management (Laurent et al., 2014a, 2014b). When it comes to LFM, however, several economic assessments were done in recent years (Krook et al., 2018b). However, there is not yet any systematic synthesis of their main findings regarding the feasibility and challenges for the implementation of such projects. In addition, acknowledging that LFM is still an emerging concept with large practical knowledge deficits (e.g. lack of actual data, setting of best estimates, and upscaling), inherent large assessment uncertainties are expected and have to be properly addressed as pointed out in ex-ante assessments (Clavreul et al., 2012; Hellweg and Milà i Canals, 2014; Martinez-Sanchez et al., 2015). Thus, a methodological review of what uncertainties were accounted for and how they were subsequently handled is deemed necessary to reveal the quality of the main findings.

This review aims to critically analyze previous economic assessments of LFM in terms of the usefulness and validity of their provided results. In doing so, we consider their individual objectives and employed methods as well as their collective contribution towards a generic understanding of the economic potential of LFM. Here, usefulness therefore both corresponds to the fulfilment of the intended objective of the assessment and the type of knowledge of relevance for LFM implementation that was addressed. The validity refers to whether the expected methodological rigor was followed according to certain standards (Swarr et al., 2011). Apart from that different objectives of economic assessments require different methodological approaches, assuring validity also qualifies the real usefulness of provided results. That is, the results may have perceived usefulness as presented in the studies, but the corresponding validity may indicate otherwise, revealing their real usefulness. The specific research aims are (i) to review the methods in terms of goal and scope definition, key technical parameters and data inventory, and key modelling choices, and (ii) to synthesize main findings in terms of net performance and economic performance drivers. In the end, this review reflects on the key methodological shortcomings and provides a recommendation to improve the usefulness and validity of future economic assessments to support further LFM development and implementation.

2. Methodology

2.1 Search and selection of studies

The identification of studies dealing with the economic assessment of LFM was performed through a literature search using multidisciplinary science databases such as Scopus (1960-present) and Web of Science (1975-present) with restriction in publication date until 2017. To be able to account for all possible synonymous terms, the following search strings were used (i) for economic assessment: (economic* OR financial OR cost* OR benefit* OR expense*) AND (assessment OR analysis OR feasibility OR evaluation OR impact*); and (ii) for LFM: "landfill mining". It should be noted that this search may not be exhaustive of all LFM studies as there is also proprietary grey literature by private companies and consultancy firms. In addition, it was assumed that possible search terms such as landfill reclamation and landfill rehabilitation meant LFM without special emphasis on resource recovery, which was beyond the scope of this review.

The selection procedure had a particular focus on studies available as full papers (e.g. journal articles, conference proceedings, technical reports) with quantitative economic assessments covering the entire LFM process chain. It was done to acknowledge that LFM is composed of an array of processes and technologies, and to allow for a balanced evaluation of the main findings and employed methods among the studies. In summary, a two-step studies search and selection procedure (Pinior et al., 2017) was used as illustrated in Figure 1.

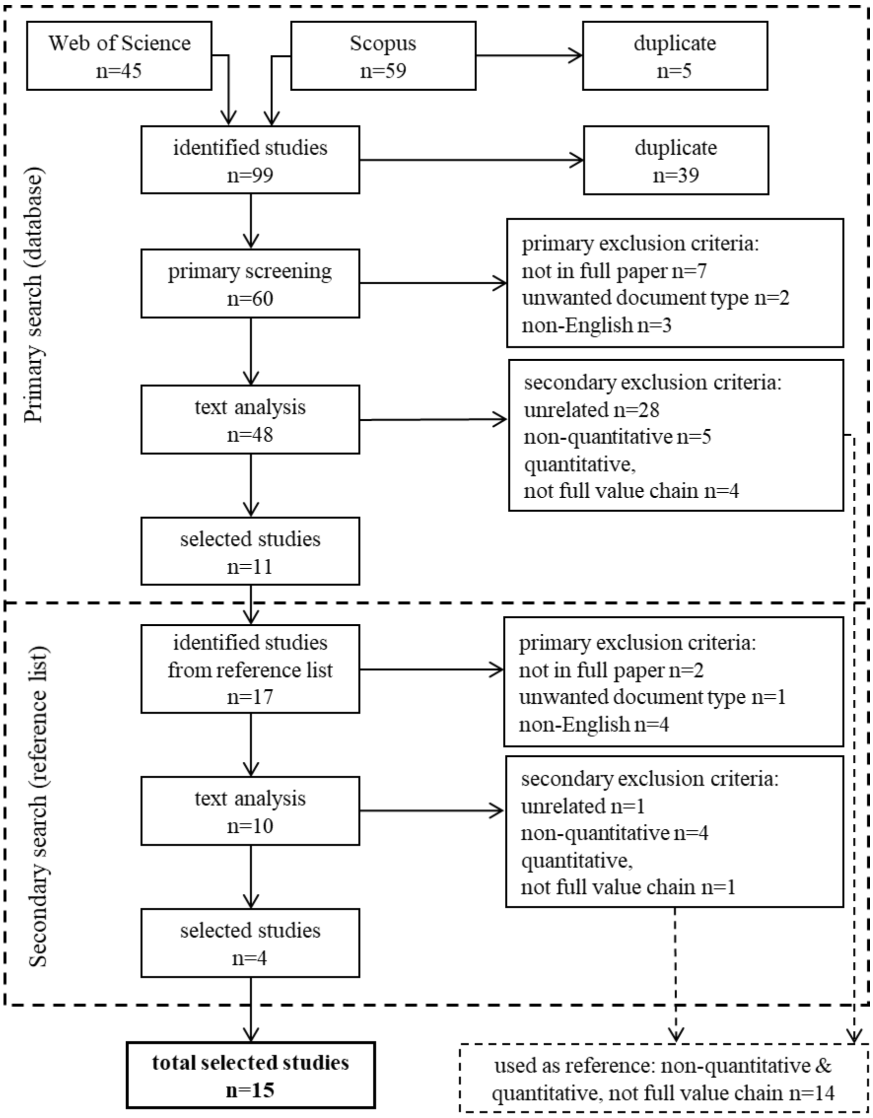

Figure 1. Flow diagram describing the literature search and selection procedure and the corresponding number of studies (n) for the review of economic assessment of landfill mining.

The first step involved the search for studies in the databases (primary search) while the second step retrieved studies from the reference lists of the previously selected studies (secondary search). Duplicate studies from the two databases were excluded. To narrow down the identified studies from databases and reference lists, preliminary exclusion was done based on the content of title and abstract with the following criteria: (i) unavailability in full paper such as conference abstracts, (ii) unwanted document type such as science magazines and conference reviews, and (iii) written in non-English language. Subsequently, secondary exclusion was done based on the content of the full paper with the following criteria: (iv) being unrelated, the paper was not about LFM or did not include any economic assessment at all; (v) being non-quantitative, these papers were typically about economic frameworks suggesting cost and benefit items; and (vi) being quantitative, the paper did not consider the entire LFM process chain. The studies in the latter two exclusion criteria (v-vi) were not completely excluded but were instead used for further exemplification and elaboration in the discussion part.

2.2 Analytical review approach

The overall analytical review method was divided into three main parts (Figure 2). The first two parts focused on the critical review of (i) methods and (ii) main findings. These parts aided to contextualize the provided results, thereby offering a better understanding of the study objectives and limitations prior to the subsequent (iii) assessment of usefulness and validity of their provided results. Categories for usefulness were introduced here in terms of the four types of questions that the studies can address. These questions were based on two dimensions, that is the type of analysis (*case study-specific* or *generic*) and the type of application (*decision-oriented* or *learning-oriented*) that the studies intend to fulfill. In the end, these categories were also used to discuss what type of usefulness is common in the selected studies, as well as what type is relevant to support further LFM development and implementation.

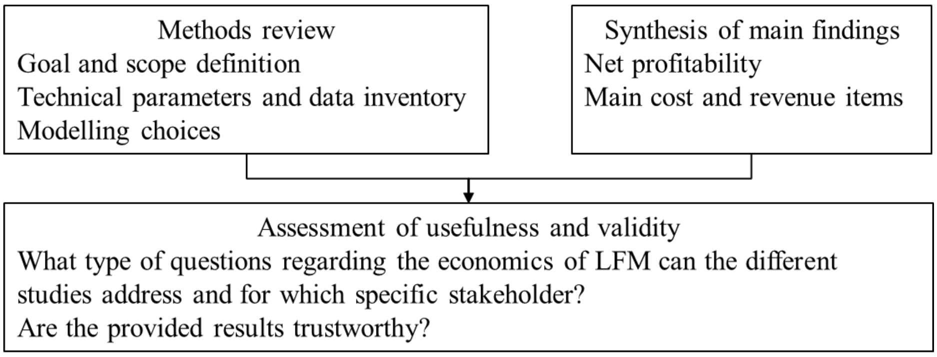

Figure 2. The overall analytical review approach.

2.2.1 Methods review

The methods review was based on several analytical criteria (Table 1) to determine the specific goals and corresponding methodological rigor of the studies. These criteria were selected and modified based on the main steps of the code of practice in life cycle costing (LCC by Swarr et al., 2011) and related reviews on systems analysis of waste management systems (Astrup et al., 2015; Laurent et al., 2014a, 2014b; Martinez-Sanchez et al., 2015). The main steps are goal and scope definition, technical parameters and data inventory, and modelling choices. By going through these main steps, the inherent uncertainties in assessing the economic performance of LFM were highlighted.

Goal and scope definition were analyzed to determine the type of analysis (*case study-specific* or *generic*) and the type of application (*decision-oriented* or *learning-oriented*) that the individual studies intended to fulfill, which corresponds to the perceived usefulness. The type of application refers to whether the main objective of the study was to obtain accurate results on the economic feasibility of LFM (decision-oriented) or if the emphasis was rather on assessing what factors build up such performance (learning-oriented), while the type of analysis instead refers to the explored settings for LFM and thus which scenarios were assessed in the studies. According to Laner et al. (2016), LFM could be realized in a wide range of different settings, and these variations can be classified at different levels such as site level (e.g. waste composition, landfill size, etc.), project level (e.g. technological and organizational set-up for separation, thermal treatment, and/or further residue valorization), and system level (e.g. surrounding policy and market conditions). Here, these different levels were used to categorize which scenario variations have been explored in the economic assessments of LFM, both for case specific and more generic studies. For a more comprehensive description of the assessed LFM scenarios, the corresponding geographical, technological and temporal scopes were also classified as well as the applied economic perspective (i.e. conventional LCC, environmental LCC and social LCC according to Swarr et al., 2011).

To investigate the technical specificity and corresponding data quality, descriptions of employed technical parameters and data inventories were analyzed for each LFM value chain process (i.e. separation, thermal treatment, and residue management), also including landfill settings and waste composition. The respective data sources were noted in terms of whether the studies used primary data, secondary data, mixed primary and secondary data, or were not specified at all. Specific modelling choices were analyzed in terms of the considered reference scenario (incumbent landfill management alternative instead of LFM), externalities (environmental and social), marketability and market prices of recovered resources, and economic indicator (direct or discounted cash flow analysis). In addition, the handling of uncertainties was also enumerated in terms of the type of employed uncertainty and sensitivity analyses. Parametric uncertainty analysis accounts for the uncertainties of input parameters (range of values instead of an absolute value per parameter), which gives additional information on the confidence level of the provided results. Sensitivity analysis, on the other hand, accounts for the robustness of results when input parameters are changed either one at a time as in local sensitivity analysis, or simultaneously as in global sensitivity analysis (Saltelli et al., 2008).

Table 1. Analysis criteria addressed in this review. The classification under each analysis criterion is listed and described (in *italics*) when deemed necessary. “Mixed” refers to either comparison or combination of preceding stated classification.

Analysis Criteria	Classification
Goal & scope definition	
Type of application	Decision-oriented, learning-oriented
Type of analysis	Case study-specific: single-subject assessment *(case study only)*, comparative assessment *(case study + scenarios of varying conditions at project and/or system level)* Generic: *(case study + scenarios of varying conditions at site, project and system levels)*
Geographical scope	Continent, country, region, multiple sites, single site
Technological scope	Separation: conventional, advanced, mixed *(depending on the number of secondary materials recovered)* Thermal treatment: incineration, plasma gasification, mixed, internal/external Residue management: re-landfill (internal/external), metal recovery, construction aggregates Reference scenario, *avoided costs if LFM is not performed:* do nothing, aftercare, aftercare with energy recovery
Temporal scope	Project duration *corresponds to total process capacity (Mg/yr)*
Economic perspective	Conventional LCC (C-LCC) *purely financial,* environmental LCC (E-LCC) *accounts environmental costs/savings,* social LCC (S-LCC) *accounts broader societal costs/benefits*
Technical parameters and data inventory	
Landfill settings and waste composition	Type: municipal solid waste (MSW), industrial waste (IW), mix MSW-IW, mixed Size: Small (<1 Mt), medium (1 to <10 Mt), large (>10 Mt) Composition: Material fraction, material fraction + chemical composition, not specified Data source: primary, secondary, mixed
Separation	*Separation efficiency* Data source: primary, secondary, mixed
Thermal treatment	*Energy efficiency* Data source: primary, secondary, mixed
Residue management	*Amount of secondary waste/intermediary materials produced* Data source: primary, secondary, mixed
Modelling choices	
Reference scenario	*Length of reference scenario implementation*
Externalities	*Valuation of cost/benefit items for E-LCC and S-LCC*
Marketability and market prices	Materials (ferrous metals, nonferrous metals, construction aggregates, RDF, valorized residues, etc.), energy (electricity, heat), land, landfill void space
Economic indicator	Direct cash flow, discounted cash flow (*accounts time-value of money i.e. lower value for future revenues and avoided costs)*
Uncertainty & sensitivity analysis	Parametric uncertainty analysis, local sensitivity analysis, global sensitivity analysis, mixed, none

2.2.2 Synthesis of main findings

The main findings were assessed in terms of the reported net performance and main economic drivers. For net performance, apart from being net profitable or not, potentially profitable cases were noted if at least one of the considered scenarios generated a positive economic result. Main economic drivers referred to the cost and revenue items with the highest values. Cost items were noted as expenditures at each LFM process (i.e. excavation, separation, thermal treatment, transportation, and residue disposal), while revenue items were categorized into direct revenues from process outputs (e.g. material sales, energy sales and value of reclaimed land or landfill void space) and indirect revenues caused by avoided aftercare costs or governmental support (e.g. tax breaks or other policy instruments internalizing environmental externalities).

2.2.3 Assessment of usefulness and validity

From the goal and scope definitions, the perceived usefulness of the reviewed studies was categorized based on the type of analysis (*case study-specific* or *generic*) and the type of application (*decision-oriented* or *learning-oriented*). Here, these two dimensions were taken further and used as an analytical framework for assessing both the usefulness and validity of the synthesized main findings (Figure 3). Usefulness was described through enumerating the type of questions the studies could answer, while validity was described through the specific methodological rigor focusing on the extent of scenario development and employed uncertainty and sensitivity analyses, apart from other possible general issues such as transparency in data inventories and modelling choices. This was done acknowledging the emerging character of LFM with inherent large uncertainties that must be handled.

Categories A (Is it economically feasible to mine the specific landfill in question?) and B (How can we improve the economic performance of the specific LFM project?) relate to the types of usefulness on the project level, concerning a specific case and a specific LFM practitioner. Categories C (Which landfills are suitable for mining, and which projects deserve political support due to clear societal benefits?) and D (How can we develop a profitable LFM project and facilitate its implementation through policy and market interventions?) relate to broader types usefulness, related to policy and to research for further LFM development, respectively. Methodologically, it follows that the scenario development for both Categories A and B are limited to variation at the project level (e.g. technological and organizational set-up for separation, thermal treatment, and/or further residue valorization), while for Categories C and D, they extend to also consider variation at the site level (e.g. waste composition, landfill size, etc.) and system level (e.g. surrounding policy and market conditions). Regarding the employed sensitivity analysis, local sensitivity analysis is proven to be inefficient in revealing the underlying interactions among the parameters, unlike the global sensitivity analysis (Ferretti et al., 2016; Saltelli and Annoni, 2010) that is particularly relevant for the *learning-oriented* type of application. Hence, local sensitivity analysis is at least expected for Categories A and C as they only intend to know the net performance, while global sensitivity analysis is expected for Categories B and D (“How” questions) as they are after the principles of performance. Lastly, to handle the inherent parametric uncertainties, parametric uncertainty analysis is expected for all types of usefulness to properly account for the variation of data values and the extent of their effect to the spread of the study results.

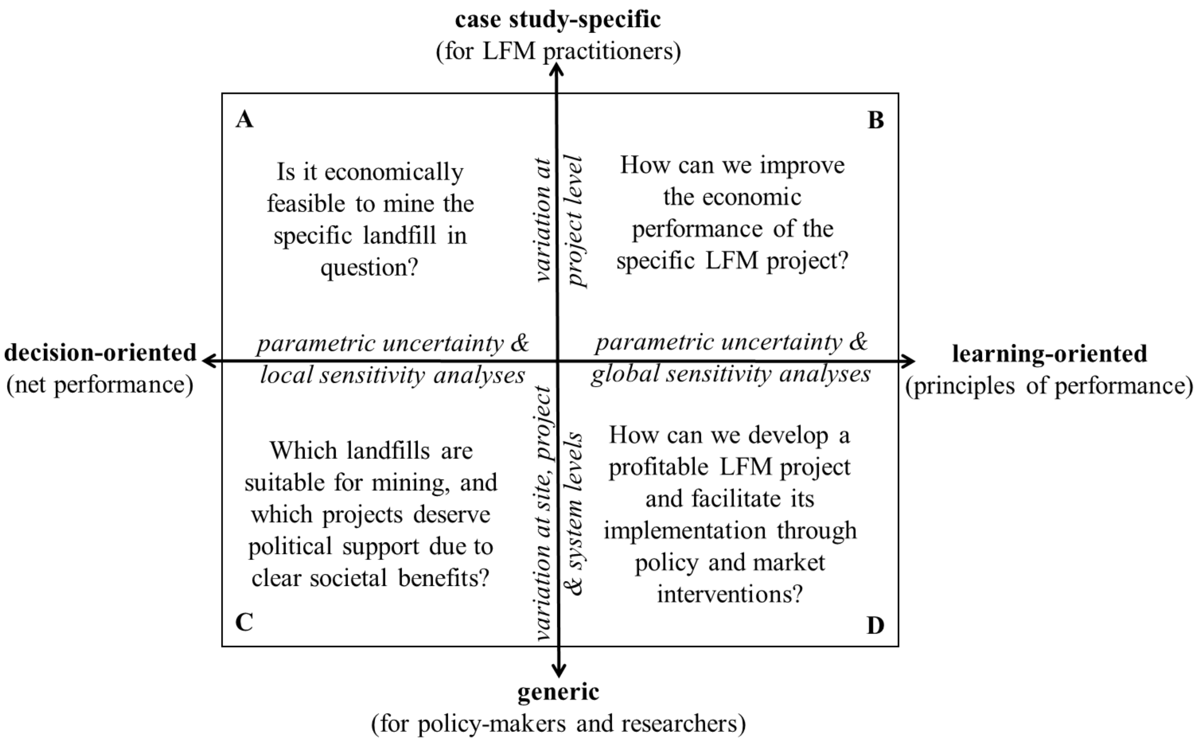

Figure 3. Analytical framework for assessing the usefulness and validity of the selected studies. Four categories of usefulness and related methodological requirements were developed based on two dimensions: the type of analysis (*case study-specific* or *generic*) and the type of application (*decision-oriented* or *learning-oriented*).

This analytical framework helped in revealing the real usefulness of the provided results by contrasting the perceived usefulness with the corresponding validity. For instance, issues on validity due to unsatisfactory methodological rigor directly led to problematic real usefulness. Furthermore, beyond the reviewed studies, this analytical framework was utilized to discuss which questions are relevant to be addressed in contrast to key research challenges identified in recent LFM studies and related ex-ante assessments, in general.

3. Results and Discussion

3.1 Goal and scope definition

In total, this review includes 15 studies (see Appendix). Most of them involve specific LFM case studies with a decision-oriented type of economic analysis. The key objective of these studies is thus to assess the net performance of a specific LFM project, often by accounting for a limited number of scenario alternatives. Several studies (n=6), however, only assess the economic outcome of a single scenario for realizing a specific LFM project. The extent of assessed LFM processes and explored scenario alternatives in all of the reviewed studies are shown in Figure 4.

At the site level, variation in waste composition is seldom accounted for (n=1) in the explored scenarios, since most of the studies address a specific landfill. Different waste compositions are considered, such as municipal solid waste (MSW, n=6), industrial waste (IW, n=3) and mixed MSW and IW (MSW-IW, n=5). For the same reason, variation in system-level conditions (n=3) is also seldom investigated. The explored system-level variation is limited to inclusion/exclusion of re-landfilling tax, availability/unavailability of the market for recovered materials, and varying the required length of time of the reference scenario. The reference scenario is classified at both site and system level variation together with land resources. The former depends on both the regulatory requirements as well as the type of landfill waste composition (do nothing n=1, aftercare n=6, aftercare with energy recovery n=3), while the latter depends on both market conditions and the location of the landfill site (land recovery n=5, landfill void space recovery n=4, mixed n=4). Not all of the studies accounted for these two aspects, hence underestimating the economic performance of LFM by missing possible revenue items.

Variation at the project level is commonly investigated (n=8), and is done in different ways in individual studies. For the separation process, investigated technologies include a conventional separation process (n=5) that recovers metals and construction aggregates, or an advanced separation process (n=7) that additionally recovers combustibles (including refused derived fuel or RDF) and glass. A comparison between these separation technologies is also performed in the rest of the studies (n=3). For the thermal treatment process, investigated technologies include incineration (n=3), gasification (n=3), or the comparison between the two. Apart from these variations in technological set-up, variation in organizational set-up (n=3) is also investigated, which means the thermal treatment process is considered either internal or external to the LFM project. Similarly, variation in organizational set-up (n=5) is investigated for the disposal of separation residue, while the rest have individually considered either internal (n=6) or external (n=4) disposal. For thermal treatment residue, apart from the disposal in hazardous landfill (n=3), further valorization such as metal recovery from incineration bottom ash (n=1) and construction aggregates (n=2) from plasma gasification slag is also considered. It is notable that fewer studies investigated more downstream processes starting from thermal treatment, which is reflective of the emerging character of LFM.

Variation in scope is also observed geographically, technologically, and temporally. Regarding the geographical scope, a single landfill site (n=9) is typically considered, while some also covered a wider scope in terms of national (n=3) such as Scotland, Sweden, and Greece; regional (n=2) such as Flanders in Belgium and Styria in Austria; and also continental (n=1) such as entire Europe. It is notable that most of the selected studies come from Europe (n=12), and only a few come from Asia (n=2) and North America (n=1). The countries where these case studies are located are categorized as nations with high-income economies (World Bank, 2016), with more stringent standards expected for landfill management. This situates LFM to having a promising business case due to a favorable market (i.e. higher material prices) and aftercare obligations (i.e. higher avoided costs). Regarding the temporal scope, most studies considered the specific LFM project duration. As different case studies are considered, project duration depends on landfill settings, processing capacity, and length of landfill aftercare. Regarding the economic perspective, most of the studies were assessed based on conventional LCC (n=8), while the rest were based on environmental LCC (n=5) and social LCC (n=2). This highlights that most of the studies were intended for LFM practitioners with a private economic view. Although a broader sustainability consideration has been suggested, this also implies additional complexity in terms of the valuation of external cost and revenue items (Burlakovs et al., 2017).

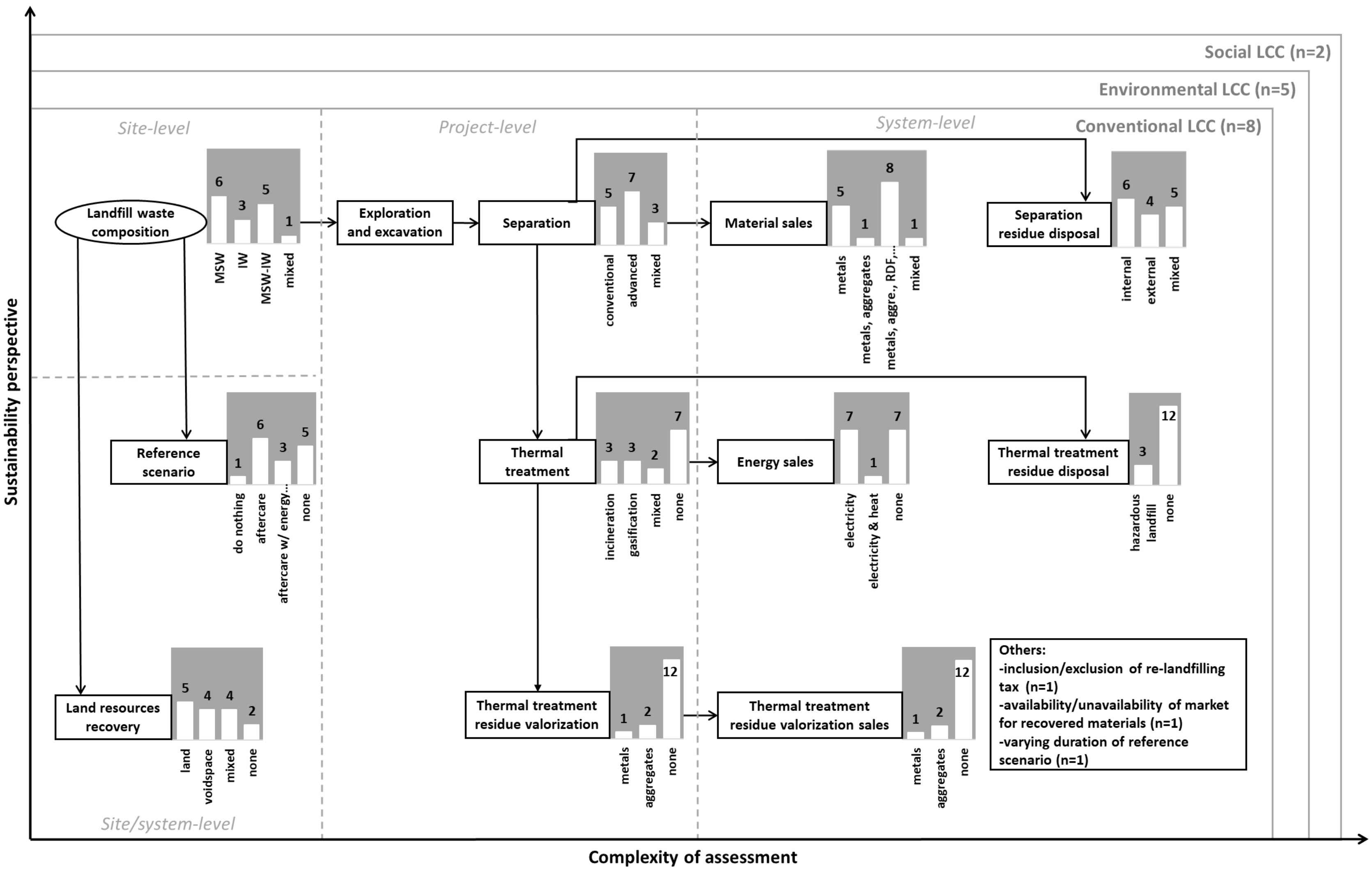

Figure 4. LFM processes included in the selected studies (n=15), with their respective variations categorized at different levels such as site, project and system (in dashed lines). The complexity of economic assessment is expected with the extended technological scope and broader sustainability perspective. “Mixed” refers to either comparison or combination of preceding stated classifications, while “none” refers to studies which excluded, or implicitly included, such processes.

3.2 Key technical parameters and data inventory

3.2.1 Landfill settings and waste composition

In terms of landfill settings, studies consider varying landfill sizes, including small (<1 Mt, n=6), medium (1-10 Mt, n=5) and large (>10Mt, n=4) sites. The case studies are typically described in terms of the mass of landfill waste and seldom in terms of more specific information such as area, depth, and density. Without such information, the effect of excavation and internal transport logistics to the economic performance of LFM may be overlooked (Hogland et al., 2018; Hölzle, 2019). In terms of waste composition, it is typically presented by material fractions (e.g. metals, paper, wood, aggregates, etc.) and seldom by chemical composition. Consequently, it makes it difficult to qualify the material outputs as to whether they satisfy standard material quality requirements for the proceeding processes, may it be thermal treatment, material sales or even disposal.

Most of the studies use primary sources (n=9), and the rest use secondary (n=4) and mixed sources (n=2). Only a few of the primary sources are based on full-scale excavation (n=2), and the rest (n=7) are based on logbooks, preliminary sampling campaigns, and pilot-scale excavation. The apparent use of primary sources corresponds to case-specific studies, while the use of secondary and mixed sources corresponds to either hypothetical case studies or studies with a wider geographical scope. The average of waste compositions from different landfills is used to represent continental (Van Vossen and Prent, 2011), national (Ford et al., 2013; Frändegård et al., 2015), and regional levels (Damigos et al., 2016; Danthurebandara et al., 2015b; Van Passel et al., 2013). Clearly, there is a large uncertainty to be accounted for, both within and among reported waste compositions (Hernandez Parrodi et al., 2018; Hogland et al., 2018; Hölzle, 2019).

3.2.2 Separation

Specifics of the separation process are typically presented through process flow diagrams. However, the corresponding separation efficiencies and the underlying machine specifics are seldom stated. Separation efficiencies are from 40% to 100% of the total waste composition, with most studies adopting the higher end. In addition, most of the primary sources are based on laboratory-scale separation. For hypothetical cases, secondary sources are often not closely related to the studied case but rather are obtained from industry estimates for fresh MSW processing. Similarly, secondary costs data are directly adopted from different geographical and temporal contexts. To assure representativeness to the case study of interest, these data have to be harmonized. Temporal cost harmonization can be done through a financial approach to remove the effect of inflation using indicators such as a gross domestic product deflator and consumer price index, while geographical cost harmonization can be achieved through purchasing power parity (World Bank, 2014).

3.2.3 Thermal treatment

Irrespective of the type of thermal treatment technology, energy efficiencies are reported from 25% to 30%, accounting for optimum performance. For this process, the considered RDF quality requirement in terms of input heating value is from 16 to 20 MJ/kg, which corresponds to high-quality input materials (Bosmans et al., 2013). Both of these specifics, however, are often based on secondary sources, either from existing pilot plants for plasma gasification or large-scale plants for incineration. Such plants use other process input such as fresh municipal solid waste that is not representative of landfill waste. For the secondary cost data, as previously stated, temporal and geographical cost harmonization is not performed.

3.2.4 Residue management

The amount of residue from the separation process is not clearly stated, despite the fact that about 30% to 45% of the total excavated waste ends up as residues (Hernandez Parrodi et al., 2018). A similar issue on material flow transparency is observed for the valorization of residue from thermal treatment. Specifically, separation efficiency and market quality requirements are seldom mentioned for the metal recovery, and construction aggregates production from incineration and plasma gasification processes, respectively. In addition, information about the hazardous waste fraction is seldom noted that could significantly affect the total re-landfilling costs. Hazardous waste is significantly more expensive (100 to 200 Euro/ton) than its non-hazardous counterpart (10-50 Euro/ton).

3.3 Key modelling choices

3.3.1 Reference scenario

For the potential avoided costs, a reference scenario is stated acknowledging that there is an incumbent landfill management alternative instead of LFM. However, a significant number of studies (n=5) do not mention any reference scenario. However, for the ones that are mentioned, specific technical requirements and costs of aftercare vary widely depending on national or regional regulatory requirements. For example, landfill cover is commonly required but not in the Netherlands (Van Vossen and Prent, 2011) and Denmark (Rosendal, 2015), or none is required at all (do nothing) as in Sri Lanka (Danthurebandara et al., 2015b). Moreover, the model for leachate production and landfill gas emission is seldom specified, which directly affects the number of emissions and consequent treatment costs. Also, the length of the aftercare period varies from 25 to 100 years, with 30 years as the most commonly used. This uncertainty is primarily due to the vague description in Article 12d of the EU Landfill Directive (1999/31/EC), which states that aftercare duration halts when "the competent authorities consider the landfill likely to cause a hazard to the environment".

3.3.2 Externalities

Some studies (n=5) internalize environmental benefits, which are limited to avoided climate impact in terms of carbon dioxide equivalent (CO_2 eq.). Different databases are used to quantify process-related environmental emissions (subsequently converted to CO_2 eq.), such as Bilan Carbone™ (Association Bilan Carbone, 2007), PROBAS (German Federal Environmental Agency, 2013), and EcoInvent v2.2 (Ecoinvent, 2010). According to the ILCD Handbook (European Commission-Joint Research Center, 2010), the selection of database must be based on completeness, representativeness and up-to-date datasets, however none of the studies justified such choices. Regarding the monetary valuation, CO_2 eq. savings are valuated differently showing wide variation in prices such as the hypothetical carbon tax (10 Euro/ton, Winterstetter et al., 2015), the social cost of carbon (20 Euro/ton, Tol, 2008), and the EU Emission Trading Scheme (40 Euro/ton, EU, 2007). Even wider variation is notable for the prices of incentives for renewable energy production such as the green certificate (108-117 Euro/MWh) in Belgium (Danthurebandara et al., 2015c; Van Passel et al., 2013) and the renewable obligation certificate (5-42 Euro/MWh) in Scotland (Ford et al., 2013).

3.3.3 Marketability and market prices

Most of the studies (n=13) assume the marketability of materials that they plan to recover and valorize. However, specific market quality requirements are seldom mentioned, and that all recovered and valorized materials are assumed to be saleable. There are also some studies that account for marketability and market price though preliminary discussions with potential buyers. Examples include plantation owners for the soil residues as fertilizers (Zhou et al., 2015) and construction companies for plasma gasification residue as construction aggregates (Danthurebandara et al., 2015c; Van Passel et al., 2013). However, there are also studies that have contradictory assumptions. For example, instead of the production of construction aggregates, Winterstetter et al. (2015) considered the re-landfilling of plasma gasification residue, arguing that such a valorization process has not gone beyond laboratory tests. Moreover, none of the studies consider the broader market dynamics of supply and demand upon the introduction of exhumed materials to the market competing with primary sourced materials.

3.3.4 Economic indicator

Studies perform either direct cash flow (n=7) or discounted cash flow (n=8) analysis. For the former, it follows that the studies consider small landfill size with high LFM processing capacity, leading to a project duration of about a year. For the latter, project duration is much longer, from 3 to 20 years, in which the time value of money has to be considered (Brealy et al., 2011). The discount rate varies from 3% to 15%, depending on if public or private financing is considered, respectively. In essence, the project duration and type of financing constitute a downplaying of the value of future revenues and avoided costs, in comparison to the initial investments accounting for higher risks.

3.3.5 Uncertainty/sensitivity analysis

From the previous sections, several possible variations are discussed along the LFM value chain processes (i.e. separation, thermal treatment and residue management), as well as in other aspects such as waste composition, externalities and some general assumptions (Table 2). These correspond to the uncertainties that occur in scenario building (scenario uncertainties) and data gathering (parameter uncertainties), which have to be properly addressed for all systems analyses, in general (Clavreul et al., 2012; Huijbregts et al., 2003).

Table 2. Overview of uncertainties in the economic assessment of landfill mining.

	General	Waste composition	Separation	Thermal treatment	Further valorization/ residue management	Externalities
Scenario uncertainties	- Inclusion/ exclusion of reference scenario	- Type of landfill waste -Inclusion/ exclusion of hazardous waste	- Technology choice (conventional to advanced technology) - Internal or external organizational arrangement - Marketability of secondary materials and energy (substitution: full, partial, no market)			- Inclusion/exclusion of environmental and social costs and benefits/revenues
Parameter uncertainties	- Origin of costs/price data (where and when) - Amount of leachate and landfill gas - Discount rate	- Amount in terms of waste fraction or chemical composition	- Separation efficiencies - Material market prices	- Energy recovery efficiencies - Energy market prices	- Material market prices	- Values of environmental and social costs and benefits/revenues

Despite the abovementioned uncertainties, more than half of the studies (n=8) have not performed any parametric uncertainty or sensitivity analyses, of which the majority (n=6) have not considered even any scenario alternatives but instead just a single scenario for a specific LFM project. For the rest of the studies, sensitivity analysis is more commonly performed, that is, either alone (n=2) or in combination with uncertainty analysis (n=5). About the same share of studies have performed either global sensitivity analysis (n=4) and local sensitivity analysis (n=3). This uncommon practice of performing uncertainty and sensitivity analyses indicates that the majority of the studies lack information on the robustness of their provided results, hence posing questionable usefulness and validity of fulfilling their intended objectives. Poor uncertainty management may lead to faulty decision support with missing risks information that is related to the net performance of LFM, as well as misunderstanding the principles of performance of LFM with the lack of systematic identification of its main economic drivers.

3.4 Synthesis of main findings

Despite the unique considerations of individual studies, it can be generalized that LFM is a challenging business venture based on the collective net economic performances. Only a few of the studies are profitable (n=3), while most are not (n=7); see Appendix for individual study results. Converting the results per ton of excavated waste, net profit ranges from +€3 to +€49 while net deficit ranges from -€3 to -€91. It is noted, however, that for some studies (n=2), actual values are not explicitly stated. This may be intended due to proprietary reasons, but at least, net profitability (positive or negative) can be inferred. The remaining studies show potential profitability (n=5) that ranges from a deficit of -€91 to a profit of +€33. These studies individually explore selected circumstances on how certain case studies can be profitable through scenario analysis. They hinted at the importance of different variations at the project level (maximization of material separation, internalization of separation and thermal treatment processes, etc.) and/or system level (lifting of the re-landfilling tax, a longer aftercare period, a higher value of land, a higher market price for materials, etc.). However, these insights remain case study-specific, as some variations may even be contradictory leading to either net profit or net deficit. For example, the costs for maximization of material separation may not be compensated for by subsequent material sales, which is also intuitively dependent on the amount of valuable materials in the considered landfill waste composition.

For more granular insights, the main economic drivers that largely contributed to the net performance are derived. However, economic drivers are accounted for at different levels of aggregation among the studies. As previously stated in key technical parameters, this is accountable to the differences in the level of specificity and complexity of the employed method or the limitations due to proprietary reasons. Thus, the collective determination of the main economic drivers is limited to the aggregated cost and revenue items. To show the significance of these cost and revenue items, its frequency of reoccurrence was quantified, as shown in Figure 5. For the main cost items, separation process is the most frequently mentioned (n=10), followed by transportation (n=8), thermal treatment (n=8), secondary waste disposal (n=7), and excavation (including exploration) (n=6). For the main revenue items, material sales is the most frequently mentioned (n=12), followed by energy sales (n=7), value of recovered land (n=7), value of landfill void space (n=4), externalities (n=3), and avoided aftercare (n=1).

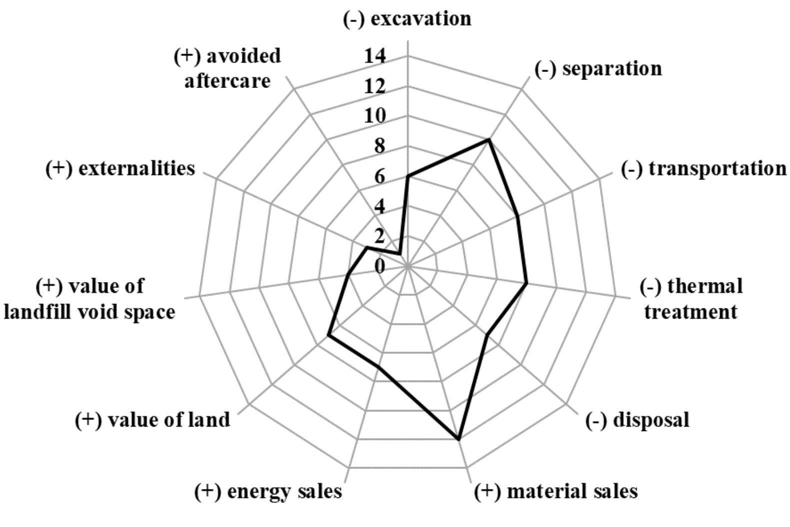

Figure 5. Simple synthesis of main economic performance drivers of LFM in terms of the top three main cost (-) and revenue (+) items as frequently mentioned in selected studies (n=15). Note: (i) the figure displays the number of times that a driver is mentioned, and this does not reflect the importance (in Euros) of the driver, and (ii) this only serves as hints with respect to a more generic understanding.

However, just like the superficially considered important variations for potential profitability, these main cost and revenue items only serve as hints with respect to a more generic understanding. Considering the differences in scope and modelling choices, some studies excluded thermal treatment, avoided aftercare, value of landfill void space, and/or value of land. Moreover, as most studies are case study-specific, site and system-level variations were unaccounted for, leaving out their possibility of being the main drivers. Hence, there is insufficient knowledge about the overall economic potential of LFM that can be derived from this simple synthesis of the main findings. Consequently, there is a possibility of stagnation of LFM research and implementation, acknowledging that LFM is an economically challenging business venture, yet current studies do not provide transferrable conclusions for its improvement, in general.

3.5 Usefulness and validity of selected studies and recommendations for future assessments

Most of the studies (n=6) are categorized as *case study-specific* and *decision-oriented* (Category A, Figure 6), which means that they primarily provide estimates on the economic feasibility of conducting a planned LFM project. Although such knowledge is essential for supporting decisions on project investments, the validity of the obtained results from most of these studies could actually be largely questioned, due to the lack of performed parametric uncertainty and local sensitivity analyses. That is despite the scenario uncertainties regarding the multiple possibilities of technological and organizational set-ups, as well as the parametric uncertainties, especially with the typical use of secondary data. These inherent large uncertainties are inevitable for emerging concepts with limited practical implementations but are left unaccounted for, and hence, its effect on the robustness of results remains unknown. As a consequence, the revealed real usefulness of the studies relates to that LFM practitioners are prone to making decisions based on results with implicit risks information. Hence, it is suggested to account for the aforementioned uncertainties through parametric uncertainty and local sensitivity analyses. For instance, instead of a single value result, a range of values can be generated that corresponds to the explicit risks information. In addition, studies could provide knowledge on the main economic drivers of the LFM projects in question, although limited and superficial. That is typically through the main cost and revenue items with the highest absolute contribution to the results, or through local sensitivity analysis investigating the effect of one-at-a-time variation of subjectively chosen parameters to the overall economic performance.

An in-depth and systematic analysis of the main economic drivers and their interrelations is expected for studies that are *case study-specific* and *learning-oriented* (Category B). Several studies (n=5) fall under this category, which means that they aim to provide improvement opportunities for the economic performance of the LFM project. The provided results addressed parametric uncertainties, and the main economic drivers are systematically determined through global sensitivity analysis. However, the studies failed to reveal the interrelations among the main economic drivers. The lack of such knowledge makes it difficult to identify potential strategies and measures to improve economic performance. As a consequence, the real usefulness is limited to just knowing the economic feasibility of the LFM project (as in Category A), and the provided results may lead to unhelpful recommendations. For example, if the main economic driver is the market price of the recovered metals, the corresponding improvement strategy is not limited to just making it expensive. If so, the resulting breakeven market price becomes unrealistically high, leading to the misinterpretation that such an LFM project has no possibility to at least reach breakeven, if not net profitability. Apart from the market price of the recovered metals, the increase in revenues from metal sales is also intuitively interrelated to other parameters, such as the employed separation technology. The LFM practitioner is not limited to waiting for the market price to increase, but they could also opt for separation technology with better efficiencies, considering that the corresponding costs could be compensated for by the revenues. One way to reveal such interrelations is by performing both first-order and higher-order variance-based global sensitivity analyses, covering both direct and indirect effects of the economic drivers to the net performance, respectively (Saltelli et al., 2010). Although done for a *generic* type of application, both sensitivity analyses are used by Laner et al. (2016) to systematically identify the main drivers and their interrelations to understand what builds up the climate impact of LFM. For a *case study-specific* type of application and concerning certain LFM practitioners, this direction for future studies, from Category A to Category B, is recommended to have an in-depth understanding of the respective cases and to guide in strategic project design and development.

As a *case study-specific* type of application is common among the selected studies, the knowledge about main economic drivers and the corresponding improvement strategies at large remain scattered, and obtaining widely accepted conclusions by mere synthesis (as in Section 3.4) is invalid. From a research perspective, a *case study-specific* type of application cannot provide any novel insights, which may limit the role of performing economic assessments towards the widespread and full-scale implementation of LFM in the future. This lack of a generic approach is not just observed for LFM, but also in waste management systems in general (Laurent et al., 2014a, 2014b).

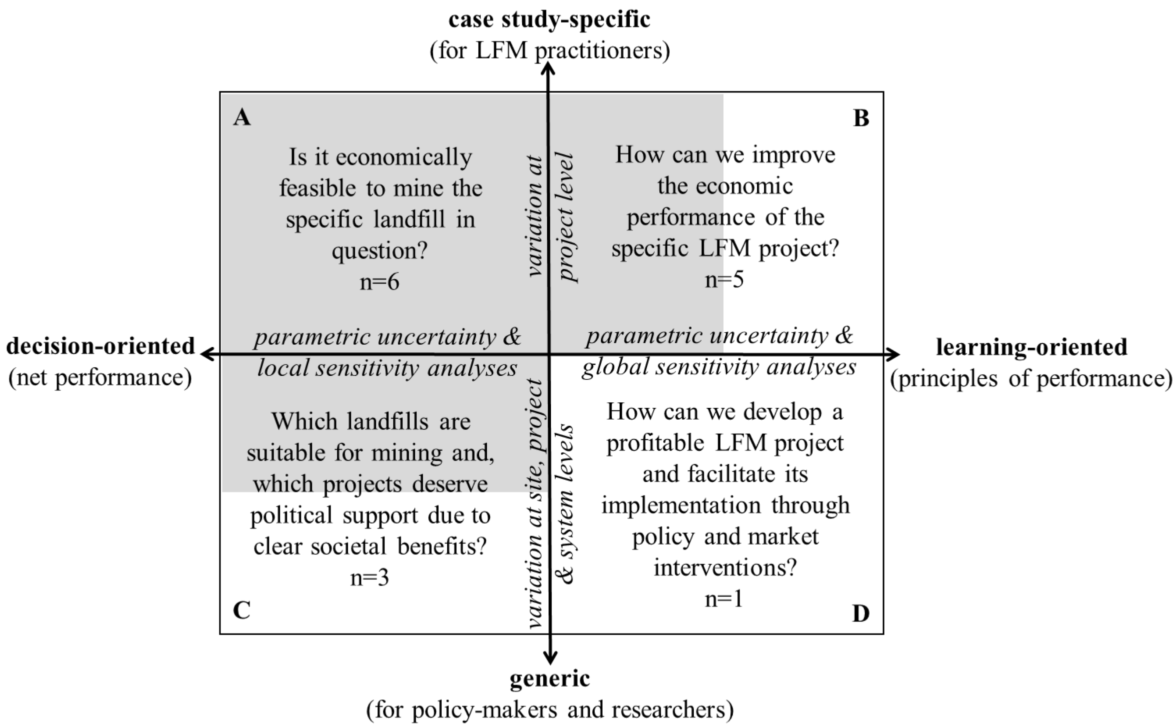

Figure 6. The categorization of the selected studies (n=15) in terms of perceived usefulness. However, with the arguable validity of provided results, the real usefulness is only partially fulfilled, if not failed (shaded region).

There are few studies (n=3) that covered wider geographical scope in terms of country (e.g. Scotland, Sweden, Greece) and continent (e.g. Europe), so they can be categorized as *generic* and *decision-oriented* (Category C) concerning policy-makers, among others. Relative to categories A and B, additional variation in the site and system levels is accounted for in the scenario development. But still, the provided results only refer to the economic feasibility of a limited number of scenarios. As a consequence, these results could give limited understanding in terms of what type of landfill composition to prioritize as well as what kind of political support to implement, which could enable a profitable LFM project. Similar validity issues are observed due to insufficient parametric uncertainty and local sensitivity analyses. With multiple expected variations, uncertainties further propagate, and hence, proper handling is required. In addition, the representativeness of used data is questionable due to the direct adoption of values from related studies and industries. Hence, the resulting *generic* conclusions are invalid, providing decision support for policy-makers with implicit risks information. For instance, a single project set-up based on one LFM pilot project is used to represent wider geographical scope, and worse, the project set-up is directly adopted from the processing of fresh municipal solid waste and not of landfill waste. Apart from the transparency issues regarding the sources of data, addressing data representativeness by assigning wider parameter uncertainty could be done to account for such practical knowledge deficit.

Similar validity issues are observed from the single study that even aimed to generate generic conclusions and recommendations for the improved economic feasibility of LFM in Greece, which can be categorized as *generic* and *learning-oriented* (Category D). This category is yet to be explored, and hence this review recommends this direction for the future economic assessment of LFM. Especially due to the emerging character of LFM, more explorative assessment is deemed necessary to account for multiple paths for development and consequently be guided on the key LFM challenges and potentials that are systematically determined. In general, ex-ante assessments have been proposed to promote further knowledge development (Fleischer et al., 2005; Wender et al., 2014). Through participatory scenario development, it could account for a wider array of possibilities done together with the experts (Voinov et al., 2016; Wender et al., 2014). On the other hand, Villares et al. (2017) designed an ex-ante framework that highlights the use of upscaling and the setting of future scenarios to allow for comparison between emerging and conventional technologies. These could be the bases for the future economic assessment of LFM. Although most ex-ante studies focused on the implications of environmental assessments, similar challenges are observed in economic assessments (Caduff et al., 2011). As presented, inherent large uncertainties are expected in this approach, accounting for the lack of actual data, the setting of best estimates, and upscaling, among others (Clavreul et al., 2012; Hellweg and Milà i Canals, 2014; Martinez-Sanchez et al., 2015). However, by addressing these wide knowledge gaps through parametric uncertainty and global sensitivity analyses, systematic results can guide various stakeholders with more informed decisions. In this way, LFM practitioners could be guided on landfill site selection, choices for technology and organizational set-ups, and policy-makers on setting regulatory and market quality standards and policy instruments.

4. Conclusion

A total of 15 studies are selected in this review, which quantitatively assessed the economic potential of LFM. The majority of the studies are *case study-specific*, with a *decision-oriented* type of application. This accounted for individually assessed cases, offering a wide variation of LFM project descriptions, and considered scenarios classified at the site, project and system level. These scenario as well as parameter uncertainties were highlighted to be due to the emerging character of LFM, with the inevitable use of secondary data sources or primary sources that are based on laboratory to pilot-scale tests. In this case, a transparent description of goal and scope, data inventory and estimations, and model assumptions are called for. These are typical recommendations as stated in existing method guidelines (ISO, 2006a, 2006b; Swarr et al., 2011), but they remain unaddressed in the following LFM studies as well as in most of the current systems analysis in the field of waste management (Astrup et al., 2015; Laurent et al., 2014a, 2014b; Martinez-Sanchez et al., 2015). Apart from transparency, subsequent management of these uncertainties must be addressed accordingly to ensure the usefulness and validity of study results. Moreover, *learning-oriented* assessments are recommended to provide a more granular understanding of the principles of performance to avoid stagnancy of LFM as a field, but instead focus on the determination of promising paths for future development, irrespective of whether a *case study-specific* or a *generic* type of assessment is aimed for. By doing so, the role of specific stakeholders could be identified as well, and the respective strategic actions could be done based on widely accepted conclusions that reveal the real economic potential of an emerging concept like LFM.

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Appendix. Overview of the empirical findings from the selected studies.

Selected studies (n=15)	Landfill characteristics waste type (W), size (S), and location (L)	Scale of excavation	Net result, €/ton of excavated waste	Economic performance drivers	
				Main costs	Main benefits/revenues
Zanetti & Godio, 2006	W: monolandfill (foundry) S: medium (85 000 m^2) L: Crescentino landfill, Italy	pilot	not profitable (-3)	treatment & re-landfilling (fines), fuel, amortization, transportation, labor	material sales (silica sands & iron powder), value of landfill void space (mentioned but not valuated)
Van Vossen & Prent, 2011	W: mix MSW-IW S: small (0.5 Mt) 60 European landfill sites) L: Europe	hypothetical	potentially profitable (-22 to +1.7) *complete material separation and sales*	separation, transport on- & off-site, excavation, unforeseen costs	material sales (metals, plastics, CDW, stones, soil), value of landfill voidspace & land, reduction in process costs of materials, avoided aftercare costs
Ford et al., 2013	W: MSW S: medium (1.3 Mt), L: Scotland	hypothetical	potentially profitable (-91 to +33)* *WtE int with energy recovery and sale of land*	separation, excavation, re-landfilling, WtE int.	green certificate, value of land, electricity
Rosendal, 2015	W: monolandfill (shredder residue) S: small (0.3 Mt) L: Reno Djurs landfill, Denmark	full	potentially profitable (-22 to +20) *w/o re-landfilling tax, on-site separation, w/ tax refund, longer aftercare period (50-100 yrs)*	re-landfilling, separation, WtE (incineration), transportation, excavation	material sales (metals), tax refund, financial provision refund, value of landfill voidspace, avoided aftercare (valuated but excluded in net result)
Van Passel et al., 2013	W: mix MSW-IW S: large (16 Mt, 182 Mt) L: REMO landfill and Flanders Region, Belgium	pilot	potentially profitable (-unspecified to +12) *societal benefit, sale of land*	WtE (incineration), sorting & pre-treatment, contingency, excavation	electricity, material sales (shredder, metals, slag), value of land

Danthurebandara et al., 2015b	W: MSW S: medium (1 Mt, 50 000 m^2) L: open dumpsite, Sri Lanka	hypothetical	not profitable (-13 to -8)	transportation, WtE, sorting, re-landfilling	electricity, material sales (metals, RDF, glass aggregates, glass), value of land
Danthurebandara et al., 2015c	W: mix MSW-IW S: large (16 Mt, 130 000 m^2) L: REMO landfill, Belgium	pilot	not profitable (- unspecified)	WtE (plasma gasification)	electricity, calorific value of RDF, green certificate
Frändegård et al., 2015	W: MSW S: small (0.1 Mt) L: hypothetical landfill, Sweden	hypothetical	potentially profitable (-14 to +23, 5% probability) *w/o re-landfilling tax, WtE int.*	re-landfilling, WtE, separation, landfill reconstruction, transport	electricity & heat, material sales, value of land
Winterstetter et al., 2015	W: mix MSW-IW S: large (16 Mt, 130 000 m^2) L: REMO landfill, Belgium	pilot	not profitable (-19 to -12)	WtE, separation, excavation & storage	electricity, material sales (metals), avoided aftercare
Wagner & Raymond, 2015	W: monolandfill (ashfill) S: large (725 700 Mt) L: Ecomaine landfill, USA	full	profitable (+49)**	separation, excavation, fuel, labor, maintenance	material sales (metals), value of landfill voidspace
Zhou et al., 2015	W: MSW S: small (0.5 Mt) L: Yingchun Landfill, China	pilot	profitable (+3 to +29)**	excavation, separation, transportation	electricity, value of land, recycling soil-like materials
Damigos et al., 2016	W: MSW S: small (0.4 Mt) L: Polygyros landfill, Greece	pilot	potentially profitable (-5.4 to +170) *socioeconomic costs & benefits*	socioeconomic costs (harmful effects of excavation & processing, waste disposal, etc.), excavation, separation	socioeconomic benefits (direct employment, minimization of contamination, etc.), material sales (plastic, metals)

Wolfsberger et al., 2016	W: MSW S: small (0.7 Mt) L: Ave. Sanitary Landfill, Austria	pilot	not profitable (-40)	re-landfilling (incl. transport), separation	material sales (metals, aggregates)
Hermann et al., 2016	W: MSW S: small (0.7 Mt) L: Ave. Sanitary Landfill, Austria	pilot	not profitable (-39 to -12)	re-landfilling separation, excavation	value of landfill voidspace, material sales (metals)
Kieckhäfer et al., 2017	W: MSW S: medium (2.6 Mt, 270 000 m^2) L: Pohlsche Heide Landfill, Germany	pilot	not profitable (-62 to -35)	WtE (waste incineration & RDF incineration plant)	value of land & landfill voidspace, material sales (metal)

*1 £=1.14 €

**1 USD=0.85 €

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