Economics of Landfill Mining:

Usefulness and Validity of Different Assessment Approaches

John Laurence Esguerra

Linköping Studies in Science and Technology

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Abstract

Landfill mining (LFM) is an alternative strategy to manage landfills that integrates remediation with secondary resource recovery. At present, LFM remains as an emerging concept with a few pilot-scale project implementations, which presents challenges when assessing its economic performance. These challenges include large knowledge deficits about the individual processes along the LFM process chain, lack of know-how in terms of project implementation and economic drivers, and limited applicability of results to specific case studies. Based on how these challenges were addressed, this thesis aims to analyze the usefulness and validity of different economic assessments of LFM towards the provision of better support for decision-making and in-depth learning for the development of cost-efficient projects. Different studies were analyzed including the previous studies through a systematic literature review and the factor-based method that is developed in this thesis. Four categories of economic assessment approaches were derived in terms of the study object that is about either an individual LFM project (case-study specific) or multiple LFM projects in a region (generic); and in terms of the extent of analysis that is about either the identification of the net economic potential (decision-oriented) or extended towards an in-depth learning of what builds up such result (learning-oriented). Across the different approaches, most of the previous studies have questionable usefulness and validity. The unaddressed parametric uncertainties exclude the influence of using inherently uncertain input data due to large knowledge deficits. While the narrowly accounted scenario uncertainties limits the fact that LFM can be done in various ways and settings in terms of site selection, project set-up and regulatory and market conditions. In essence, these uncertainties propagate from case-study specific to generic study object. From decision-oriented to learning-oriented studies, the identification of what builds up the result are unsystematically determined that raises issues on their subsequent recommendations for improvement based on superficially derived economic drivers. The factor-based method, with exploratory scenario development and global sensitivity analysis, is presented as an approach to performing generic and learning-oriented studies. As for general recommendations, applied research is needed to aid large knowledge deficits, methodological rigor is needed to account for uncertainties and systematically identify economic drivers, and learning-oriented assessment is needed to facilitate future development of LFM. This thesis highlights the important role of economic assessments, which is not only limited for the assessment of economic potential but also for learning and guiding the development of emerging concepts such as LFM.

Keywords: economic assessment, uncertainty management, landfill management, landfill mining

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List of appended papers

- 1 Esguerra, J.L., Krook, J., Svensson, N., Van Passel, S. 2019. published
Assessing the economic potential of landfill mining: Review and recommendations. In *Detritus. Special Issue on Resource Recovery Through Enhanced Landfill Mining*

My contribution: I conceptualized the paper, selected and analyzed previous studies, and wrote the original draft and revision during the review process.
- 2 Laner, D., Esguerra, J.L., Krook, J., Horttanainen, M., published
Kriipsalu, M., Rosendal, R.M., Stanisavljević, N., 2019.
Systematic assessment of critical factors for the economic performance of landfill mining in Europe: What drives the economy of landfill mining? In *Waste Management*

My contribution: I took part in the model set-up, collected the data and wrote the original draft together with David Laner and Joakim Krook. I was also responsible for the revision during the review process.
- 3 Esguerra, J.L., Laner, D., Krook, Svensson, N. 20XX. Exploring in
strategies for an improved economic performance of landfill manuscript
mining in Europe.

My contribution: I revised the model from Paper 2, updated the relevant input data, analyzed the results and wrote the original draft.

Other related outputs

Journal Article

Hernández Parrodi, J.C., Lucas, H., Gigantino, M., Sauve, G., Esguerra, J.L., published
Einhäupl, P., Vollprecht, D., Pomberger, R.,
Friedrich, B., Van Acker, K., Krook, J., Svensson, N., Van Passel,
S. 2019. Integration of resource recovery into current waste
management through (Enhanced) Landfill Mining. In *Detritus.
Special Issue on Resource Recovery Through Enhanced Landfill
Mining*

Conference Papers

Esguerra, J.L., Svensson, N., Krook, J., Van Passel, S., Van Acker, K. 2018. The
economic and environmental performance of a landfill mining project from the
viewpoint of an industrial landfill owner. 4th International Symposium on
Enhanced landfill Mining, 5-6 February, Mechelen, Belgium, pp. 389-396.

Esguerra, J.L., Krook, J., Svensson, N., Van Passel, S. 2018. Is enhanced landfill
mining profitable? International Solid Waste Association (ISWA) 2018 World
Congress, 22-25 October, Kuala Lumpur, Malaysia, pp. 240-245.

Hernández Parrodi, J.C., Lucas, H., Gigantino, M., Sauve, G., Esguerra, J.L.,
Einhäupl, P. 2019. Strategies for landfill mining–Integrating resource recovery
into current waste management. 17th International Waste Management and
Landfill Symposium, 30 September-4 October, Sardinia, Italy.

Conference Abstracts

Sauve, G., Esguerra, J.L., Krook, J., Svensson, N., Van Passel, S., Van Acker, K.
2019. Integrated ex-ante environmental and economic assessment of plasma
gasification for enhanced landfill mining. SETAC Europe 29th Annual Meeting,
26-30 May, Helsinki, Finland.

Esguerra, J.L., Sauve, G., Krook, J., Svensson, N., Van Passel, S., Van Acker, K.
2019. A systematic method for ex-ante assessment of critical factors for the
economic and environmental performance of emerging concepts. 10th
International Conference on Industrial Ecology, 7-11 July, Beijing, China.

1. Introduction

1.1 Background

Globally, continuous production and consumption have led to the accumulation of materials in the anthroposphere (Cossu and Williams, 2015; Zhang et al., 2019). These materials eventually turn into waste upon reaching their end of life, of which more than half is landfilled as such a disposal option is still considered cost-efficient in many parts of the world (Kaza et al., 2018). Within the European Union (EU), several countries have recently developed more advanced waste management and recycling systems, but landfilling remained important, and still, a quarter of the generated municipal waste in this region ends up in such deposits (Eurostat, 2019). Consequently, there are more than half a million landfills in Europe, most of them being old and non-sanitary deposits predating the EU Landfill Directive 1999/31/EC (Hogland et al., 2010). Such landfills are associated with several environmental and health hazards as well as land-use restrictions (El-Fadel et al., 1997; Porta et al., 2009). In addition, a higher risk of flooding due to climate change further aggravates these hazards in some regions (Laner et al., 2009; Wille, 2018). The proper management of landfills must be practiced to address such hazards, such as aftercare that involves collection and treatment of leachate and landfill gas, and remediation, which typically involves the excavation of waste and disposal to sanitary landfills (Brennan et al., 2016; Laner et al., 2012). Despite the recently-amended EU Landfill Directive (2018/850), there is, however, still no coherent strategy for the management of these landfills, and the public funding for aftercare and remediation are often insufficient among the member states (Krook et al., 2018).

Apart from the perspective of hazard avoidance, another motivation to manage landfills is through the perspective of resource recovery, acknowledging landfills as resource reservoirs. Over time, massive amounts of metals, combustibles and minerals have been disposed of in such deposits (Frändegård et al., 2013; Kapur and Graedel, 2006; Müller et al., 2006). Several recent studies, therefore, proclaim that landfills should, in fact, be considered as potential sources of secondary raw materials that can contribute significantly to the EU's material autonomy (Frändegård et al., 2013; Johansson et al., 2012; Jones et al., 2013). In line with this, an integrative landfill management approach called landfill mining (LFM) has recently gained attention. LFM extends traditional aftercare and remediation with resources recovery, thereby accounting for a more exhaustive process chain including excavation, separation and sorting, thermal treatment, material recycling, and in some cases, also further valorization of subsequent residues (Burlakovs et al., 2017; Jones et al., 2013; Krook et al., 2012). As suggested in several studies, the potential benefits of LFM include remediation of malfunctioning landfills (Hogland et al., 2018; Johansson et al., 2012), recovery of obsolete metals (Gutiérrez-Gutiérrez et al., 2015; Wagner and Raymond, 2015), minerals and energy carriers (Bosmans et al., 2013; Rotheut and Quicker, 2017), as well as reclamation of land resources (Damigos et al., 2016; Van Passel et al., 2013). By bringing such resources back into society and addressing the environmental and health hazards of such

deposits, LFM is increasingly being acknowledged as a strategy to achieve a circular economy (Machiels et al., 2019; UN Economic Commission for Europe, 2018) and contribute to several sustainable development goals (Calderón Márquez et al., 2019).

However, LFM remains as an emerging concept with few real-life and full-scale projects validating its feasibility (Calderón Márquez et al., 2019; Johansson et al., 2012). At present, the realization of such projects is subject to multi-faceted challenges in terms of several influencing technological, political, market, organizational, social, environmental and economic conditions (Hermann et al., 2016; Johansson et al., 2017; Krook et al., 2015; Van Der Zee et al., 2004). These challenges are typical for emerging concepts and technologies since the incumbent conditions are not yet adapted for such unconventional practices (Hekkert et al., 2007). As a consequence of its emerging character, studies on where and how to implement LFM as well as its overall sustainability performance (i.e., economic, environmental and social aspects) are limited. Such studies are necessary to earn the support of stakeholders towards its widespread adaptation as an alternative strategy for landfill management. In essence, further development of LFM relies on extensive research targeting the challenge of how such projects can be developed cost-efficiently and with clear environmental and societal benefits (Hermann et al., 2016; Johansson et al., 2017; Krook et al., 2015; Van Der Zee et al., 2004).

As for many other waste management and recycling solutions, a lack of knowledge about how to obtain cost-efficiency of LFM remains as one of the main bottlenecks for implementation (Martinez-Sanchez et al., 2015; Van Der Zee et al., 2004; Van Passel et al., 2013). Here, economic assessment tools such as life cycle costing (LCC) can enable structured assessments aiming to address different types of challenges and knowledge needs (Finnveden and Moberg, 2005; Swarr et al., 2011). When it comes to LFM, our knowledge about the economic potential is still limited and incoherent. There are, for instance, studies that evaluate the net economic potential of LFM on the regional level in order to support policy-making (Ford et al., 2013; Van Vossen and Prent, 2011), or assess the feasibility of planned projects to support specific investment decisions (Hermann et al., 2016; Kieckhäfer et al., 2017; Wolfsberger et al., 2016). Some of them conclude that LFM is not profitable (Danthurebandara et al., 2015a, 2015c; Kieckhäfer et al., 2017; Winterstetter et al., 2015; Wolfsberger et al., 2016), while others present opposing results (Damigos et al., 2016; Van Passel et al., 2013; Wagner and Raymond, 2015; Zhou et al., 2015). Beyond such decision-oriented studies, there are also a few examples of more learning-oriented assessments determining what builds up the net economic potential of LFM. But they also present different conclusions about important economic drivers (Danthurebandara et al., 2015c; Frändegård et al., 2015; Van Passel et al., 2013). These contradictions are rather expected given that LFM can be realized in many different ways and settings, which involve different landfills, technical and organizational project set-ups, and surrounding policy and market conditions. However, the current lack of reviews and scrutiny of these studies makes

it difficult to understand their different knowledge contributions and identify in which ways and settings LFM can become a cost-efficient landfill management alternative.

There are, however, also concerns that previous assessments of LFM are faced with large uncertainties and various methodological issues, influencing the usefulness and validity of their obtained results. This is because such assessments of emerging concepts and technologies, or so-called *ex-ante* assessments, are inherently challenging, and their aim to analyze unconventional practices requires special attention to the selection of modelling principles and assessment methods (Cucurachi et al., 2018; Hetherington et al., 2014; van der Giesen et al., 2020; Villares et al., 2017). Given the lack of real-life and full-scale projects, most assessments of LFM are constrained to forecasts of the economic outcome of initiatives that are yet to be realized. Although uncertainties are inherent in any assessments, they are particularly compounded in such *ex-ante* assessment due to largely insufficient knowledge and data about the modeled processes. The fact that previous assessments of LFM seem to have employed different approaches to the handling of such deficits in knowledge and data about the LFM process chain (Kieckhäfer et al., 2017; Wolfsberger et al., 2016; Zhou et al., 2015) raises concerns about the validity of the results and thus their trustworthiness as a means to support various decisions.

Moreover, there is also a concern about the usefulness of the results of previous assessments in terms of their relevance for establishing know-how to facilitate LFM implementation. In order to identify measures and strategies for improved performance, detailed knowledge about what builds up such performance is important (Ferretti et al., 2016; Laner et al., 2016a; Saltelli and Annoni, 2010). By knowing the key performance drivers, the development of measures and strategies can be facilitated by prioritizing the improvements of such drivers. There are, however, few studies on LFM in this respect, and these assessments also seem to use different methods and present economic drivers on different levels of aggregation, i.e., process, sub-process or specific parameters (Danthurebandara et al., 2015c; Winterstetter et al., 2015). This raises concerns on the validity of how previous assessments develop knowledge about the key economic drivers of LFM and the subsequent measures and strategies for improved economics of LFM.

Many of the previous assessments of LFM are case-specific, and the applicability of their results are, therefore, often limited to the specific conditions and settings of the studied project in question. Considering that LFM can be implemented in many different ways and settings, there is a need to develop a more generic and systematic understanding about the economic potential. Such generic knowledge can facilitate cost-efficient LFM implementation in broader regions, by giving insights on the importance of landfill site selection and policy and market conditions apart from the influence of different technological and organizational project set-ups as typically addressed in many of the case-specific assessments. In line with this, the

ex-ante assessment literature recommends an exploratory scenario development, which means accounting for multiple scenario possibilities in order to identify the potential of various paths for development (van der Giesen et al., 2020; Villares et al., 2017; Voinov et al., 2016). However, despite the fact that LFM can be done in many ways and settings, even in specific projects, several of the previous assessments tend to employ a selective approach to scenario development and thus only study a few alternatives for implementation (Ford et al., 2013; Van Vossen and Prent, 2011). Such a methodological approach displays concerns regarding to what extent plausible options for developing cost-efficient LFM projects actually have been addressed in previous research.

In essence, this thesis acknowledges that economic assessments are performed to serve different objectives, but that the usefulness of their obtained results is strongly related to validity by addressing the aforementioned empirical constraints and methodological challenges. As a way forward for LFM, there is a need to systematically synthesize the knowledge contributions of performed economic assessments and critically analyze their usefulness and validity. Such a synthesis is imperative, especially for guiding method development for assessing emerging concepts and technologies and facilitating future LFM research and project implementation. In this way, the early discrimination of concepts and technologies can be avoided, and instead promote their responsible innovation (Hetherington et al., 2014; Wender et al., 2014).

1.2 Aim and research questions

The aim of this thesis is to analyze the usefulness and validity of different economic assessments of LFM towards the provision of better support for decision-making and in-depth learning for the development of cost-efficient projects. Here, usefulness refers to the fulfillment of the objective of a certain type of assessment and thus the applicability and relevance of the obtained results for facilitating LFM implementation, while validity refers to whether the results are substantiated with respect to the used empirical data and the applied methodological rigor referring to LCC guidelines and ex-ante assessments. In essence, different objectives of economic assessments require different methodological approaches, hence assuring that the validity also qualifies the intended use of the provided results. That is, the results may have a perceived usefulness as presented in the studies, but the corresponding validity may indicate otherwise, revealing their real usefulness. In order to address this aim, a review of the main findings and employed methodologies of previous economic assessments is combined with the development and application of a specific method, which involves generic modeling and systematic methods for the identification of critical factors and conditions that build up the economy in a wide range of LFM scenarios.

To reach the thesis aim, the following research questions (RQs) have been formulated:

RQ 1: What are the knowledge contributions of different types of performed economic assessments of LFM?

This RQ aims to categorize different types of economic assessments of LFM based on their stated objectives, and subsequently display their usefulness by presenting their corresponding results. More specifically, the intended knowledge contributions of different assessments are here analyzed in terms of their study object and extent of analysis. The former influences the applicability of the results and can be either as narrow as a certain landfill site or as broad as multiple sites situated in a region. The latter can be either limited to the net economic potential to support “go or no go” investment decisions or more extensive targeting the constituent critical factors that build up the economic potential to identify measures to improve the performance. This RQ contributes to the aim by giving clarity to the intended usefulness of different economic assessments of LFM and what type of questions and knowledge needs they attempt to address.

RQ 2: In what ways can empirical constraints and methodological challenges influence the usefulness and validity of the results from different types of economic assessments of LFM?

This RQ aims to provide an in-depth understanding of the limitations of the knowledge contributions provided by different types of economic assessments of LFM. Following the established categories of economic assessments in RQ 1, categorical discussion on corresponding empirical constraints and methodological issues are enumerated. Here, empirical constraints refer to the kind of data used and the corresponding estimations or proxies in case of unavailability, while methodological issues refer to the consequent methodological rigor as in the handling of various assessment uncertainties and methodological choices enabling different types of analyses. This RQ contributes to the aim by highlighting the specific validity issues related to the different categories of economic assessments and exemplifying the implications on their usefulness if these issues are left unaddressed.

RQ 3: How can the identified empirical constraints and methodological challenges be addressed?

This RQ aims to enumerate improvement measures for each of the different categories of economic assessments, specifically targeting the empirical constraints and methodological challenges identified in RQ 2. In this thesis, addressing the empirical constraints means specifying key limitations and gaps in knowledge that need to be addressed for improving the quality of input data in terms of its completeness and representativeness. When it comes to the methodological challenges, operational guidance is provided to assure the validity and usefulness of the results in different types of analyses.

The thesis ends with a discussion about the role of economic assessments for supporting and facilitating the development of emerging concepts such as LFM. The intention of this reflection is to put the findings from the thesis in relation to previous research on emerging concepts and ex-ante assessments, thereby highlighting its empirical and methodological contributions to these knowledge areas.

1.3 Thesis outline

The proceeding sections are structured as follows. The broader scientific context on concepts and methods is presented in the theoretical background (Section 2). In the same section, the motivation for narrowing down the research scope is also stated. The methodology used (Section 3) is then specified, starting from the research context and journey that explains the choices made in the project, the economic assessment methods that detail the systematic literature review and the developed method, an overview of the appended papers, and the overall thesis method that integrates the appended papers and research questions. The results and discussion (Section 4) are then presented in terms of the categories of economic assessment studies based on their intended objectives. It includes the definition and exemplification of the type of results based on a systematic literature review and an own-developed method, alongside the encountered empirical constraints and methodological challenges that qualify the validity of the presented results. Subsequently, the corresponding recommendations for improvement of the economic assessments in each category are presented. Further reflection highlights the role of economic assessments for emerging concepts like LFM. Finally, the conclusion (Section 5) and research outlook (Section 6) provide direct answers to the research questions and research aim and the next steps on expanding the research scope and extending the own-developed method, respectively.

2. Theoretical background

2.1 Landfill mining, circular economy, and sustainability

Landfills have long been considered as final waste deposits and are associated with environmental and health hazards as well as land-use restrictions, as landfills sometimes interfere with urban and regional development (El-Fadel et al., 1997; Laner et al., 2012; Johansson et al., 2012; Porta et al., 2009). Hence, appropriate landfill management is needed, such as traditional landfill aftercare where monitoring, collection, and treatment of leachate and landfill gas are assured, or remediation for malfunctioning sites wherein the waste is excavated and transferred to sanitary landfills. These landfill management alternatives obviously entail costs. Although revenues are expected for recovered land or landfill void space, additional sources of revenues can be integrated considering the potential for recovery of resources from landfilled waste. Several recoverable resources are found in such waste deposits, such as ferrous and non-ferrous metal scraps that can be recycled, combustibles that can be used as fuels for energy recovery (residue-derived fuel, RDF), and various inorganic materials that can be used as construction materials. This concept of integrated remediation and resource recovery through LFM has influenced the perception of landfills from final waste deposits to temporary material storages, which can be exploited to recover both materials, energy carriers and land resources (Cossu and Williams, 2015; Johansson et al., 2012; Krook and Baas, 2013).

Rooted in the material perspective of industrial ecology (Saavedra et al., 2018), the circular economy concept addresses keeping the materials being used in society and minimizing waste (Ellen MacArthur Foundation, 2013). The current focus of the circular economy is typically on the future waste streams, and LFM contributes to this concept by addressing the waste from the past. LFM is even tagged as the missing link to achieve a more comprehensive circular economy approach (Machiels et al., 2019). Some policy efforts have been initiated for supporting LFM in the EU by directly linking it to the current attention on the circular economy. There is, for instance, an ongoing adaptation and inclusion of landfills as an anthropogenic stock of resources in the United Nations Framework Classification for Resources (UN Economic Commission for Europe, 2018). There was also a recent amendment of the EU Landfill Directive (2018/850) that aimed to include LFM as one landfill management alternative, among others (European Parliament, 2018). Although this amendment was stopped, as LFM still only is a proof of concept with a lack of real-life applications, the revised directive does not directly prohibit LFM implementation. There are, however, several ongoing LFM research projects and initiatives that are funded by the European Commission (European Enhanced Landfill Mining Consortium, 2019), aiming to develop know-how and technologies for how to realize such projects (Danthurebandara et al., 2015c; R. Hermann et al., 2016; Hogland et al., 2018; Winterstetter et al., 2018).

As a consequence of its emerging character, studies on where and how to implement LFM from a broader sustainability perspective (i.e., economic, environmental and

social aspects) are scarce (Hermann et al., 2016; Pastre et al., 2018). In addition, these assessments only focus on single landfill projects, which means that their knowledge contribution to the general sustainability potential of LFM is largely limited. At present, we thus know very little about the positive and negative sustainability consequences of LFM. This situation underscores the policy-relevant question of how LFM should be evaluated—to pinpoint the need for conducting sound research that can guide further development of the area, and set priorities on where and how to implement sustainable LFM projects (Hermann et al., 2014; Krook et al., 2018; Van Der Zee et al., 2004).

2.2 Sustainability assessments and the ex-ante approach

Different sustainability assessment tools (Ahlroth et al., 2011; Finnveden and Moberg, 2005) have been widely used to enable structured assessments of various systems (e.g., products, services, projects and policies). In general, these tools follow a common methodological framework that includes the definition of goal and scope, inventory of data, modeling and calculation, and interpretation of results (ISO, 2006a; Swarr et al., 2011). This framework is developed and standardized for the environmental assessment through life cycle assessment (LCA). Subsequently, in consideration of different sustainability perspectives (Purvis et al., 2019), the development of a methodological framework for economic (life cycle costing, LCC) and social (social LCA, SLCA) aspects are based on LCA to ensure compatibility for integrated sustainability assessment (Guinée, 2016; Hoogmartens et al., 2014; UNEP/SETAC Life Cycle Initiative, 2011).

Goal and scope definition sets the extent of the analysis and study object, in a way specifying the intended knowledge contribution of the assessment (Finnveden and Moberg, 2005; ISO, 2006a; Swarr et al., 2011). The choice of sustainability perspective is also decided in this step, and either an individual or integrated sustainability assessment can be chosen (Guinée, 2016; Hoogmartens et al., 2014; UNEP/SETAC Life Cycle Initiative, 2011). In terms of the extent of analysis, the assessment can be decision-oriented and aim to evaluate the net performance, which is typically done to support decisions for capital investments or marketing purposes. It can also be extended to a more learning-oriented approach that seeks a more in-depth understanding in terms of what builds up the net performance, which is common in optimization and design studies. The study object can be products, services, projects or policies. For LFM, the study object can either be case study-specific or more generic and cover multiple landfills on the regional, national or global scales.

Data inventory refers to the collection of input data in which representativeness and transparency have to be assured. The data sources have to be noted in terms of whether they are primary data or, in the case of unavailability, secondary data, or a combination of the two. Modeling and calculation include the actual numerical analysis to ensure mass and energy balance of input and output flows, and the impact assessment based on environmental impact categories in LCA, different

economic indicators in LCC and different social impact categories in SLCA. Finally, the interpretation step serves as a check to ensure that the results are adequately supported by the data and the methods used and that the derived conclusion is well substantiated. This step also includes uncertainty and sensitivity analysis.

Recent development of sustainability assessment focuses on the concepts and technologies at an early stage of development, and such studies are called *ex-ante* assessments (Cucurachi et al., 2018; Hetherington et al., 2014; van der Giesen et al., 2020; Villares et al., 2017). This is particularly timely and relevant due to the overwhelming rise of various innovative concepts and technologies. However, due to the lack of practical experiences and large-scale implementation, several empirical constraints and methodological challenges are apparent that bring large uncertainties into the assessments (Clavreul et al., 2012; Fleischer et al., 2005; Hellweg and Milà i Canals, 2014; Martinez-Sanchez et al., 2015). In contrast to assessing conventional technologies, insufficient data is expected as these technologies are often in the laboratory or pilot scale, if not completely hypothetical. Especially, if the analysis is to be compared with conventional technologies, upscaling of data and scenario development must be done to ensure comparability (Hetherington et al., 2014; Villares et al., 2017). Scenario analysis based on such laboratory-scale processes must be done on a large scale to facilitate the assessment of the technologies at a similar scale. More explorative approaches to scenario development are recommended to scope in multiple possibilities with a wider degree of freedom (Voinov et al., 2016; Wender et al., 2014). That is, apart from the different upscaling possibilities of each process, the project setup of LFM may also differ through multiple combinations of technology alternatives. Moreover, in the future, technological maturity, as well as the surrounding policy and market conditions, may also change. Consequently, these open up for further propagation of uncertainties that must be handled and understood in sustainability assessments. In this way, the future sustainability performance of emerging concepts and technologies can be assessed, which can provide guidance for further development and promotion of responsible innovation (Hetherington et al., 2014; Wender et al., 2014).

2.3 Economic assessment methods

In assessing the economics, life cycle costing (LCC) is the common tool that is used to account for all the costs and revenues associated to a product or production system in consideration of its whole life cycle (Huppel et al., 2008; Swarr et al., 2011). It is coined and specified in the so-called code of practice in LCC by the Society of Environmental Toxicology and Chemistry (SETAC), a recognized group that develops sustainability assessment methods and tools (Swarr et al., 2011). With respect to the three pillars of sustainability, namely, economic, and environmental and social aspects (Purvis et al., 2019), LCC can be classified as conventional (C-LCC), environmental (E-LCC), or social (LCC), respectively. C-LCC is about pure financial accounting as in business accounting and techno-economic assessment, E-

LCC includes monetized environmental gains/deficits, and S-LCC includes monetized impacts on human health and welfare, among others. For LFM, these external costs for E-LCC and S-LCC may include noise and traffic, while benefits may include less environmental pollution, restoration of nature and biodiversity, and reduction of import dependency (Damigos et al., 2016; Marella and Raga, 2014; Van Passel et al., 2013). However, in this thesis, private economics is chosen as a particular focus that corresponds to the utilization of C-LCC and sets the boundaries for which cost and revenue items to account for. Such a perspective is chosen to support landfill owners and project managers, as they are at the forefront of adopting new alternatives for landfill management and, in doing so, have to bear all the subsequent costs on their own. At present, there are limited policy instruments that internalize such environmental and social externalities into the project economy (Damigos et al., 2016; Ford et al., 2013; Van Passel et al., 2013).

For the economic calculation step, several economic indicators are available for assessing the economic potential of different projects such as payback time, net present value (NPV) and internal rate of return (IRR), among others. Frequently, these indicators are applied to verify whether or not investing in a project is worthwhile financially (Brealy et al., 2011). The payback time is determined as the time needed to cover the initial investment with the incoming direct cash flows. This method has the advantage of being generally known and easy to apply, but it does not take the time value of money into account. In addition, it does not provide information about the profit generated from the investment during the further lifetime of the project, i.e., after the investment has been paid back. The NPV is calculated by subtracting the investment cost from the sum of the discounted cash flows and can be considered as the expected profit of the investment. Unlike the payback time, it takes the time value of money and all the relevant cash flow elements over a pre-defined period into account. The IRR, the discount rate at which the NPV is zero, gives an idea about the relative return of the investment but does not consider the scale of the project: while the IRR of two projects can be the same, the NPV of one project can be larger than the NPV of the other. On the other hand, the calculation of IRR does not require assumptions about the discount rate.

When it comes to LFM, previous economic assessments use different economic indicators. Several studies account for direct cash flows in terms of costs, revenues and net results, while discount rates are not considered (Ford et al., 2013; Rosendal, 2015; Van Vossen and Prent, 2011; Wagner and Raymond, 2015; Zhou et al., 2015). The main reason for such a choice is that these studies often consider small landfills with high LFM processing capacity, leading to a project duration of only about a year. For other studies, the project duration is much longer (i.e., from 3 to 20 years), and the time value of money, therefore, becomes more important to account for (Danthurebandara et al., 2015c; Frändegård et al., 2015; Winterstetter et al., 2015; Wolfsberger et al., 2015). However, the employed discount rate can also vary significantly (i.e., from 3% to 15%), depending on if public or private financing is considered (Van Passel et al., 2013; Winterstetter et al., 2015). From a practical

point of view, this means that the present value of money is lower the farther we go in the future and the higher the selected discount rate is. As this thesis is concerned with economic assessments of different LFM cases with different financing considerations and project durations, NPV is the preferred indicator of economic profitability. In a way, this indicator accounts for the way of budgeting that details the up-front investments as wells as the revenue cash flows that are distributed over the years (e.g., electricity and material sales), or only materialize in a distant future (e.g., avoided landfill aftercare and reclaimed land).

2.4 The economics of landfill mining

2.4.1 Factors influencing the economics of landfill mining

A simplified physical and economic flow diagram is shown in Figure 1, which provides an overview of processes that can constitute the economics of LFM (Danthurebandara et al., 2015c; Van Passel et al., 2013). However, these processes are not necessarily part of all LFM cases or accounted for in all studies, as the objectives for LFM and thus what outputs and values that are targeted could vary between different projects. In principle, the main project costs are caused by expenditures for excavation, transportation, processing and treatment of materials, while revenues consist of direct revenues for, for example, the valorization of materials and recovered value of land or void space, as well as indirect revenues from avoided costs of alternative landfill management like aftercare or remediation costs.

Figure 1. The simplified scheme of the landfill mining process chain (including the expenditures for disposal and treatment such as transportation costs, taxes and gate fees). The corresponding sources of cost and revenue items are also shown (broken line).

Each of the processes in Figure 1 can be disaggregated into their constituent model parameters. For example, a particular landfill can be disaggregated into its characteristic waste composition, size and geometry. In this thesis, the term “factor” is used for disaggregating the economy of LFM into different processes and model parameters (Laner et al., 2016; Van Der Zee et al., 2004). These factors can refer to both a whole process or its constituent model parameters and are generally

classified into site, project and system levels. Such classification is useful to pinpoint specifically critical factors and identify which stakeholder that can influence the economics of LFM.

At the site level, factors refer to the characteristics of a landfill in terms of its waste composition, landfill size and geometry and management alternatives. Such site-specific factors and local settings could be influenced by landfill owners and project managers, for instance, through the selection of landfills for mining. Knowledge about the waste composition of landfills is essential as it entails the potentially recoverable amounts of different resources as well as non-recoverable and hazardous materials in need of disposal and special treatment. The material composition of landfills varies widely depending on the type of deposited waste such as municipal solid waste, industrial waste or mixed waste. Also, the age and the region of the landfills influence their material constituents. It has to be acknowledged that there are, in general, large uncertainties regarding the material composition of the deposited waste, both within specific landfills and among different landfill sites (Hernandez Parrodi et al., 2018; Hogland et al., 2018; Hölzle, 2019). The size and geometry of landfills are also of relevance because they influence the economy of scale for excavation, materials processing, internal logistics and landfill management alternatives (Hogland et al., 2018; Hölzle, 2019). Moreover, for landfill management alternatives such as aftercare or remediation, the choice is also influenced by the characteristics of the landfill, its content and its surroundings. In case of the need for land conversion such as for industrial and residential use, remediation that typically involves the excavation of waste and disposal to other landfills is preferred over aftercare that only involves collection and treatment of leachate and landfill gas (Brennan et al., 2016; Laner et al., 2012).

At the project level, factors refer to the LFM project setup, such as the choice of technologies, and organizational setup, such as if a certain process is done internally or externally to the project. Landfill owners and project managers primarily influence these project factors. The choice of sorting, upgrading and recovery technologies is fundamental as it influences both the quantity and quality of different materials and energy carriers that can be recovered from the deposited waste. Technology setup can vary in terms of the advancement of technology used as well as the combination of technologies along the LFM process chain. There are studies that account for variations and implications of employing different advancements of separation and sorting technologies (Kieckhäfer et al., 2017) and thermal treatment technologies (Danthurebandara et al., 2015b, 2015d; Winterstetter et al., 2016). In principle, more advanced technologies lead to higher recovery rates, but such improvements in processing efficiencies also come with higher costs. For varying project organizational setup, such differences affect the distribution of costs and benefits in LFM projects. For example, if thermal treatment is considered external, the gate fee for sending the combustibles to a waste incinerator is accounted for, while if the thermal treatment is done within the

project organization, both waste-to-energy processing costs and revenues from the generated energy need to be taken into account.

At the system level, policy and market conditions influence the costs and benefits of most of the processes along the LFM value chain. Relative to the factors at the site and project levels, system-level factors are more or less fixed as the incumbent background conditions. To some extent, policy-makers can influence these conditions through various interventions, but they are, in general, regionally contingent and beyond the authority of any individual stakeholder to influence directly. For instance, apart from site-specific factors, the choice of management for landfills is also defined by specific process requirements that depend on national or regional regulations. The required actions and costs for landfill closure, aftercare and remediation can, therefore, vary widely between different regions (Rosendal, 2015; Van Vossen and Prent, 2011). Such variations among countries are also relevant when it comes to available treatment and recycling facilities, accessible markets and current price settings for different materials extracted from landfills. Here, the lack of real-life projects that actually involved sales of recovered materials from waste deposits also displays large uncertainties regarding their marketability. In order to handle such uncertainties, different studies have employed different assumptions regarding both the marketability and potential revenues for such materials. However, it is commonly assumed that the materials that they plan to recover and valorize will be accepted by existing markets (Danthurebandara et al., 2015c; Van Passel et al., 2013; Winterstetter et al., 2015). Apart from marketable materials, an LFM project also typically generates significant amounts of other materials (e.g., fines and combustibles) that are bound for disposal or further treatment (Hernández Parrodi et al., 2018). Consequently, the management expenditures for these waste fractions in terms of gate fees for landfilling and incineration can vary considerably among nations and regions due to their imposed taxes and waste market conditions (Confederation of European Waste-to-Energy Plants, 2017).

2.4.2 Challenges of performing an economic assessment of landfill mining

Our current knowledge about the economics of LFM is limited and incoherent. In total, there are about 15 published assessments throughout the world, and they present contradictory conclusions regarding the overall economic potential. Most of them conclude that LFM is not profitable (Danthurebandara et al., 2015a, 2015c; Kieckhäfer et al., 2017; Winterstetter et al., 2015; Wolfsberger et al., 2016), while others have opposite conclusions (Damigos et al., 2016; Van Passel et al., 2013; Wagner and Raymond, 2015; Zhou et al., 2015). Moreover, the reported critical factors that build up the net economic potential are also inconclusive. These observations boil down to challenges that are related to the assessment of an emerging concept, or ex-ante assessment, with inherent knowledge deficits as well as the differences in applied assessment methods.

Firstly, large knowledge deficits about different processes along the LFM process chain can be expected due to the absence of real-life and large-scale project implementation. For instance, because of the lack of large-scale processing of actual landfill waste, there is an apparent use of data from the processing of other waste in other situations like fresh municipal waste or direct use of laboratory-scale data (Ford et al., 2013; Van Vossen and Prent, 2011). The use of such proxy data and knowledge from neighboring fields is inevitable, but such empirical constraints also highlight the need to address the related uncertainties in an ex-ante assessment (Hetherington et al., 2014; van der Giesen et al., 2020). Otherwise, if left unaddressed, the validity of the presented results can be questioned.

Secondly, there is a lack of know-how when it comes to the implementation of LFM and the identified economic drivers. These drivers are often presented at different levels of aggregation, which relates to the differences in the level of specificity and complexity of the employed method. For instance, some studies provide aggregated information in terms of the main cost and revenue items (Kieckhäfer et al., 2017; Wolfsberger et al., 2016; Zhou et al., 2015), while other studies present more disaggregated results, such as how changes in specific parameter values influence the overall result (Danthurebandara et al., 2015c; Van Passel et al., 2013; Winterstetter et al., 2015). Such detailed information on critical factors for performance can facilitate the development of specific measures and strategies for improved cost-efficiency. This pertains to the validity of the applied methods in previous assessments and to what extent they manage to systematically identify the critical economic factors of LFM.

Lastly, when it comes to the usefulness of results in terms of applicability, most studies are case-specific with conclusions that are limited to a certain landfill and regional context. Variations of factors at the project level are thus often in focus, while landfill site and system-level factors are fixed. For instance, there are studies that focus on the importance of different advancement levels of technologies (Danthurebandara et al., 2015a; Kieckhäfer et al., 2017; Winterstetter et al., 2015), while others rather target the potential of different policy instruments (Ford et al., 2013; Frändegård et al., 2015; Rosendal, 2015; Van Passel et al., 2013). Some studies have also applied different modeling principles and thus which processes (e.g., thermal treatment, avoided aftercare, value of landfill void space or land) of the LFM chain that actually are accounted for. These individual considerations limit the understanding of what influences the overall economics of LFM in different situations and settings. Nevertheless, such generic knowledge can be generated from the synthesis of results from previous studies, or so-called meta-analysis (Glass, 1976; Lifset, 2012; Shelby and Vaske, 2008). At least in the field of sustainability, such meta-analysis is relatively new, and there are different employed methods. This displays a concern that such analysis can only provide a crude understanding and only serve as a hint for generic knowledge, due to several harmonization challenges such as differences in case-specific considerations and lack of transparency, as well as variations in the applied modeling principles and

assessment methods of individual studies (Brandão et al., 2012; Lifset, 2012). In this regard, more quantitative meta-analysis methods can offer a more systematic approach to synthesize the available information from different case studies (Shelby and Vaske, 2008). Several such sustainability assessments have recently been done to provide generic knowledge on the environmental performance of various systems (Brandão et al., 2012). Different studies on specific systems can be harmonized and integrated to elicit generic knowledge. In line with this, it can guide the explorative approach that is recommended for ex-ante assessment, which means accounting for multiple scenario possibilities in consideration of various paths for development as used in previous studies as well as with the aid of experts in the field (van der Giesen et al., 2020; Villares et al., 2017; Voinov et al., 2016).

Such an explorative approach, both for an individual landfill in a case study-specific assessment or for multiple landfills in a generic assessment, accounts for extensive options for developing cost-efficient approaches that are actually addressed in previous assessments. The methodology developed by Laner et al. (2016) was used for analyzing the climate impact of LFM in Europe. Almost 3,000 LFM scenarios were generated and analyzed through a variance-based approach, accounting for different variations at the site, project and system levels. Such an approach is rooted in the field of engineering called the statistical design of experiments, which is typically utilized for process improvement through the screening of alternatives (NIST/SEMATECH, 2012). In this thesis, this variance-based approach is also adopted for a generic economic assessment of LFM in Europe. Through the variance-based approach, critical economic factors can be identified as well as their interrelations, which is necessary for the development of cost-efficient LFM projects.

2.5 Uncertainty and sensitivity analyses

From the previous sections, several sources of uncertainties are mentioned that may occur during scenario building, model development and data gathering (Clavreul et al., 2012; Huijbregts et al., 2003). The nature of these uncertainties can be classified as either stochastic or epistemic (Clavreul et al., 2013; Saltelli et al., 2008). Stochastic uncertainty refers to the variability of data, for example, in time, space and technology, which can be attributed to outcomes that for practical purposes cannot be predicted. Epistemic uncertainty, in contrast, refers to the lack of knowledge, for example, due to measurement errors, an insufficient number of measurements or a lack of expertise. Uncertainties are inevitable, and for LFM, it is highlighted that more epistemic uncertainties are expected as it is still an emerging concept with large empirical knowledge deficits.

To handle such wide uncertainties, the employment of uncertainty and sensitivity analysis methods is key (Ferretti et al., 2016; Saltelli and Annoni, 2010). Such methods explicitly account for the uncertainties, and it also enables fine-grained assessments of various factors and their interactions that jointly build up the net results. Uncertainty analysis accounts for the uncertainties of input parameters (i.e.,

range of values instead of an absolute value per parameter), which gives information about how much the output value could vary. Sensitivity analysis, on the other hand, apportions that variation of the output value to the input parameters. This could be done 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). The former is a classical approach to sensitivity analysis, and it is the most frequently used method. However, it is proven to be inefficient in revealing the underlying interactions, among other factors. Hence, global sensitivity analysis is instead recommended for a granular system understanding (Ferretti et al., 2016; Saltelli and Annoni, 2010). Through global sensitivity analysis, the variation in output is apportioned to the variation in each input factor over their entire range of value. 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.

Global sensitivity analysis methods can be classified into generalized sensitivity analysis methods, variance-based methods, globally aggregated measures of local sensitivities methods, density-based methods and meta-modeling methods. These methods are based on different theories and principles, and as a result, have different efficiencies. Saltelli et al. (2008), Ciuffo et al., (2012), and Pianosi et al. (2016) provided a useful overview of these sensitivity analysis concepts, methods, and framework, with suggestions on how to choose specific methods. But often, the choice of method is largely research field-dependent. Variance-based methods are the most popular approaches for global sensitivity analysis (Saltelli et al., 2019). The main advantage of global sensitivity analysis is that it can compute the main effect and higher-order effect of factors, respectively, and make it distinguishable which factors have a high influence on the output on their own, and which factors have high interaction with others, respectively. These are particularly important to elicit an in-depth understanding of the factor importance, which significantly constitutes the economic potential of LFM. In this way, a systematic determination of critical factors can be derived, which can guide the development of cost-efficient LFM projects and the identification of priority research areas to improve the current knowledge deficits. The previously mentioned methodology developed by Laner et al. (2016), used for analyzing the climate impact of LFM in Europe, employed variance-based global sensitivity analysis. Such features motivated the choice of adopting and developing a similar approach in this thesis for the economic assessment of LFM.

3. Methodology

3.1 Research context and journey

To contextualize, this research began as part of the NEW-MINE project or the EU Training Network for Resource Recovery through Enhanced LFM, which is a Marie Skłodowska-Curie Action under the EU Framework Programme for Research and Innovation Horizon 2020 (Grant Agreement No. 721185). NEW-MINE involves a consortium of higher education institutions and companies that mainly work with development of LFM technologies. In addition, civil society organization, governmental and non-governmental institutions are also involved as part of the advisory committee. In total, there are 15 PhD students whose research topics are distributed into four Work Packages (WPs). Three of which are about the development of innovative technologies along LFM process chain in terms of exploration, excavation and sorting (WP1), thermal treatment (WP2), and upgrading of residues from thermal treatment to high-added value products such as geopolymers (WP3). In contrast, WP4, to which my research belongs, focuses on the development and application of different sustainability assessment methods (environmental, economic, and social) for analyzing and comparing the impacts of different landfill mining and landfill management scenarios. Some of these scenarios involve the technologies and findings from WPs 1-3.

Under WP 4, the pre-defined milestones for my research are to develop and apply (i) a generic economic assessment method that can address both the net economic potential of LFM and critical factors for performance, and (ii) an extended economic assessment method for analyzing trade-offs between environmental and economic performance and evaluating the potential of policies and strategies for facilitating implementation. In this thesis, the focus is mainly related to the former that generated the three appended papers. The connections of *Papers 1-3* are illustrated in Figure 2.

Figure 2. The consecutive development of the appended papers (*Papers 1-3*) from the systematic literature review to the own developed method called the factor-based method.

To address the first milestone, it was necessary to do a systematic literature review of the previous economic assessments of LFM (*Paper 1*). Acknowledgement of the different empirical and methodological contributions of previous studies served as the basis for the development of a generic economic assessment method. In the review process, input data and presented results of different studies were collected and various method features were noted. In the process, knowledge gaps were identified that includes the empirical (i.e. data along the LFM value chain that are lacking or of limited availability) and methodological (i.e. physical and economic modeling and uncertainty and sensitivity analyses) aspects, as well as the relevant knowledge for further LFM development. The developed method is called factor-based method (*Paper 2*). The factor-based method was modified from that of Laner et al., (2016), which performed generic environmental assessment of LFM. Such approach is rooted from the field of engineering called statistical design of experiment, which is typically utilized for process improvement through screening of alternatives (NIST/SEMATECH, 2012). Additional data collection effort was done by taking advantage of the affiliation with the working group on LFM within the European Cooperation for Science and Technology - Mining the European Anthroposphere (COST-Action MINEA, Action No CA15115). Economic data on processes and price levels of relevance for LFM were collected, as well as landfill management and waste management practices and policies in different European countries (i.e., Austria, Denmark, Estonia, Finland, Serbia, Sweden). In terms of technological scope, only conventional technologies were considered, which are different from the innovative technologies in NEW-MINE, but with readily available data to be used. It was the only way to go forward, as no immediate primary data was expected within the NEW-MINE consortium because we all started our respective research at the same time. With the identified economic potential of LFM in Europe as well as the understanding of the generic critical factors that drive the net results, *Paper 3* was conceptualized. The model used in *Paper 2* was extended to explore strategies to improve the economics of LFM that was essentially done to show the practical application and flexibility of the factor-based method. Both *Papers 2 & 3* dealt with MSW landfills.

3.2 Economic assessment studies

The analyzed economic assessment studies in this thesis were identified from the systematic literature review (*Paper 1*) and the factor-based method (*Papers 2-3*). The overview of these methods are presented below, and for more specific description kindly refer to the Appended Papers in Section 8.

3.2.1 Systematic literature review

For the literature search, multidisciplinary science databases were used such as Scopus (1960-2017) and Web of Science (1975-2017). The search strings used were (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”. The subsequent literature selection was limited to studies that are available as full papers (e.g. journal articles, conference proceedings, technical reports) with quantitative economic assessments covering the entire LFM process chain. The coverage of the entire LFM process chain was selected 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. The selection of economic assessments was kept open and included all types of economic perspective (C-LCC, E-LCC, S-LCC), technologies involved (conventional technologies, best available technologies, emerging technologies), and geographical contexts (global, national, regional).

The contributions of selected studies were synthesized based on the reported net economic potential and main economic drivers. Apart from their contributions as individual studies, which are mostly case study-specific, the synthesis of individual results was done to represent a generic knowledge on the economics of LFM. In addition, a methodological review was performed based on criteria that were selected from the code of practice in LCC (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).

Through the review, knowledge gaps were identified in terms of empirical and methodological aspects, as well as the relevant knowledge for further LFM development. An analysis framework was elicited based on two dimensions such as the study object (*case study-specific* or *generic*) and extent of analysis (*decision-oriented* or *learning-oriented*). This analytical framework was used for assessing both the usefulness and validity of the synthesized main findings. 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 modeling choices. This was done acknowledging the emerging character of LFM with inherent large uncertainties that must be handled.

3.2.2 Factor-based method

The factor-based method adopted conventional LCC and involved only traditional and best available technologies. It is intended to only cover private economics taking primarily the perspective of landfill owners and LFM project managers, as they are in the forefront of adopting new alternative landfill management and bear the subsequent costs. It is also reflective of the primary interest of the NEW-MINE project. In addition, already existing large-scale LFM technologies were considered due to data availability, as previously mentioned. In a way, the technological consistency from upstream to downstream of the LFM process chain was assured in terms of level of maturity, as these technologies have proven practical use in conventional waste sorting and treatment.

The factor-based method applied here is an economic adaptation of the method developed by Laner et al. (2016) for environmental assessment of LFM. It is divided into three parts such as exploratory scenario development, physical flow and economic modeling, and global sensitivity analysis (Figure 3). Provided here is only a brief overview of the factor-based method. For more detailed description, see *Papers 2-3* in Section 8. Appended Papers.

Figure 3. Schematic illustration of the factor-based method that is developed to evaluate the importance of different factors for the economy of LFM.

The first part, exploratory scenario development, accounts for different scenario possibilities through factor variations at site, project and system levels. 12 factors were considered, each with 3 alternative datasets that generated 531,441 (3^{12}) unique LFM scenarios. The factors and the three specific datasets represent discrete choices such as minimum, average and maximum possibilities as used from selected studies in different countries in Europe through the systematic literature review (*Paper 1*), and through the LFM experts within COST-Action MINEA, as previously mentioned.

The second part, physical flow and economic modeling, specifies the respective material flows and economic accounting. The LFM process chain shown in the physical and economic flow diagram in Figure 4 is used for the modeling.

Prior to economic assessment, a balanced material and energy flow was assured through accounting for the fate of each material fraction and their properties as they transfer from each process steps. Then, each of the generated LFM scenarios were assessed economically to determine the individual project potential. The economic assessment accounted for project costs that corresponded to the processing and transporting of materials (internally and externally), and project revenues that corresponded to both direct revenues such as valorization of materials and recovered value of land or void space, as well as indirect revenues from avoided management costs in the reference case. The net present value (NPV) of the overall project was calculated for one metric ton of excavated waste using discounted cash flow analysis. The NPV was calculated as the cash flow over the period T using discounted cash flow analysis as in Equation 1,

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

wherein 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.

The last step, global sensitivity analysis, defines the granular analysis of critical economic factors that builds up the results. The sensitivity of the output with respect to varying factors was expressed by variance-based sensitivity indices. These sensitivity indices represented the quantitative measures to express the criticality of specific factors on their own through the first-order sensitivity index (S_i), in combination with other factors through higher-order sensitivity index (S_{Hi}), or both through the total-order sensitivity index (S_{Ti}).

The main effect contribution of input factor to the output is represented by the first order sensitivity index S_i that is calculated according to Equation 2. In Equation 2, 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_{F_i} 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).

$$S_i = \frac{V_{F_i}(E_{F_{\sim i}}(Y|F_i))}{V(Y)} \quad (\text{Equation 2})$$

The main and higher-order effects of factor F_i are represented by total-effect sensitivity index S_{Ti} that is calculated according to Equation 3. In Equation 3 the numerator is the first order effect of F_i , so that $V(Y)$ minus this term gives the contribution in the variance decomposition of all terms containing F_i (Saltelli et al., 2010).

$$S_{Ti} = 1 - \frac{V_{F_{\sim i}}(E_{F_i}(Y|F_{\sim i}))}{V(Y)} \quad (\text{Equation 3})$$

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 as in Equation 4. In this study, these sensitivity indices represented the quantitative measures to express the importance of specific factors (on their own and in combination with others) for the economy of LFM with respect to the overall project.

$$S_{Hi} = S_{Ti} - S_i \quad (\text{Equation 4})$$

3.3 Overview of appended papers

The contents of each appended paper are presented in terms of their aims, scopes, methods and results as shown in Table 1. The abstracts of each appended papers are provided below.

Paper 1: As 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 modeling 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.

Paper 2: 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.

Paper 3: Based on the results of *Paper 2*, this paper used an explorative approach to determine improvement strategies through different project organizational set ups, which involves value creation of bulk fractions such as RDF and fines residue. Specifically, RDF is internalized to the project that means accounting for an internal incineration process. While treatment of fines residue is further considered accounting for its potential high-value application instead of being re-landfilled. Similar to *Paper 2*, the implication of such variation in project organizational set up is investigated in terms of specific regional settings. Moreover, the importance of such variations in project organizational set ups are compared to other factors at site and system levels, with respect to their influence on the overall economic potential of LFM in Europe.

Table 1. Overview of the appended papers.

	Paper 1: Assessing the economic potential of landfill mining: Review and recommendations	Paper 2: Systematic assessment of critical factors for the economic performance of landfill mining in Europe	Paper 3: Exploring strategies for an improved economic performance of landfill mining in Europe
Aim	To critically analyze previous economic assessments of LFM in terms of the usefulness and validity of their provided results.	To enhance both the applicability and depth of current knowledge regarding what builds up the economic performance of LFM in different conditions and settings. A model for assessment is developed and tested.	To explore economic improvement strategies through different project organizational set ups, which focuses on the value creation of bulk fractions such as RDF and fines residue. The model from <i>Paper 2</i> is extended.
Scope	In terms of literature search and selection: <ul style="list-style-type: none">• Sustainability perspective: All, conventional, environmental and social LCC• Technological: All, traditional, best available, and emerging technologies in the entire process chain of LFM• Geographical: Global• Temporal: 1975-2017	In terms of modeling: <ul style="list-style-type: none">• Sustainability perspective: Conventional LCC• Technological: Traditional and best available technologies, specifically: excavation → separation and sorting → external WtE treatment (gate fee for incineration) → internal/external re-landfilling of fines residue• Geographical: EU• Temporal: Project duration	In terms of modeling: <ul style="list-style-type: none">• Similar with that of <i>Paper 2</i>, but with extended technological scope:• RDF is treated internally instead of externally (accounting for internal incineration process)• Fines residue is utilized instead of re-landfilled (accounting for potential uses)
Method	<ul style="list-style-type: none">• Literature search and selection<ul style="list-style-type: none">◦ Databases: Scopus and Web of Science◦ Search string: (economic* OR financial OR cost* OR benefit* OR expense*) AND (assessment OR analysis OR feasibility OR evaluation OR impact*) AND “landfill mining”◦ Selection criteria: quantitative economic assessment of the full process value chain of LFM	<ul style="list-style-type: none">• Data collection: Secondary (literature review, desktop search, COST Action MINEA experts’ group)• Economic assessment:<ul style="list-style-type: none">◦ Exploratory scenario development (531,441 scenarios)◦ Physical and economic modeling◦ Global sensitivity analysis	<ul style="list-style-type: none">• Data collection: Secondary (literature review, desktop search, COST Action MINEA experts’ group)• Modified economic assessment from <i>Paper 2</i>:<ul style="list-style-type: none">◦ WtE treatment with varying energy (heat and/or electricity) recovery efficiencies◦ Fines residue with varying fractions that are utilized

- Analysis of usefulness and validity by contrasting:
 - Methodological review (based from LCC Code of Practice)
 - Empirical review (net result and main cost and revenue items)

Results

• Studies are mostly decision-oriented than learning-oriented and cases are within EU • There is a limited large-scale LFM implementation posing inherent uncertainties • Issues on usefulness and validity are apparent primarily due to unaddressed uncertainties • LFM has a weak economic potential but studies lack guidance for improvement hence, learning-oriented analysis is recommended	• 80% (439,276) of the generated LFM scenarios show negative results • System-level factors are critical for the economic feasibility of LFM • Main costs are related to treatment and disposal of excavated and processed materials • Main revenues account to avoided landfill management costs - an indirect revenue • Site selection is of key importance from a practical perspective	• Profitable LFM scenarios increased by 18% (95,659), mainly due to the utilization of fines residue • System-level factors remain critical for the economic improvements of LFM • In practice, internalization WtE may also mean shared capital assets among landfill owners, or special agreement between landfill owners and WtE owners. In addition, subsidies as in production of renewable energy will further increase the revenues. • In practice, utilization of fines residue requires favorable quality standards for secondary material

3.4 Thesis method

The appended papers are utilized as means to address the research questions and thus, the thesis aim through the overall synthesis of their contributions as shown in Table 2. It is notable that all the *Papers* contributed to addressing each of the *RQ*, which is expected since they were developed as a spin-off of one after the other.

Table 2. The specific contributions of the appended papers to the corresponding research questions.

	<i>Paper 1:</i> Assessing the economic potential of LFM: Review and recommendations	<i>Paper 2:</i> Systematic assessment of critical factors for the economic performance of LFM in Europe	<i>Paper 3:</i> Exploring strategies for an improved economic performance of LFM in Europe
<i>RQ 1:</i> What are the knowledge contributions of different types of economic assessments of LFM?	<ul style="list-style-type: none"> • Categorization of intended usefulness of different economic assessments approaches • Synthesis of reported results in terms of net economic potential and constituent economic drivers 	<ul style="list-style-type: none"> • Determination of net economic potential and constituent critical factors using the factor-based method 	<ul style="list-style-type: none"> • Similar to <i>Paper 2</i> but more explorative targeting specific strategies for the development of cost-efficient LFM projects
<i>RQ 2:</i> In what ways can empirical constraints and methodological challenges influence the usefulness and validity of the results from different types of economic assessments of LFM?	<ul style="list-style-type: none"> • Demonstration how the real usefulness is influenced by empirical constraints and methodological challenges of different categories of economic assessments 	<ul style="list-style-type: none"> • Demonstration of how the factor-based method facilitates identification of generic economic drivers 	<ul style="list-style-type: none"> • Demonstration of how the factor-based method facilitates the development of strategies for cost-efficient LFM projects following <i>Paper 2</i>
<i>RQ 3:</i> How can the identified empirical constraints and methodological challenges be addressed?	<ul style="list-style-type: none"> • Highlights empirical knowledge needs along the LFM process chain • Methodological recommendations for different categories of economic assessments 	<ul style="list-style-type: none"> • Determination of priority setting for investments in know-how based on the identified generic economic drivers 	<ul style="list-style-type: none"> • Determination of priority setting for facilitating strategies for the development of cost-efficient LFM projects

The overall methodology for this thesis is shown in Figure 5, which illustrates the connections between the *RQs* and the *Papers* as well as the subsequent analysis and reflection.

Figure 5. Illustration of the overall thesis method as means to address the aim by showing the connections between the research questions and the appended papers. The flow diagram specifies the methods used and the integration of stepwise results.

RQ 1 aims to provide an overview of different knowledge contributions from different types of economic assessments of LFM. Through the systematic literature review in *Paper 1*, categories of the intended usefulness of different types of economic assessments is elicited based on two dimensions, i.e. their study objects (*case study-specific* or *generic*) and extent of analysis (*decision-oriented* or *learning-oriented*). This contextualizes each of the economic assessment studies in relation to the type of results they have presented in terms of the net economic potential, constituent economic drivers, and recommended strategies for economic improvement. Both the results from individual studies and more generic conclusions from the synthesis of the reviewed studies in *Paper 1* are used to exemplify the intended usefulness of different types of assessments. *Papers 2-3* contribute to *RQ 1* by exemplifying the type of results that can be provided by using the developed factor-based method. This approach is intentionally developed to systematically synthesize the *case study-specific* studies, and elicit *generic* knowledge. *Paper 2* focuses on the determination of the net economic potential and constituent economic drivers for LFM in Europe, while *Paper 3* explores specific strategies for economic improvement based on the identified economic drivers.

RQ 2 questions the usefulness and validity of presented results by focusing on the empirical constraints and methodological challenges for each of the categories of economic assessments from *RQ 1*. The empirical constraints and methodological challenges are connected to the fact that LFM is still an emerging concept. The results in *RQ 1*, are here critically analyzed for their usefulness and validity through their applied methodological rigor. Individual studies from *Paper 1* are compared with how the results from *Papers 2-3* are generated using the factor-based method. *Paper 2* demonstrates how the generic economic drivers for LFM in Europe are identified, while *Paper 3* demonstrates how the factor-based method can be used to facilitate the development of strategies for cost-efficient LFM projects. In essence, the generalizability of *case study-specific* studies is problematized and discussed against the *generic* studies using the factor-based method. The limitations of the factor-based method are also discussed.

In response to the observed empirical constraints and methodological challenges in relation to *RQ 2*, *RQ 3* aims to specify methodological approaches to improve the usefulness and validity of each of the identified economic assessment categories. This involved several different methodological approaches identified in connection with the studies in *Paper 1*, as well as in *Papers 2-3*. In addition, apparent knowledge needs are highlighted along the LFM process chain. From the identified generic economic drivers in *Paper 2*, different knowledge needs are identified and their prioritization are discussed i.e. which among the economic drivers needs further improvement. It is similar in *Paper 3*, but with particular focus on facilitation of targeted strategies for the development of cost-efficient LFM i.e. how can the knowledge of the economic drivers be used in improving the economics of LFM.

Furthermore, the role of economic assessments for emerging concepts like LFM is reflected upon in relation to ex-ante assessments. Specifically, reflecting on the importance of performing economic assessments that are *learning-oriented*, which can facilitate the development of concepts and technologies at the early stage of development.

4. Identified categories of economic assessment of landfill mining and their related challenges

Virtually all economic assessments of LFM are faced with large knowledge deficits because of the limited implementation of real-life and large-scale projects. As they are ex-ante assessments, the modelling of LFM is expected to involve many assumptions when it comes to both the selection and settings of the entire process chain and the use and treatment of underlying input data. These assumptions translate as the scenario and parameter uncertainties of the assessments, respectively. Table 3 shows an overview of the main scenario and parameter uncertainties identified in previous economic assessments of LFM (*Paper 1*).

Scenario development specifies the set of considerations to be investigated that includes the chain of processes and the surrounding policy and market conditions, which affects the relevant material, energy, economic flows. Here, the different processes, conditions and underlying model parameters that define the scenario are collectively called factors. Scenario uncertainties refer to the varying factors at the site, project, and system levels, which are used to develop unique LFM scenarios. It is expected that the choices made among such variations during the scenario development are discussed. When it comes to previous economic assessments of LFM, the selection criteria for the chosen landfill and its local settings are often unclear. The sites, therefore, seem to have been more or less randomly selected without any clear motivation of whether they were chosen due their content of potentially recoverable materials and energy carriers, a high potential for reclamation of valuable land area or creation of new landfill voidspace or for any other reason. For the project set-up, the main processing and treatment chains are typically fixed, with only some minor variations on the advancement of the involved technologies. Similarly, the criteria for such technology choices are seldom discussed, but rather the processing lines are treated as black boxes in which the underlying sub-processes are not specified. Furthermore, the recovered resources from the landfills are typically assumed to be of an acceptable quality and saleable to the existing markets. In the case of market rejection, subsequent treatment and disposal of the then secondary wastes are subjected to incumbent policy instruments such as taxes and gate fees. Although such system conditions could vary significantly among different regions and also due to the specific characteristics of the waste in question, the employed policy and market conditions and their possible implications on the results are rarely discussed. In essence, the lack of transparency regarding the support and motivations for the developed LFM scenarios in previous assessments limits the understanding of the implications of the results and other possibilities for the development of such projects, involving different site-specific settings, project set-ups and system conditions.

Apart from these scenario uncertainties, the corresponding input data also introduces additional uncertainties to the assessments. Parameter uncertainties refer to the quality of data that is used to quantify the material and energy flows of the LFM scenarios and related economic costs and benefits. In general, uncertainties of the underlying data employed in the reviewed assessments increase along the LFM value chain. Primary data is often used upstream for the waste

composition of the landfills, but still, it remains uncertain as it is not based on extensive material characterization studies but rather on limited sampling campaigns or estimates from logbooks of landfilled waste. Going further downstream the LFM process chain, the use of secondary data is more common. Here, the data for modelling the excavation, sorting and treatment of the landfilled waste often originates from other LFM pilot tests or, even more commonly, from the processing of other types of waste such as fresh MSW. Subsequently, for the recovered resources and produced secondary waste, the price for selling and disposal also varies, respectively. The price settings, even within a certain region, can vary widely due to the quality of the separated materials and energy carriers. However, such information on output quality and market quality requirements is also typically not addressed. The use of proxy data is inevitable for emerging concepts and technologies. However, the challenge is to address such parametric uncertainties and their implications to the results, which is often not done. Failure to address such parameter uncertainties limits the understanding of its influence, either driving negatively or positively, on the assessment result.

Clearly, there are several scenario and parameter uncertainties that must be addressed when assessing the economics of LFM. However, different assessments are done for different purposes, and the importance of addressing these uncertainties and the implications of doing so by different approaches could thus vary between different types of studies.

Table 3. 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	• Technology choice (conventional to advanced technology)	• Internal or external organizational arrangement	• Inclusion/exclusion of environmental and social costs and benefits/revenues	• Inclusion/exclusion of environmental and social costs and benefits/revenues
	• Inclusion/exclusion of hazardous waste	• Inclusion/exclusion of hazardous waste	• Marketability of secondary materials and energy (substitution: full, partial, no market)			
Parameter uncertainties	• Origin of costs/price data (where and when)	• Amount in terms of waste fraction or chemical composition	• Separation efficiencies	• Energy recovery efficiencies	• Material market prices	• Values of environmental and social costs and benefits/revenues
	• Amount of leachate and landfill gas		• Material market prices	• Energy market prices		
	• Discount rate					

Figure 6 shows the four categories of different types of economic assessments (Categories A-D) that were elicited in *Paper 1* based on their study object (*case study-specific* or *generic*) and extent of analysis of the economics of LFM (*decision-oriented* or *learning-oriented*). For each of the categories, specific methodological concerns are here raised using the findings from the systematic literature review (*Paper 1*) and the factor-based method (*Papers 2 & 3*).

Figure 6. The categorization of economic assessments (Categories A-D) in terms of study object (*case study-specific* or *generic*) and extent of analysis (*decision-oriented* or *learning-oriented*). The economic assessments from the systematic literature review (gray) and the factor-based method (blue) are categorized accordingly.

Most of the previous economic assessments on LFM fall under *Category A* (*decision-oriented and case study-specific*). These assessments aim to obtain an estimate of the net economic potential of a specific LFM project. Such aggregated forecasts on whether the realization of a planned project will end up with a net profit or net deficit can be useful to support the investment decisions of a certain landfill owner or project manager. Most of the studies explored the potential feasibility of LFM based on small-scale or pilot tests (Hermann et al., 2016; Wolfsberger et al., 2016; Zanetti and Godio, 2006; Zhou et al., 2015), or on other related projects for hypothetical studies (Danthurebandara et al., 2015b). Considering that these studies involve a specific LFM project, the explored scenarios are expected to be limited to a fixed landfill and its site-specific settings and the regionally-contingent system conditions in terms of different policy and market conditions. However, even for these fixed scenario levels, large parametric uncertainties are expected due to, for example, the lack of in-depth knowledge about the landfill content and how surrounding policy and market conditions will apply to unconventional practices such as LFM (Hernández Parrodi et al., 2018; Johansson et al., 2017). Such parametric uncertainties are, however, typically disregarding in these assessments. For instance, the material composition of the landfills in question is often based on average estimates despite the fact that large variations can be expected within most

landfill sites. Nevertheless, for these case-study specific assessments (*Category A*), the largest uncertainty on the scenario level involves the project set-up, and thus which processes and technologies that are to be combined to realize LFM. Here, however, only one project set-up is typically considered, which is mostly focused on the recovery of metals (Hermann et al., 2016b; Wagner and Raymond, 2015; Wolfsberger et al., 2016; Zanetti and Godio, 2006). The details on the separation and sorting processes are seldom specified, especially the efficiencies of separation. This lack of support and argumentation for the selected process chain raises concerns regarding how it actually was developed and to what extent different alternatives have been looked into. For those that have mentioned, no parameter uncertainties are accounted for considering that the separation is done only for a small part of the landfill site, if not using a proxy data from a completely different case. A complete disregard of both scenario uncertainties, on the project in particular, and parametric uncertainties subjects the assessment studies with questionable validity and usefulness to serve as a decision-support for project investment.

Similar to *Category A*, assessment studies under *Category C* (*decision-oriented and generic*) also aim to forecast the net economic potential of LFM but for the realization of multiple projects within a broader geographical scope. Such results can be useful for various actors interested in investing in LFM as a new line of business or for supporting landfill management policy-making. Although the scenario and parameter uncertainties discussed for *Category A* also are relevant here, they propagate significantly as more LFM scenario possibilities are expected, not just for the project set-up level, but also due to the wider scope of different landfills and their site-specific settings as well as surrounding policy and market conditions. Few of the previous economic assessments on LFM fall under *Category C*, and they have explored the economic feasibility of LFM on the national (Ford et al., 2013) and continental scopes (Van Vossen and Prent, 2011). However, despite their ambitious objective to assess the economic potential of implementing LFM on a large scale in a whole region, they only considered very limited scenario variations with different foci. For instance, the only options that were considered on the project set-up level involved different advancement levels for selected separation processes (Van Vossen and Prent, 2011) and different organizational set-up for a thermal treatment process that is either internal or external to the individual LFM projects (Ford et al., 2013). When it comes to the accounting of the waste composition of all the landfills to be mined in these regions, average values deduced from a few individual sources (e.g., waste sampling campaigns or reviews of landfill logbooks at a few sites) were used without accounting for any parameter uncertainties. For implications on LFM of policy and market conditions, policy insight was limited to showing the importance of green energy certificates for increasing the revenue from energy recovery of the exhumed combustibles. The market condition, in contrast, was kept at an ideal situation wherein the recovered materials were assumed sellable without discussing the possible quality issues of whether it satisfies the market standards or not. Apart from the neglected parametric uncertainties in this

category of assessments, which implies significant validity issues, the limited scenario considerations pose specific concerns about to what extent these assessments actually manage to account for the presumably large variations and multiple possibilities of implementing LFM in a whole region.

Going beyond knowing the net economic potential there are also economic assessments that extend the analysis towards the identification of its constituent economic drivers and their interrelations. Under *Category D (learning-oriented and generic)*, the conducted assessments aim for more disaggregated information regarding what builds up the net economic potential in multiple LFM projects within a broader geographical scope. This category of assessment has so far seldom been conducted on LFM and the ones that have suffered from several unaddressed scenario and parameter uncertainties (Damigos et al., 2016). In addition, the identification of economic drivers is only made on a highly aggregated level in terms of main cost and revenue items and without the granular understanding of the underlying factor interactions. The identified shortcomings of this category of assessments (*Paper 1*) led to the development and application of the factor-based method (*Papers 2 and 3*). Its main feature includes exploratory scenario development in which a wide range of LFM scenario possibilities that could be encountered in a certain region are generated by accounting for variations of different factors at the site, project and system levels. Then, global sensitivity analysis is performed to systematically identify the underlying critical factors and their interrelations (Ferretti et al., 2016; Saltelli and Annoni, 2010). Such a broad scope and in-depth understanding of what builds up the economy of LFM aims to facilitate the identification of strategies for the development of cost-efficient projects. That is, to provide knowledge to guide where and how cost-efficient LFM projects can be developed by considering the interplay between the selection of landfill sites for mining, technological choices and organizational set-ups, and implications of different policy and market conditions.

Similar to *Category D*, the conducted assessments under *Category B (learning-oriented and case study-specific)* also extend the analysis towards the identification of economic drivers that build up the economic potential, but in this case, for a specific LFM project. Such information can be used to facilitate strategic guidance on how the economic performance of the project in question can be improved (i.e., How can a specific LFM project be technically and organizationally set-up to improve its economic potential? How influential are the given conditions in terms of the chosen landfill site and the surrounding policy and market conditions?) (Danthurebandara et al., 2015c; Kieckhäfer et al., 2017; Van Passel et al., 2013; Winterstetter et al., 2015). At the same time, for an ex-post assessment, such information can be used to pinpoint what is accountable for a particular economic outcome of a performed LFM project (Rosendal, 2015). However, there are differences in how these studies assess and present the economic drivers of LFM compared to the approach of global sensitivity analysis used in the factor-based method. The studies belonging to *Category B* often just use hotspot analysis, which

only specifies how much some selected main cost or revenue items contribute to the net economic potential, while there are also such studies that aim for a more granular understanding through assessing the importance of underlying factors. Local sensitivity analysis is typically used, but it is unsystematic in revealing the critical factors, primarily because of its subjectivity. In addition, it is unable to address the interrelations among the input values that can be between different processes or specific parameters (Ferretti et al., 2016; Saltelli and Annoni, 2010). This poses concern on the identified critical factors and their importance, which may affect the subsequent improvement strategies expected for this category of economic assessment.

5. Usefulness and validity of the obtained results from different economic assessments

The knowledge contributions of different categories of economic assessments are discussed here, highlighting the implications on the validity and usefulness of the results from the empirical constraints and methodological challenges presented in Chapter 4. Different types of knowledge contributions are presented in terms of an increasing extent and depth of analysis of the economy of LFM, from the net economic potential, over the economic drivers and critical factors for profitability, and finally to the identification of strategies for facilitating the development of cost-efficient projects.

5.1 The economic potential of landfill mining

As previously mentioned, uncertainties are inevitable for any economic assessment, but they are particularly pronounced when it comes to studies of emerging concepts (Clavreul et al., 2012; Hellweg and Milà i Canals, 2014; Martinez-Sanchez et al., 2015). For LFM, the main problem is that most of the conducted assessments do not address them properly, thereby posing concerns both regarding the usefulness and validity of their obtained results. In Figure 7, selected results on the net economic potential of LFM from a few previous assessments are presented to illustrate the differences of information they convey. In general, accounting for uncertainties shows more information than a single value result. When scenario uncertainties are considered, several values showing the net economic potential of multiple LFM scenario possibilities are generated, while the accounting of parameter uncertainties results in a range of possible outcomes also for each of the studied scenarios due to uncertainty propagation caused by variations in the input data.

Figure 7. The net economic potential of landfill mining, as presented in the selected studies under each category of economic assessments. These studies show the differences of results depending on the scenario and parameter uncertainties accounted for; none is considered in Category A (red star), parameter uncertainties in Category B (broken yellow line), few scenarios in Category C (green triangles) and multiple scenarios in Category D (orange circles).

Most of the reviewed assessments of LFM belonging to *Category A (case study-specific and decision-oriented)* only reported the net economic potential as a single value result. In Figure 7, this is exemplified by the study of Wolfsberger et al. (2016),

where only one scenario is considered in terms of the selected landfill and its site-specific settings, the choice of technical and organizational set-up for the project and the surrounding policy and market conditions (red star in Figure 7). Such a one-scenario-only approach limits the usefulness of the results in terms of its applicability by missing out other possibilities for setting up a project for a specific landfill site. Moreover, in virtually all of these decision-oriented case studies, the input parameters are in terms of single values. This means that both stochastic uncertainties due to natural variations in the efficiency and performance of the LFM processes as well as epistemic uncertainties caused by the lack of practical experiences about these processes and thus the use of proxy data are disregarded. From a decision-making point of view, such simplified, one-value results may be desired, but their validity is largely questionable given that they involve presumably large but neglected uncertainties. As demonstrated by Frändegård et al. (2015) under *Category B (case study-specific and learning-oriented)*, the range of possible outcomes for a single LFM can vary widely if such stochastic and epistemic parameter uncertainties are accounted for. Although the inclusion of such economic risks typically generates more complicated results and is more common in learning-oriented studies (broken yellow line in Figure 7), it, in return, offers more reasonable results and provides information that an investor probably would like to know about. If such uncertainties are not considered, and the provided estimate on the net economic potential is wrong, it can either lead to a bad investment and end-up accruing economic liabilities (faulty profitability claim) or hinder further upscaling of the project (faulty non-profitability claim). For emerging concepts that are still at an early phase of development, such results with questionable validity limit the usefulness of decision-oriented assessments on emerging concepts that rather require guidance for further development.

Similar problems of the validity and usefulness of the obtained results are observed for the assessments in *Category C (generic and decision-oriented)*, where the economic potential of implementing LFM in a larger region is in focus. As exemplified by the study of Van Vossen and Prent (2011), the objective of assessing the economic feasibility of LFM in the entire European region is here addressed by only considering two scenarios involving different sorting technologies, and the obtained results are thus presented as two single values (green triangles in Figure 7). Apart from the project set-up, the variation in site-specific settings and the policy conditions are unexplored. In this case, it limits the usefulness of the result in terms of its possible applicability for identifying the influence of selecting different waste compositions as well as implementing different policy instruments. As demonstrated in *Papers 2 and 3* under *Category D (generic and learning-oriented)*, the economic potential of LFM in Europe can vary widely considering multiple discrete variations of factors (Fo-F11) at the site, project and system levels, each with three alternatives (3^{12}). For each project organizational set-up, dedicated to understanding the economic drivers (*Paper 2*) and exploring possibilities for further materials valorization (*Paper 3*), 531, 441 unique LFM scenario possibilities were generated and are presented as a cumulative distribution plot (orange circles,

Figure 7). It becomes apparent that the knowledge contribution in this case is much broader, which provides more information by showing how much the economic potential can vary within Europe as well as showing the corresponding influence of different factors at site, project and system levels. Without such an explorative approach in scenario development, the results can be of limited usefulness as decision support for landfill investors who need insights on site selection as well as for policy-makers who require insights on necessary policy instruments that can drive better economic feasibility of LFM in a region. With a broader view through the explorative scenario development, more information can lead to wider possibilities of how LFM can be developed and specify the roles of landfill investors and policy-makers, which is especially needed at this early stage of LFM development.

5.2 The economic drivers of landfill mining

Based on the reviewed economic assessments in *Paper 1*, it can generally be stated that LFM is a challenging business endeavor. So, it is imperative to extend the analysis about the economy of LFM to develop an in-depth understanding of the economic drivers that build up the net economic potential of such projects. Based on such information, measures and strategies for how to improve the cost-efficiency of LFM can be developed. However, the identification of economic drivers are done in different ways and are only assessed on the individual case studies in previous assessments. Most of the assessments in *Category A (case study-specific and decision-oriented)* only identify the economic drivers of LFM on a highly aggregated level through hotspot analysis, which specifies how much each cost or revenue items contribute to the net economic potential. While most of the assessments in *Category B (case study-specific and learning-oriented)* takes the analysis of economic drivers one step further through the employment of local sensitivity analysis, in which the overall variation of the net economic potential is apportioned to specific input parameter values. However, this approach is proven to be unsystematic in revealing the critical factors, primarily because of its subjectivity (Ferretti et al., 2016; Saltelli and Annoni, 2010). Typically, a few out of many potential factors are selected to be varied individually and investigate its influence on the results. Other potentially important factor can be missed out and possible interactions or combinational effects among the important factors are explicitly unaccounted for. In this case, the reported critical factors are of questionable validity, which may affect the subsequent improvement strategies expected for this category of economic assessment.

The fact that the previous assessments are mainly Category A and B analyze and present economic drivers on different levels of aggregation, from process and sub-process level to specific input parameters, makes it difficult to synthesize their results and come up with a generic knowledge of re-occurring economic drivers of LFM. Figure 8 shows the economic drivers in terms of main cost and revenue items

derived through an attempt to conduct such a synthesis of previous economic assessment of LFM (*Paper 1*).

Figure 8. The economic drivers of landfill mining in terms of the constituent main costs and revenue items derived from the collective studies based on the systematic literature review (*Paper 1*).

In Figure 8, most of the reviewed studies report that sales from recovered materials (which are almost exclusively related to metals) is an important revenue, while the value of reclaimed land and landfill void space or avoided landfill aftercare costs, are less frequently identified as main drivers. Here, it is however important to understand that, this does not mean that such revenue items are not important for the economic outcome of a LFM project, but rather that the so far conducted case studies have involved landfills with no or low aftercare costs situated in locations with relatively low land values and needs for new landfill void space. This inability to address the importance of case study-specific conditions (e.g. material composition and aftercare needs) and other local settings (e.g. needs and values for land and landfill void space) for the economy of LFM projects is an inherent characteristic of the reviewed assessments due to their focus on assessing only one case. Such an approach for the synthesis of results partly undermines the usefulness of the literature reviews of different case studies as a way to elicit generic economic drivers. Hence, in *Paper 1*, the identified main cost and revenue items can therefore only serve as hints with respect to a more generic understanding.

In contrast, Figure 9 shows notable discrepancies from the generated main cost and revenue items that constitute the net economic potential (NPV) of LFM by using the factor-based method (*Paper 2*). Again, the factor-based method considers an exploratory scenario development in which wide ranges of conditions and settings that can occur on the site, project and system levels are accounted for. In essence, the differences among the individual case studies are in a way normalized, by pooling in the possible variations of LFM within a region. With the considered site-specific settings as well as regulatory and market conditions, the revenue from the avoided aftercare costs is reported as more important than the sales from recovered

materials. The difference in the relative importance of these revenue streams influences the understanding about the economics of LFM. To improve the economics, the focus is not just to improve the quantity, quality and marketability of recovered materials but also strongly related to the selection of landfills with the potential for avoiding aftercare costs and prospects for other benefits due to reclaimed land and landfill void space. In terms of concerned stakeholders, such an understanding also shift the focus from the LFM practitioners to also considering policy-makers. For instance, policy-makers can influence the values of such revenue items through setting of the requirements and costs for aftercare as well as the criteria for what is an effective and sustainable use of urban land resources.

Figure 9. The economic drivers of landfill mining in terms of the component main costs and revenue items derived using the factor-based method. Note: The presented revenues from void space and land are only from one third of the scenarios due to the choice of project drivers (F4). Upon normalization, including scenarios with either land or void space recovery, their respective share of revenues are as high as or even higher than the revenues from materials.

Knowledge on the main cost and revenue items of LFM is however not sufficient for facilitating improvements of the cost-efficiency. In order to identify effective measures to decrease specific costs and increase revenues, a more systematic determination of the underlying critical factors is necessary. By using global sensitivity analysis as in *Paper 2*, a more systematic generation of such in-depth information about what builds up the economy of LFM can be provided. Through the total-sensitivity index, the influence of variation in a number of underlying factors (i.e. occurring on the site, project and system levels) on the economy of LFM can be determined. Furthermore, other sensitivity indices are also calculated to identify how these factors influence the results. The total-order sensitivity index is composed of both the influence of factor variation in terms of individual factors (first-order sensitivity index) and combinational effects due to interrelations among different factors (higher-order sensitivity index). Such in-depth understanding of what and how different factors build up the economy of LFM can facilitate the development of subsequent strategies for improvement.

In Figure 10, the relative importance of each factor variation are shown in terms of their total-order sensitivity index and specified for the NPV and main cost and revenue items of a large number of LFM scenarios that display the various conditions and settings that can be encountered in such projects within Europe.

Figure 10. The critical economic factors of landfill mining in Europe in terms of the total-order sensitivity index derived through the global sensitivity analysis (from *Paper 2*). It shows disaggregated information about the influence of variation of each factor (F0-F11) to the net present value and its component cost and revenue items.

For NPV, the three most critical factors account for about 80% of the total variation in the scenario results. These factors address the system level such as policy and market conditions that influence the costs and taxes for re-landfilling of generated residues (F9, 34%), intensity of required landfill management and aftercare (F3, 21%), and gate fees and taxes for external WtE treatment (F6, 12%). These correspond well as the underlying factors of the reported main cost and revenue items in the hotspot analysis (Figure 9). These three most critical factors primarily affect the NPV through a first-order manner. That is, the variation in NPV is influenced mainly by the variation in the datasets of these individual factors. The fact that F9, F3, and F6 address costs and prices means that their variation has a direct influence on the NPV. The information that is not shown in the hotspot analysis, but revealed here, is the importance of site-specific conditions that is the landfill settings (F1, 10%). Landfill settings refer to landfill site characteristics such as the deposited tonnage and geometry, which among other things influence LFM capacity, project duration, and aftercare costs. In contrast to the three most critical factors, landfill settings (F1) affects the NPV through combinational effects with other factors. F1 interacts with several other factors, influencing the physical flows of materials and valorization potentials throughout the entire LFM system.

Similar detailed information is also provided in *Paper 2* for the component main costs and revenue items of the NPV. For instance, such an in-depth analysis revealed that the total revenue from separated 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%). These factors influence the revenue for materials through combinational effects. That means the potential measures to improve the economic performance should collectively target the selection of suitable and more high-grade landfills for mining and the development of tailored processing and sorting lines, rather than as most of the reviewed case studies in *Paper 1* do, only call for policy and market interventions that influence raw material prices.

5.3 Generic strategies for improved landfill mining profitability

So far, it is argued that measures to improve the cost-efficiency of LFM that can be deduced from previous assessments are somewhat limited and incoherent. This is partly due to their case-specific nature but also because of their employed methodologies for assessing the economy of such projects. Typically, hotspot analysis and local sensitivity analysis are used to identify economic drivers but these methods often fail to provide a systematic understanding of how different factors and conditions along the LFM value chain jointly contribute to the economic outcome.

In *Paper 2*, the global sensitivity analysis of the factor-based method was therefore used to identify generic strategies that can facilitate the development of cost-efficient LFM projects through the selection of landfills and project set-ups in different regional settings involving different policy and market conditions. These generic strategies were simulated for two different regional archetypes in terms of high and low income and waste management standards. For each of these archetypes, the corresponding system level factors were fixed to represent their respective policy and market conditions. In total, seven factors at the system level (i.e. Fo-regional variations in excavation and sorting costs, F3-reference scenario, F6-waste-to-energy, F7-markets for materials and energy, F8-value of recovered land or landfill voidspace, F9-waste treatment, disposal and transport costs, F11-financial accounting), which can hardly be influenced by LFM practitioners were fixed to one of the three datasets. The simulation then focused on how the variation in factors on the site-specific and project-set up levels influence the economic outcome of LFM scenarios. There are five remaining factors (i.e. F1-landfill settings, F2-landfill composition and length of project duration, F4-project drivers, F5-excavation and sorting technology, F10-transport distances), which are under the influence of LFM practitioners that were allowed to vary giving a total of 243 scenarios ($3^5 = 243$). In other words, this archetype analysis targeted the key questions of how to select suitable landfill for mining by varying site-specific factors

and which organizational and technical project set-up is preferable in different site and regional settings by varying project-specific factors.

Figure 11a shows a graphical analysis of the net economic potential of the simulated LFM scenarios in the archetype region corresponding to a high income and high waste management standard. The graphical analysis shows which of the LFM scenarios are net profitable and how they are influenced by the combination of factor alternatives on the site and project levels. From such an analysis, it follows that the strategy for obtaining profitable LFM projects involve the selection of small-sized landfills with short project duration (F1-1), employment of highly advanced excavation and sorting technology (F5-3), focus on resource recovery and land reclamation (F4-2), and no particular preference (indicated by almost converging shapes) for landfill composition (F2). 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) implies that variations in revenue from recovered materials are insignificant relative to revenues from reclaimed land. In addition, 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. 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. 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).

(a) Most likely conditions for landfill mining in the present European situation, *Paper 2*

(b) Preferable conditions for landfill mining by exploring future European situation, *Paper 3*

Figure 11. Graphical analysis of the net economic potential (in NPV) of landfill mining in a European regional archetype with high level of economic income and high waste management standards. In contrast to the current system conditions (*Paper 2*, 11a), further utilization of refused-derived fuel and fines residue is shown to improve the overall economy by almost 60% (*Paper 3*, 11b). 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).

While the regional archetype analysis in *Paper 2* focused on the most likely conditions for LFM in the present situation, the factor-based model can also be used to guide future research towards promising paths of development. According to the identified economic drivers in *Paper 2*, the variation in NPV is strongly influenced by the price settings (system-level) for the management of LFM process wastes including treatment, transport and disposal (F9). However, a major model assumption in *Paper 2* is that the exhumed combustibles or RDF is merely a cost due to gate fees to external thermal treatment and fines residues as well in terms of expenditures related to their need for re-deposition.

In *Paper 3*, the economic potential for lowering these waste disposal costs by internal thermal treatment of RDF and utilization of fines residue as construction aggregates was explored. Internalization of thermal treatment means that the capital and operational costs for the construction of the WtE process are internal to the project as well as the revenues from the sales of output heat and electricity. In essence, the simulation in *Paper 3* focuses on the strategies for LFM project development in different future situations wherein both RDF and fines residue are valorized. This analysis was done for the same archetype region as in *Paper 2*. Figure 11b shows that in a region with high income and high waste management standards, further valorization of RDF and fines residue evidently improve the share of profitable scenarios by about 60% compared to that of *Paper 2*. The aforementioned strategies from *Paper 2* still hold true (i.e. selection of small-sized landfills with short project duration (F1-1), employment of highly advanced excavation and sorting technology (F5-3), focus on resource recovery and land reclamation (F4-2),). However, now with emphasis on the importance of selecting rich MSW landfills for improved economics (indicated by lowering NPV from rich to poor landfill composition). Furthermore, practical implementations of this strategies were discussed to be performed with alternative business models as well as policy instruments and regulatory requirements. Internalization of WtE may mean shared capital assets among landfill owners, or special agreement between landfill owners and WtE owners. In addition, subsidies due to the production of renewable energy will further increase the revenues. While for the utilization of fines residue, favorable quality standards for secondary material can be imposed as well as lifting of tax for re-landfilling.

6. Recommendations and reflections for the improvement of different economic assessment approaches

To address the empirical constraints and methodological challenges highlighted in the preceding sections, several recommendations are presented here to improve the usefulness and validity of future economic assessments on LFM. The recommendations correspond to the general assessment challenges; (i) applied research is needed to aid large knowledge deficits, (ii) methodological rigor is needed to account for uncertainties and systematically identify economic drivers and (iii) *learning-oriented* assessment is needed to facilitate future development of LFM.

Due to the emerging character of LFM, we are not yet in a position to make any profitability claim regarding LFM, not on the project level and certainly not on the regional scale. Before such assessments can be made useful and valid, extensive and applied research is needed to address key knowledge deficits such as the lack of information about the individual processes of the LFM value chain (parameter uncertainties) and a lack of know-how about how LFM could be realized (scenario uncertainties). Information regarding the LFM value chain include what resources can be extracted from landfills, at what quality levels, and under what conditions they will be accepted on existing markets. In order to gather such information, there is a need for a well-planned pilot projects, in which the efficiency, capacities and performance of different material and energy recovery technologies are developed and monitored on a large scale. While the LFM know-how refers to the facilitation of developing a cost-efficient LFM project. For instance, *Paper 2* identified that the most critical factors that drive the economy of LFM are at the system-level such as the costs for waste disposal, treatment and transport, as well as the imposed alternative landfill management that dictates the indirect revenue. In particular, knowing that high alternative landfill management costs drives cost-efficiency (*Paper 2*), it pinpoints the prioritization of selecting landfills with high remediation efforts (Frändegård et al., 2013) as platforms for learning about how to extract resources from deposited waste. Moreover, *Paper 3* identified the need for further research on how to valorize the bulk material fractions such as RDF and fines residue, which are otherwise disposed of, to maximize the net profitability.

If certain stakeholder demands any form of early economic assessments, the only way is to do forecasting studies with certain methodological rigor in which both parameter and scenario uncertainties are considered due to the aforementioned large knowledge deficits. Otherwise, it can lead to results with questionable usefulness and validity as in faulty results with implicit parameter uncertainties and missed out possibilities for implementation with unaccounted scenario uncertainties. The extent of the corresponding methodological rigor depends on the categories of economic assessment that is elicited in terms of the study object (*case study-specific to generic*) and the extent of analysis (*decision-oriented to learning oriented*). With broader study object, parameter uncertainties propagate as well as scenario uncertainties accounting for multiple scenario possibilities for LFM in consideration of varying factors at the site, project and system levels. With such large degrees of freedom, the question is where to draw the line of possible scenarios

for instance, in considering conventional and emerging technologies as well as current and future market and policy conditions. Such multiple degrees of freedom represents the characteristic complexity of modelling the development of emerging concepts and technologies such as LFM, which can be aided through participatory scenario development with various experts along the value chain (Voinov et al., 2016; Wender et al., 2014).

Specifically, for studies under *Category A (case-study specific and decision-oriented)* that considers a defined landfill site and under a specific system and regional condition, more scenario variations on the project-level are expected. That is to provide a decision support for landfill owner or project manager in selecting alternatives considering various technology choices (e.g., conventional or advanced process) and project organizational set-up (e.g., internal or external process, and different financing and business models). Similar scenario variations are expected for studies under *Category B (generic and decision-oriented)* but much more by also considering the variations at the site-specific settings as well as the system conditions within the addressed region in question. That is also to provide a decision support for LFM investor in prioritizing landfill sites as well as for policy-makers in implementing policy instruments to enable regional LFM development. Furthermore, with in-depth extent of analysis, more rigorous and systematic approach is expected in identifying *what* the underlying economic drivers are and *how* they build up the economy of LFM. Knowing the economic drivers (*learning-oriented*) lead to a more useful information for facilitating the development of strategies towards cost-efficient LFM, either as an individual project (*Category B, case study specific and learning-oriented*) or multiple projects in a broader region (*Category D, generic and learning-oriented*). Among the conducted studies in *Paper 1*, there are different employed approaches such as hotspot analysis and local sensitivity analysis, which provide a rather random manner of identifying the economic drivers, while global sensitivity analysis provide a more systematic understanding about what factors throughout the LFM process chain that jointly contribute to the economic outcome. For instance, the total-order sensitivity index identifies *what* factors build up the economy, while its component indices identify *how*, either in terms of direct effect by individual factors (first-order sensitivity index) or combinational effect due to interrelations among different factors (higher-order sensitivity index). Such information is important for developing subsequent improvement measures and strategies.

The factor-based method has addressed such explorative scenario development as well as the use of global sensitivity analysis. However, there are some particular challenges that are related to the factor-based method when it comes to setting up the factors and interpreting the generated scenarios. The selection of factors is tricky as it can be in different levels of aggregation like from process level to sub-process level. It should be clear that the selection of factors should depend on the purpose of the study. In the case of how it is used in *Papers 2 and 3*, it is about identifying the critical factors of the economics of LFM in Europe. So, the level of aggregation

of factors depend on the investigated scenario considerations in previous studies as well as the input of experts through the working group on LFM within the COST-Action MINEA. Hence, the selected factors are encompassing covering possible variations in the site-specific settings, project set-up as well as policy and market conditions. However, there is a difficulty in checking the plausible scenario upon allowing all factor combinations. As an approach to it, specific regional archetypes are simulated to narrow down the factor combinations and elicit more specific insights on the economics of LFM.

Regarding the parametric uncertainties, it is often unaccounted for by using single input values instead of range of values. Such range covers both the stochastic uncertainties due to natural variations in the efficiency and performance of the LFM processes as well as epistemic uncertainties caused by the lack of practical experiences about these processes and is usually substituted by proxy data, which in itself is uncertain. Accounting for parametric uncertainties is expected for all the categories of assessment to properly account for the variation of data values and the extent of their effect to the spread of the study results. For now, this is not an added feature of the factor-based method, as discreet alternatives (average value per alternative) are included. In this case, what is missed is the specific parameter improvement, beyond just pinpointing its importance. Such methodological rigor has some major implications on how to execute data collection. For better empirical support in all categories of studies, the collection of data for different processes and parameters should aim to cover the range of possible variation, rather than to obtain, as in many a single (but highly uncertain) value. In practice, this means having a detailed data collection among various experts along the LFM value chain, specifying the range of possible values accounting for both stochastic and epistemic uncertainties especially for processes that are not .

In order to guide LFM research towards addressing key challenges and potential solutions for cost-efficiency, *learning-oriented* studies are necessary (Fleischer et al., 2005; Wender et al., 2014). That means considering the available knowledge from previous studies as well as the knowledge of experts on how future scenario developments would look like (van der Giesen et al., 2020; Villares et al., 2017). Through *learning-oriented* assessments, as in the factor-based method, the future LFM research prioritization can be guided. For instance, according to their relative importance, specific factor improvements can be focused on such as selecting of landfills with richer recoverable materials at the site-specific settings, employing better separation efficiency or energy conversion efficiency at the project level, or implementing more favorable market standards and prices as well as lower taxes and gate fees at the system level.

In consideration of LFM as an investment-intensive undertaking, it is necessary to assure the usefulness of future assessments in terms of its applicability for facilitating a strategic development of future projects. As mentioned, with the emerging character of LFM, simply knowing the net economic potential (*decision-oriented studies, Categories A and C*) may hinder its further upscaling and

adaptation as an alternative landfill management, especially knowing that LFM is a challenging business endeavor. Above all, the current large knowledge deficits has to be first addressed. Figure 12 presents a scheme on how *learning-oriented* studies can work as complementary assessment approaches to the nowadays often seen *decision-oriented studies* as in *Paper 1*. As more extensive and applied research must be carried out to increase the empirical support, one fundamental question is which landfill site must be prioritized to exemplify economically favorable projects. Selection of site primarily depends on the system setting answering which are the favorable policy and market conditions (i.e., preferably with low costs for waste disposal, treatment and transport and high avoided aftercare costs). In this regard, *generic* and *learning-oriented* studies (*Category D*) can be used as in *Papers 2 and 3* to determine strategic locations for future pilot-scale and (eventually) large-scale project implementations. Then, to direct individual LFM projects in terms of technological choices and project organizational set-up, *case-study specific* and *learning-oriented* studies (*Category B*) can be used. In this way, more practical knowledge and primary sourced data will become available, feeding into the *generic* studies hence improving its results. With widely accepted conclusions that reveal the economic potential of LFM in a more systematic way, further development of favorable policy and market conditions can be advised for more cost-efficient LFM projects and provision of guidance for key research areas.

Figure 12. Illustration of the recommendations for the future use of economic assessments and their interactions towards a strategic development of cost-efficient LFM projects and directing future research.

7. Conclusions

Our current knowledge about the economic potential of LFM and its constituent economic drivers is limited and incoherent. This is rather expected as most of the studies are based on sporadic pilot-scale projects that were realized in many different ways and settings, which set a difficult basis to learn for future LFM development. As a way forward, several relevant questions need to be addressed such as for site selection (Which landfill site is suitable for mining?), project implementation (Which technological set up and project organizational set up are preferable?), and system conditions (Which policy and market conditions are favorable?) for LFM to become a cost-efficient landfill management alternative.

The review and scrutiny of various economic assessments led to better understand their different knowledge contributions by focusing on how they addressed different assessment challenges such as large knowledge deficits, lack of know-how for implementation and key economic drivers, and limited applicability of results covering the economy of LFM in general. These challenges correspond to the apparent need for addressing scenario and parameter uncertainties and the way they should be handled depends on the identified categories of economic assessment. Failure in doing so raises concerns about the respective usefulness and validity of performed assessments.

Based on the reviewed studies in *Paper 1*, four categories of economic assessment are elicited in terms of the study object (*case-study specific or generic*) and extent of analysis (*decision-oriented or learning-oriented*). Most of the previous economic assessments on LFM fall under *Category A (decision-oriented and case study-specific)*, which aim to obtain an estimate of the net economic potential of a specific LFM project. However, parametric uncertainties are typically unaddressed through single average values, which leaves the influence of inherently uncertain input data unaccounted for. Similarly, the scenario uncertainties are often unaddressed with single project set-up, missing out other project possibilities that can lead to better economic outcome. Exploration of more variations in project level in terms of technology choices and organizational set-up is needed. In this way, more scenario possibilities are considered that can be more useful for landfill owners or project managers for deciding among alternatives. This is performed in some assessments under *Category B (learning-oriented and case study-specific)*, which also extends the analysis towards the identification of economic drivers that builds up the economic potential. However, the problem is the applied methodological rigor in which more random identification of economic drivers are often employed through hotspot analysis and local sensitivity analysis. Few assessments have employed a more rigorous approach to systematically identify the critical factors using the global sensitivity analysis, indicating *what* critical factors are accountable for the variation in the economy of LFM.

Global sensitivity analysis is taken further by the factor-based method applied in *Papers 2-3* under *Category D (learning-oriented and generic)*, by also identifying *how* different critical factors build up the economy of LFM. This is done by showing the showing whether the influence of factor variation is in terms of direct-effect of

individual factors or combinational effects due to interrelations among different factors. Above all, moving from case-study specific to generic study object, more scenario variations must be considered. Apart from the variations in the project-level, variations in the site-specific settings as well as the system conditions are accounted for through the exploratory scenario development of the factor-based method. This is an improvement compared to the performed studies under *Category C (decision-oriented and generic)*, in which very limited variations are typically accounted for. In this way, the usefulness of the studies are improved in terms of producing generic knowledge on economic drivers and the subsequent facilitation of strategies for the development of cost-efficient LFM projects.

Acknowledging that LFM is still an emerging concept, more *learning-oriented* type of economic assessment is needed to account for multiple paths for development as well as to systematically identify the constituent economic drivers and facilitate the development of strategies for future LFM implementation. Through exploratory scenario development and global sensitivity analysis, the factor-based method is shown an approach for performing *learning-oriented* studies that can address relevant questions for site selection, project implementation, and system conditions for a cost-efficient LFM development. This thesis highlights the important role of economic assessments, which is not only limited for the assessment of economic potential but also for learning and guiding the development of emerging concepts like LFM, both for a single LFM project or multiple LFM projects in a region.

8. Research outlook

The ongoing research expands the scope in terms of the sustainability perspective and the emerging character of LFM technologies (Figure 13). These will enable more comprehensive sustainability understanding of the future LFM projects that involves advanced technologies. In addition, interesting methodological improvement and application of the factor-based method are foreseen when dealing with the temporal aspect such as future technological implementation as well as market and policy changes. In essence, it is anticipated to shed light on relevant LFM queries such as “Does the advancement in technologies contribute to better sustainability potential of LFM?” and “How can we guide further development of LFM technologies?” These questions target the core research endeavor of the funding project NEW-MINE, which deals with advanced technological solutions.

Figure 13. The expansion of research scope by including emerging technologies and the environmental dimension (from blue to orange region).

8.1 Economic and environmental trade-off analysis

In consideration of the same generated LFM scenarios, environmental assessment is being performed. It is of interest to show how the economically favorable scenarios compare with the corresponding environmental potential. Methodologically, as a first step, the environmental assessments are taken independently (LCA) from the economic assessment (C-LCC). The internalization of environmental costs and benefits, through monetary valuation, is not considered yet. This is due to avoidance of additional model uncertainties brought by the expected subjectivity of monetary valuation. In any case, further analysis focuses on the determination of underlying critical factors that drive both economic and environmental potential. In this way, more comprehensive information can be provided in terms of how to improve the potential of future LFM implementation in consideration of the two dimensions.

8.2 Advanced technologies from NEW-MINE

The availability of primary data from the NEW-MINE consortium is taken as an advantage to perform assessments for advanced processing of LFM. The program covers the entire LFM process chain from the exploration (non-invasive geophysical techniques), excavation and sorting (high-throughput and extended mechanical processing and sensor-based sorting), thermal treatment (incineration and hybrid solar-plasma thermochemical conversion), and upcycling of thermal treatment residues (multifunctional geopolymers such as concrete and ceramics). The collected primary data are from pilot to laboratory scales of application. Methodologically, this means additional upscaling techniques prior to the economic and environmental assessment, which further delves in the new research field of ex-ante sustainability assessments (Section 2.2).

8.3 Case study-specific and learning-oriented assessment

To further explore the flexibility of the factor-based method, it is planned to be used for the economic and environmental assessments of a specific LFM case. Currently, there is an ongoing large scale LFM project in Helsingborg, Sweden funded by the Re:Source program. In contrast with the generic and learning-oriented assessments done in Papers 2 and 3 (including Paper 4 as described in Sections 6.1 and 6.2), the final research paper (Paper 5) is planned to show how that factor-based method can also aid a case-study and learning oriented assessment. In this regard, relevant questions at the project level can be focused on such as designing of the LFM project in terms of technological and organizational-set up, which concerns specific landfill owner and LFM project manager.

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Appended papers

Papers

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