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The conceptualization of societal impacts of landfill mining – A system dynamics approach

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ABSTRACT

Landfill mining (LFM) refers to the excavation and processing of formerly buried waste streams. It offers significant environmental and societal benefits through the mitigation of greenhouse gas emissions or the reduction of long-term waste management costs. LFM's profitability, however, is still in question and public investment support might be necessary to fully exploit its potential. To enable decision-makers to identify the best solutions for a landfill site, societal impacts of LFM still have to be investigated. Throughout relevant literature, societal impacts of LFM projects have only selectively been studied and it remains unclear if and which benefits justify policy interventions. This paper firstly provides a comprehensive conceptualization of the societal impact of an LFM project and dives into the underlying societal context of this emerging industry. It disentangles formerly identified burdens and benefits by applying a system dynamics approach to LFM research. Based on this approach, four causal loop diagrams are presented showing how LFM is embedded into its societal context, analyzing the composition of the net societal impact of an LFM project, the mechanisms influencing LFM's public acceptance, and the dynamics of the market acceptance of LFM products. Key variables and leverage points have been identified, such as (i) technology choices influencing avoided impacts from the mitigations of primary resource consumption, since many societal impacts are closely related to environmental impacts, (ii) a timely and broad stakeholder involvement to prevent project opposition, and (iii) the after-use of the mined landfill, generating a major part of the local and regional societal benefits but also creating potential conflicts between stakeholder interests. Key intradimensional trade-offs and potential conflicts were identified in (i) spatial and (ii) temporal risk distribution, (iii) conflicting societal goals of the after-use such as job creations and recreation, as well as (iv) material and energy recuperation. These findings provide important insights for LFM decision-makers and can help to implement this emerging industry in a sustainable way.

1. Introduction

Landfill mining (LFM) entails the excavation and processing of formerly buried waste streams (Jones et al., 2013). The literature shows that LFM projects are likely to generate environmental benefits and reduce long-term landfill risks like groundwater contamination (Danthurebandara et al., 2015a; Frändegård et al., 2013; Pastre et al., 2018; Van Passel et al., 2013). The profitability of such projects is often uncertain and limited by specific contextual factors like tax exemptions (Krook et al., 2018; Laner et al., 2019). Besides potential environmental benefits, it is assumed that LFM projects also generate societal benefits that might justify subsidies, public-private partnerships (PPP), or other forms of investment support (Hermann et al., 2016; Winterstetter et al., 2018). Throughout relevant literature, societal impacts of LFM projects are only selectively assessed, using qualitative methods such as interviews, or ranking and monetization techniques (Einhäupl et al., 2019c). Drivers of LFM projects include urban development or socio-environmental risk mitigation, amongst others, whereas barriers are often linked to public opposition of LFM projects or the limited profitability (Einhäupl et al., 2019a; Johansson et al., 2012;

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Krook et al., 2012).[1] A clear distinction between economic, societal, and environmental factors affecting LFM implementation is not always possible as they have high levels of interlinkages and trade-offs. Often, due to a rather high degree of subjectivity and complexity, societal issues are not, or only insufficiently, considered (see section 1.1 for our definition of the societal dimension of an LFM project). There is no comprehensive societal assessment of LFM projects to date, and only a few exceptions aim at bridging the gap between qualitative and quantitative analysis (Damigos et al., 2016; Marella and Raga, 2014). While these studies provide important first insights into the magnitude of potential societal benefits of LFM, the results are also entangled with various societal factors. This makes it difficult to devise targeted steps that decision-makers could take to facilitate specific LFM projects. A learning-based approach focusing on qualitative research is needed to understand societal impacts before a meaningful quantification of impacts can take place.

In this study, we aim to disentangle and contextualize the societal dimension of LFM sustainability and conceptualize societal impacts of LFM projects. A comprehensive overview of the societal impacts of an LFM project will enable decision-makers to implement appropriate support mechanisms for LFM implementation where necessary and to fairly distribute potential benefits amongst stakeholders. To do so, we are using a system dynamics approach, developing causal loop diagrams (CLD) in the setting of sustainability research to identify indicators for the assessment of the societal dimension of LFM and enhance future modeling processes of multi-criteria assessments (MCA) in the field. We believe this methodically interdisciplinary and novel approach reveals important insights into the dynamics of the complex societal processes underlying an LFM project.

1.1. Theoretical background and research questions

The research presented in this study should be seen in the context of sustainability and sustainable development. The concept of sustainable development (SD) has emerged over time, and in 1987, the Report of the World Commission on Environment and Development (WCED): Our Common Future, also known as the Brundtland Report, gave rise to the modern definition of SD as a "development that meets the needs of the present without compromising the ability of future generations to meet their needs" (WCED, 1987). By defining the terminology, the Brundtland Commission clarified the discussion and emphasized the linkage between the three dimensions of sustainability: economy, ecology, and society. Since then the concept of SD has further been debated and developed. On the one hand, criticism about the fundamental contradiction between economic growth and ecological conservation seems confirmed over time along with the inability of institutions and governments to take sufficient action due to complex power structures supporting unsustainable development (Sneddon et al., 2006). On the other hand, climate summits have continued and the Paris Agreement marks an outstanding point of international commitment in recent history. Moreover, the United Nations (UN) has developed 17 sustainable development goals (SDG), narrowing down potential policy measures (United Nations, 2020). LFM is almost naturally affecting several of these SDGs (i.e. 6-13). The SDGs 9, industry, innovation and infrastructure, 10, reduced inequalities, 11, sustainable cities and communities, and 12, responsible consumption and production also highly interact with the societal dimension of sustainability and LFM projects. SDGs 9 and 12, especially emphasize the need for a transition to a circular economy (CE), in which LFM should be considered. The EU, for example, has about 150.000–500.000 landfill sites, and although the total potential for metal recovery is rather low, energy recovery and land reclamation are important factors to contemplate (Jones et al., 2013). Even in the EU, where a waste hierarchy has been implemented, making landfilling the least preferred option (Council of the European Union, 1999), 24% of the EU's municipal solid waste (MSW) is still being landfilled in 2018 (Eurostat, 2020). Considering the existing and emerging number of landfills, the long project duration of LFM projects (i.e. up to 20+ years), and potential environmental threats from older dump sites, LFM could play an important role in future CE models as well as for technological development in the recycling industry.

Furthermore, not only has the field of sustainable development advanced, but the concept of sustainability itself has also been subject to debate and development since the Brundtland Report. In contrast to the three pillar model of the sustainability dimensions, giving each dimension equal weight and a seemingly clear separation between them, we support a strong sustainability framework where the economic dimension focusses on microeconomic impacts and is defined within the societal dimensions, which includes macroeconomic aspects and is again defined within the environmental dimension (Hopwood et al., 2005). Fig. 1 shows the applied sustainability concept. The dimensions of sustainability are not independent of each other nor are their causes and impacts restricted within the same dimensions. Industrial projects like LFM interact with all three dimensions and link them through the derived impacts of their processes.

We define the limits of the economic dimension of LFM to (private) microeconomic impacts affecting the costs and revenue streams of a landfill. Even if the landfill is owned and operated by a public entity, as many landfills are, the cost and revenue structure still follows general microeconomic principles and is thus not assigned to the societal dimension. While the environmental dimension of LFM comprises the interaction of LFM processes with the natural environment through emissions to soil, air, and water, the societal dimension comprises the interaction of LFM processes with macro- or socio-economic and societal impacts, as well as interactions of environmental impacts with society, i.e. socio-environmental impacts. While the added complexity of the societal dimension helps to conceptualize impacts, it also makes the modeling process of these impacts difficult to generalize and leaves room for subjective interpretation (Einhäupl et al., 2019b).

Nonetheless, attempts are made to develop a general methodological framework for the assessment of societal impacts. These include social life cycle assessment (sLCA) (Traverso et al., 2013) and social life cycle costing (sLCC) (Hoogmartens et al., 2014), amongst others. Due to their general approach to include everything from a local to a global scale, or their limited scope considering only monetary and monetizable impacts, respectively, and often not considering social ones, these methodological approaches are not immediately suited to assess impacts of a specific type of industrial projects, like LFM, and often have to be adapted heavily. A common sLCA framework similar to the ISO norms for life cycle assessment (LCA) (c.f. ISO, 2006), for example, is still under development but already covers a vast amount of indicators that often do not reflect the needs of stakeholders involved in a European LFM project (c.f. Einhäupl et al., 2019a; Traverso et al., 2013).

To tackle these challenges, we are following an anticipatory approach, including stakeholder perspectives and uncertainty through prospective modeling to assess societal impacts of LFM projects (Einhäupl et al., 2019a; Wender, 2016). Through this approach we are able to integrate different stakeholder values and, step by step, build an assessment model, using stakeholder

[1] More detailed literature reviews of the societal assessment of LFM projects can be found in Einhäupl et al. (2019a), and Einhäupl et al. (2019c).

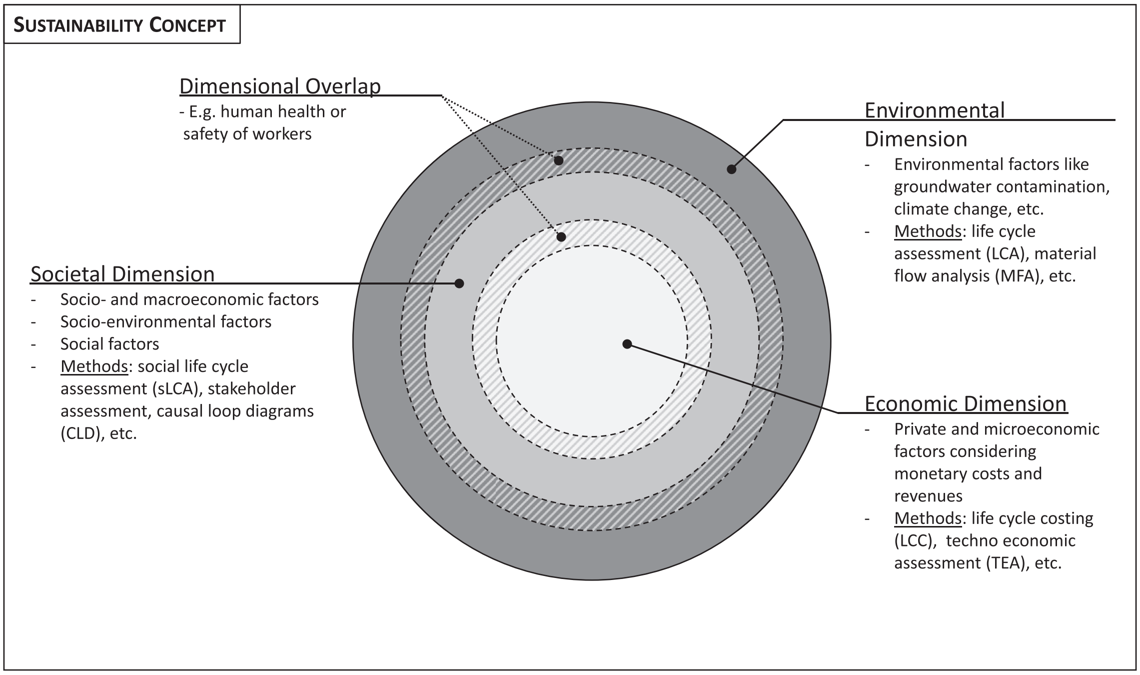

Fig. 1. The sustainability concept applied to define the various aspects and factors of the societal dimension of LFM.

interviews and focus groups and build upon our learning based approach.

This also defines the scope of this paper, including socio-environmental as well as socio-economic, and social impacts but not impacts attributed to the other dimensions of sustainability. Furthermore, this paper considers an industrial scale of one LFM project. This means the research is following a project-based viewpoint and macroeconomic effects of implementing LFM at a systemic scale that could lead to higher European resource independence or accumulated welfare gains are therefore not considered. The goal of the paper is to conceptualize former and new findings in the field of societal assessments of LFM projects, define key variables for future modeling processes, and identify leverage points to influence these societal impacts. To do so, we have developed CLDs showing relations and effects of LFM processes based on the system dynamics methodology (Forrester, 1994; Sterman, 2000).

After defining the scale and scope of the research we have developed four essential research questions to investigate the societal dimension of LFM:

1. How does LFM production relate to its societal context?
2. What are societal benefits and burdens of an LFM project comprised of and affected by?
3. What affects the acceptance of an LFM project by both the public and the market?
4. What key variables and leverage points can be identified to enable LFM practitioners and policymakers to influence societal impacts of an LFM project?

1.2. Research context

The study at hand is a continuation of two former studies where we elicited 18 stakeholder needs of LFM practitioners (Einhäupl et al., 2019a) and developed five stakeholder archetypes to outline major differences in approaching LFM implementation (Einhäupl et al., 2019b) by conducting 13 semi-structured interviews.[2] Both studies evolved around the Remo landfill, located in the Flanders region of Belgium, where the operator aims to develop an LFM project with a high degree of stakeholder involvement. The total area of the site comprises about 230 ha, of which about 160 ha are dedicated to landfilling. It carries industrial waste (IW) as well as MSW to roughly equal parts amounting to a total of about 16.5 million metric tons. Necessary leachate collection and treatment facilities, soil protection measurements, and methane recovery systems are installed. The landfill lies within a densely populated area and is surrounded by several small communities where public support as well as public opposition for the project has formed (Geysen, 2017; Group Machiels, 2018; Quaghebeur et al., 2013). LFM operations are expected to last for about 20 years, after which the construction of a recreational area in the form of a park is planned on the excavated landfill area. The Remo case should be kept in mind by the reader as an example of an LFM project, as many participants of the focus group for our study at hand, held at OVAM, the Flemish waste agency, did the same.

2. Method

Causal loop diagrams (CLD) are a part of the system dynamics methodology developed at the Massachusetts Institute of Technology (MIT) Sloan School of Management in the 1950s that has since progressed (Forrester, 2007a). Originating from business economics, system dynamic tools have been adapted over time, and their scope of application has widened. Being a relatively young field of research, the methodology will advance further as new use-cases are applied as our understanding of the complex world around us progresses (Forrester, 2007b). Through an iterative process, complex systems are analyzed (1) and modeled (2 & 3) to derive policy implications (4), consequently make new

[2] A descriptive summary of the 13 stakeholder interviews can be found in Einhäupl et al. (2019b).

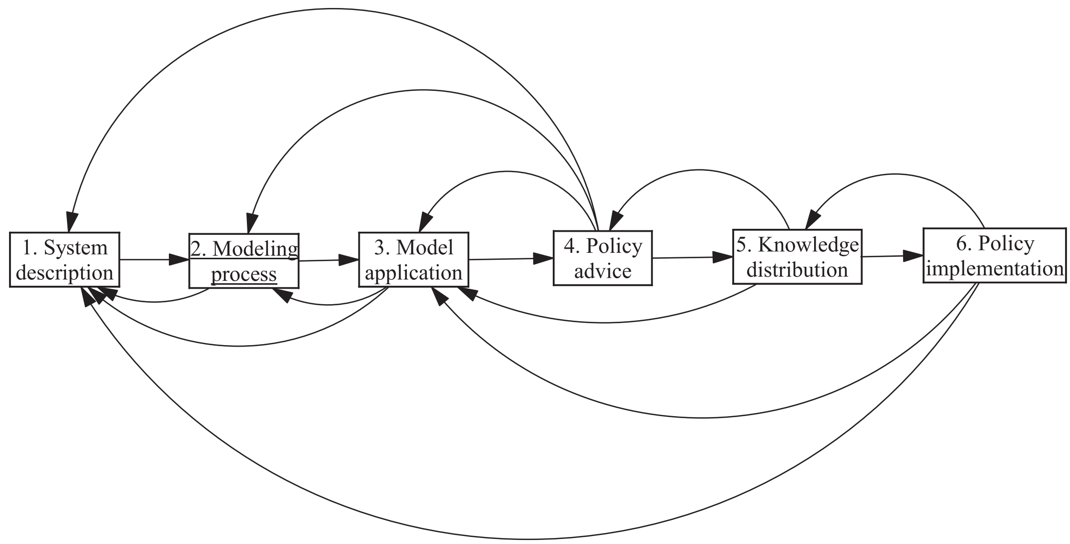

Fig. 2. The iterative system dynamics approach (Forrester, 1994).

observations (5) to refine the underlying model, to then adjust the policy implications (6). Fig. 2 shows this iterative process (Forrester, 1994).

The current study is focusing on the modeling process (2) of this iterative process. Within this methodology, CLDs are a common tool used to model the processes in question. We are using this tool to develop a quantifiable model for societal impacts of LFM projects in the long run. However, we need to understand the relations of societal impacts qualitatively first to build a sensible, quantifiable model.

CLDs connect different, previously defined variables through causal relations represented by arrows. A positive relation, represented by a plus sign (+), indicates a change induced by the causal variable in the dependent variable in the same direction, whereas a negative relation, represented by a minus sign (−), indicates a change induced by the causal variable in the opposite direction of the dependent variable. A delay of the effect is indicated by two parallel lines crossing the arrow (||). Through this practice, linear and circular relations of different variables become visible. In the case of a circular relation, a causal loop is created that can either reinforce (R) change over time, or balance (B) the effects of the different variables involved (Morecroft, 2015; Sterman, 2000). Our goal of using this method is to identify the relevant variables and potential indicators needed to model societal impacts of LFM projects and scenarios, to formalize causal relations between them, and to detect potential leverage points to influence the system at hand. A schematic representation of a CLD can be seen in Fig. 3.

Throughout our research, the CLDs were designed using a six-step process: (i) the categorization of key variables, (ii) the development of CLD drafts, (iii) the conduction of one-on-one workshops with LFM experts,[3] (iv) the refinement of the CLD drafts, (v) the triangulation of the preliminary results with a focus group, and (vi) the finalization of the CLDs.

The first set of key variables (i) were derived from the literature as well as the preceding research.[4] This included 13 interviews from the two former studies with LFM stakeholders, who were selected along a quadruple-helix framework, including industrial, institutional, communal, and scientific actors (c.f. Einhäupl et al., 2019). The variables were then categorized in a two-dimensional matrix defining the level at which the variables apply as one dimension (i.e. site, project, or system level), and their role within an LFM system as the second dimension, differentiating between exogenous variables, which influence but are not influenced by the societal LFM system itself, and endogenous variables, which are intrinsic to the LFM system. From these variables, CLD drafts (ii) were created. A table with the categorized variables can be found in Appendix A (Table A.1 and A.2).

The preliminary results were then discussed with four LFM experts in one-on-one workshops (iii). These workshops consisted of three essential parts. First, semi-structured interviews were held where participants (a) described their role in LFM implementation, (b) shared their experiences with LFM and/or remediation projects, and (c) explained what public benefits and burdens, (d) external influencing factors, and (e) uncertainties they perceived in LFM projects, and (f) characterized the roles of the most influential actors in LFM projects (cf. Appendix A). During the second part of the workshops, participants were asked to define key variables of societal processes underlying an LFM project and consequently define relations between those variables. The third and last part of the

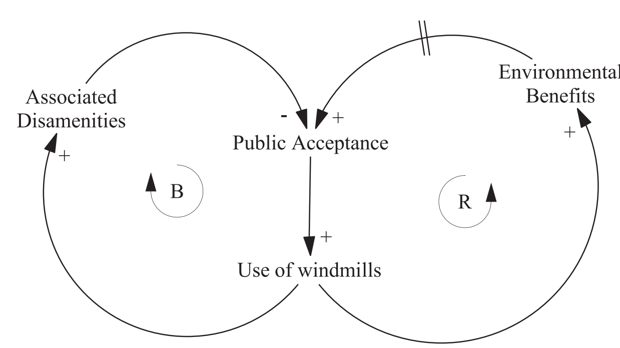

Fig. 3. A generic example of a causal loop diagram containing both a reinforcing (R) and a balancing (B) loop. Simplified, we can assume that with the growing use of windmills environmental benefits increase, and this again, with some delay (||), increases the public acceptance of windmills (R). On the other hand, with increasing use of windmills, the associated disamenities will also grow, which could lead to a decrease in public acceptance (B).

[3] The experts included actors from research, landfill operations, as well as environmental and waste agencies.

[4] A table with an overview of the societal factors of LFM derived from literature can be found in Einhäupl et al. (2019c), including case data, assessment type and method, and a summary of the results of each study.

one-on-one workshops left room to discuss some aspects of the CLDs previously designed by the researchers. One workshop took approximately two hours. From the gathered data the CLDs were further refined (iv).

To triangulate the data (v) one final focus group was organized in cooperation with OVAM (the Flemish waste agency) including 12 participants from industry, governmental, non-governmental, and scientific institutions. During the focus group, an introduction to LFM was given by the researchers and OVAM. Participants were then subdivided into three groups to complete two exercises developing CLDs, with an even distribution of stakeholder types overall groups. First, participants were asked to define a list of key causal variables as well as dependent variables, including the level of application (site, project, or system). Second, the identified variables were then used to develop CLDs of societal impacts underlying an LFM project. The results were presented by each group and discussed. Fig. 4 shows the workflow followed to develop the CLDs. The group discussion, as well as the semi-structured interviews, were recorded and findings tabulated for analysis. Materials developed during the focus group (i.e. the variable lists and CLDs) were also integrated into the analysis. Some identified variables were consequently dismissed by the researchers as they were considered to be out of scope, having only (private) economic impacts or relating to strictly environmental issues. The following section shows the results of this iterative process. The final CLDs (vi) were designed using VENSIM® PLE 8.0 software.

3. Results

The results are presented in four CLDs. The first CLD shows how LFM production is embedded in its societal context. The other three CLDs zoom in on specific aspects of the societal dimension of LFM (c.f. underlined variables in Fig. 5, Section 3.1), namely the composition of the societal impact, the causal relations underlying LFM-project acceptance, as well as the market acceptance of LFM products. Key variables and potential leverage points are described throughout this section according to the CLDs.

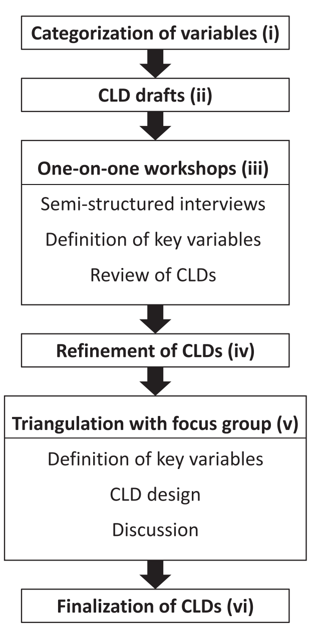

Fig. 4. The workflow to develop the causal loop diagrams (CLDs).

3.1. Societal aspects of LFM production

The first CLD gives a simplified overview of the most important societal aspects affecting and being affected by a specific LFM project. Its main purpose is to guide the reader through the following CLDs by providing an overview of how the main societal aspects of LFM production are related to each other. It should be noted that the details of effects taking place will be shown in the following CLDs, and that additional causal relations exist at a systemic level of LFM implementation, i.e. an industrial implementation with many LFM projects as well as their relations to the general socio-economic system, but these are considered out of scope for this study.

As can be seen in Fig. 5, LFM production consists essentially of material and energy recuperation during the industrial project's runtime, as well as the land to be used after operations are finished, i.e. the after-use utility. Through the excavation and processing of the waste, as well as the construction of the after-use downstream of the excavation work, LFM produces pollution that affects the societal impact of an LFM project negatively. If the actual societal impact decreases, then, according to the LFM stakeholders, the perceived societal impact also decreases, and with it the LFM-project acceptance. Thus, the regulatory uncertainty increases, and the market acceptance of LFM products decreases, resulting in less material and energy recuperation, which ultimately decreases LFM production and its related pollution. This balancing loop (B1) counteracts the reinforcing loop (R1) initiated by the beneficial effects of LFM production, i.e. the after-use utility and the avoided impacts through the mitigation of primary resource production, affecting the societal impact positively.

A growing, positive societal impact will also increase the perceived societal impacts and with it LFM-project acceptance, therefore lowering the regulatory uncertainty and increasing market acceptance and LFM production (R1). It is important to note that the reinforcing loop (R1) takes effect with a delay (||). The avoided impacts can only be accounted for after the excavation, processing, sale, and use of the recuperated materials and energy, whereas the after-use utility only takes effect after industrial LFM operations are completed.

3.2. The composition of the societal impact

The societal impact can be separated into societal burdens and benefits, which can take effect at different scales, i.e. local, regional, and systemic. Local and regional burdens and benefits are joined into one variable, respectively, as LFM usually impacts both in similar ways. The traffic resulting from the transport of LFM products, for example, has to go through the local community but also the region. If a landfill is situated in the middle of various communities, local effects can accumulate to regional effects. Only in exceptional cases can these contradict each other: if, for example, housing is created in the after-use phase, this could be interpreted as a benefit for the region but as a burden for the community, which has to endure the constructions and might resent new residents. Systemic impacts, like CO_2 reduction or avoided impacts from mitigated primary resource production, on the other hand, often manifest in different locations than their related burdens, and are thus considered separately. Monetary benefits and burdens are separately considered and defined as societal revenues or societal costs.

The research shows that the burdens (c.f. underlined variables) generated by LFM projects, as well as the systemic benefits (c.f. italic variables), derive from LFM operations (capital letters), i.e. the material and energy recuperation, whereas the local and regional benefits almost exclusively derive from the after-use of the landfill

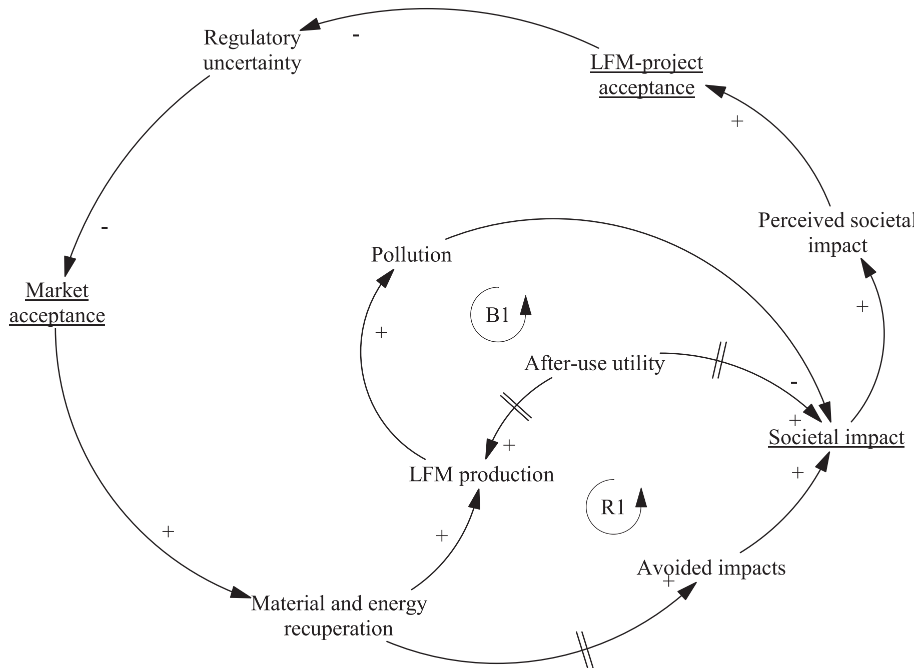

Fig. 5. The main societal aspects of LFM production. The green arrows lead to the reinforcing loop (R1), whereas the red arrows lead to the balancing loop (B1).

area. Societal revenues (c.f. bold and italic variables) are generated through welfare effects and tax income. Societal costs (c.f. bold and underlined variables) are generated through subsidy schemes. Nonetheless, the benefits of LFM take a delayed effect (||), and burdens have to be endured first by local and regional stakeholders. Fig. 6.

Employment, but also LFM production, generate tax income, which is considered a societal revenue. Tax exemptions that might be granted to the operator for re-landfilling would decrease the societal revenue. The mitigation of long-term risks related to landfills, like groundwater contamination or landfill gas (LFG) leakage, is another societal benefit that can reduce long-term waste fees. In addition to the long-term risk mitigation, the avoided primary resource production is considered the largest systemic benefit.

On the other side, societal burdens mostly originate from pollution through the material and energy recuperation and local and regional disamenities, i.e. dust, odor, noise, and traffic. These cannot only directly cause health impacts but also generate stress and affect community well-being. This could lead to anger and also increase the risk of opposition. Subsidy schemes are considered the counterpart to tax income and would generate a societal cost at different scales depending on their origin.

As most burdens and benefits originate from LFM operations these are also considered the crucial leverage points for LFM practitioners. The choice of waste-to material (WtM) and waste-to-energy (WtE) technology can influence the avoided primary resource production significantly. However, it should be noted that a trade-off between energy and material valorization has to be considered. As the waste quantity is limited by the landfill, all materials that are treated thermally cannot be recycled as secondary raw materials, and vice versa. Moreover, these impacts, of course, also highly depend on the waste composition at the landfill site that ultimately limits the extent of the avoided impacts and affects the choice of technology. However, being an exogenous variable only indirectly influencing societal impacts through direct environmental impacts, it is left out of the diagram to reduce its complexity.

A key variable and leverage point for local and regional benefits is the after-use utility. It depends highly on exogenous variables, of which some, like rents or house prices, could be regulated by institutional and governmental actors to some extent. The regulation of these effects, however, takes place at a systemic level and would impact communities at a much broader scale than the effects of an LFM project. It is, thus, considered out of scale of this study. As can be seen in the diagram, a trade-off between rising house prices and rising rents might have to be considered. If public recreational infrastructure is created on the excavated landfill area, house owners would benefit from a value increase of their property, while tenants might have to pay higher rents. These value changes cannot simply be offset with each other. The number of affected people, as well as the income distribution amongst them, have to be taken into account. For tenants with relatively low incomes, even a small increase in rents can put considerably more pressure on their budget constraints. Additionally, local and regional burdens though disamenities can be leveraged through protective measures like the use of water sprinklers to avoid dust creation, the use of conveyor belts to avoid traffic, or noise-canceling facilities at roads and around the landfill.

Another exogenous variable that affects burdens, as well as benefits of LFM, is the distance to residential areas. While a greater distance can reduce the burden of disamenities to the surrounding communities, they would also benefit less from the after-use. Seemingly, no causal loops are expressed in the diagram. This is a consequence of looking at only one detailed section of the whole societal context of LFM only. Embedded into the bigger picture (c.f. Fig. 5) of an LFM project, the societal impact affects LFM-project acceptance and is affected by the (private) economic dimension of LFM through technology choices or the project runtime, for example.

3.3. *The dynamics of LFM-project acceptance*

The variables affecting and being affected by LFM-project acceptance, shown in Fig. 7, can be subdivided into four clusters. The first cluster can be described as the stakeholder involvement

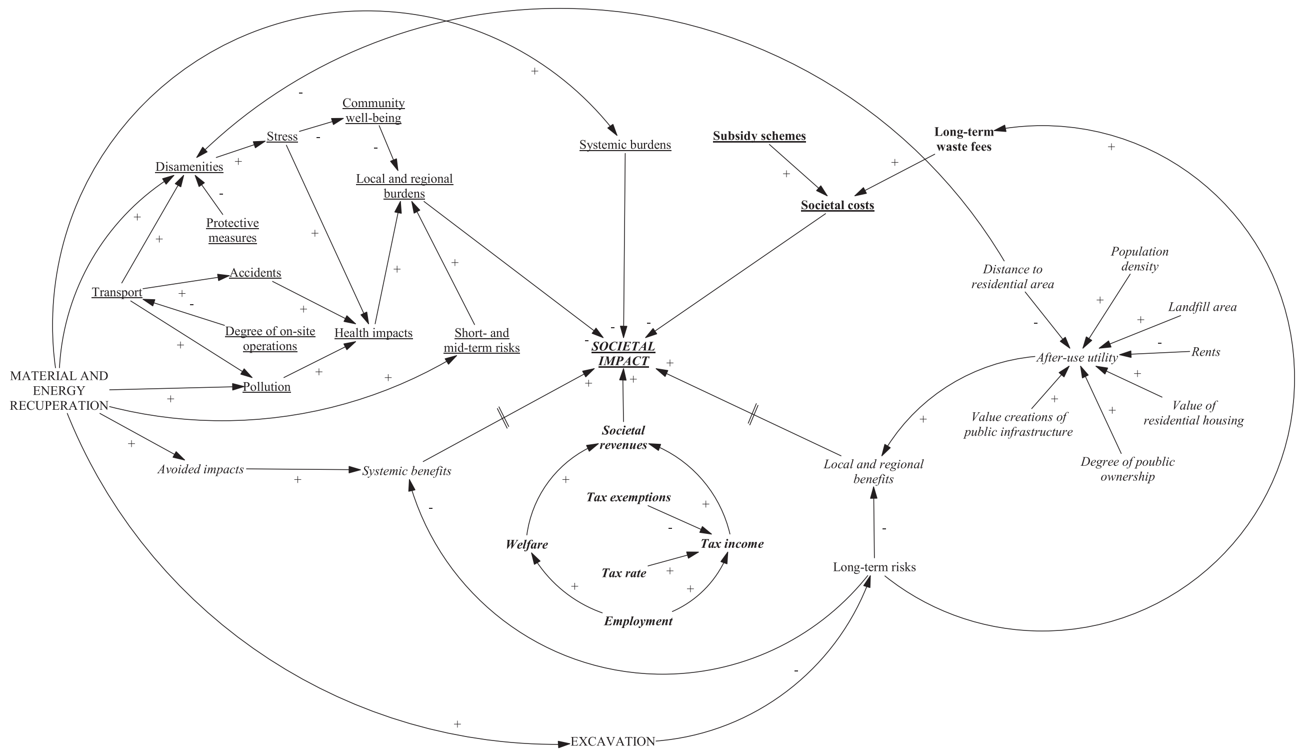

Fig. 6. The composition of the societal impact of an LFM project. Societal benefits and revenues are displayed in italics, while societal burdens and costs are displayed as underlined variables.

cluster (c.f. underlined variables). The second cluster refers to variables in the context of regulatory aspects (c.f. italic variables), whereas the third cluster addresses operational factors (c.f. no emphasis). The last cluster considers variables affecting the perceived societal impact and their relation to LFM-project acceptance (c.f. bold variables).

The main leverage point to influence LFM project acceptance is stakeholder involvement. The scale of stakeholder involvement describes how many stakeholders are involved in the implementation of an LFM project, while the scope describes what kind

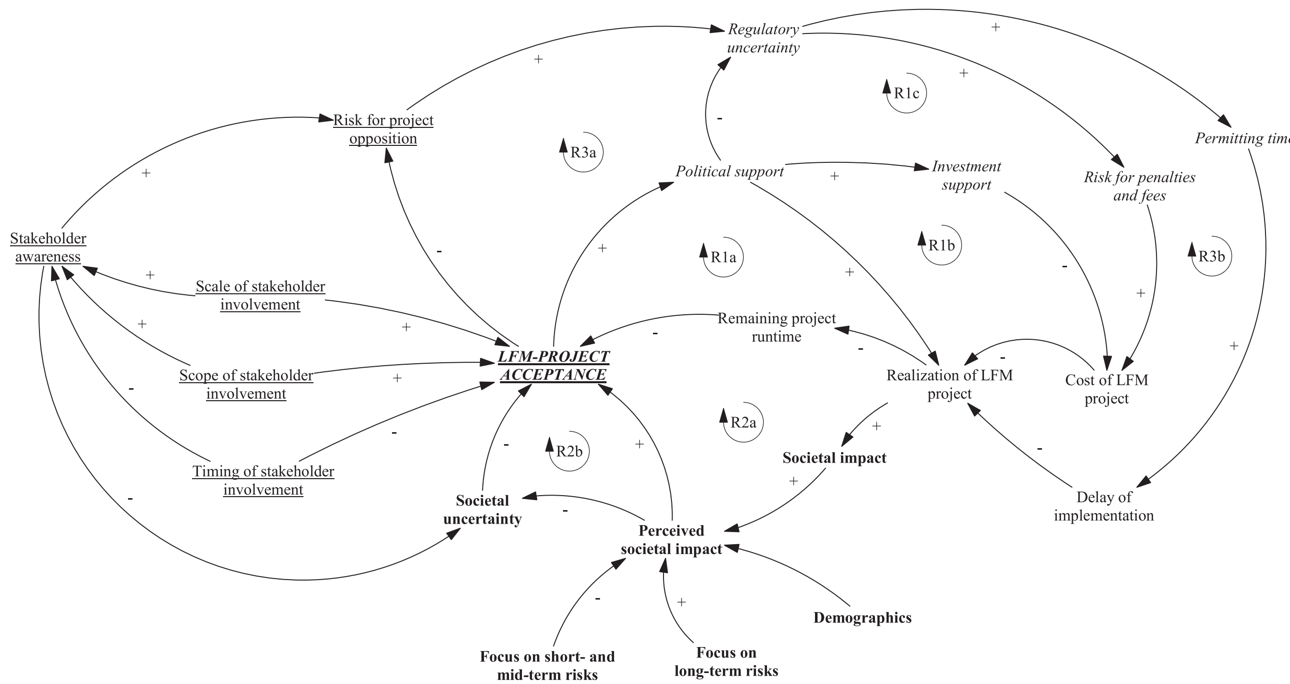

Fig. 7. The dynamics of LFM-project acceptance. Stakeholder aspects are displayed as underlined variables, regulatory aspects as italic variables, operational aspects without emphasis, and aspects affecting the perceived societal impact in bold.

of different stakeholders are involved, e.g. governmental, communal, and/or industrial stakeholders. The timing of stakeholder involvement is another important factor to consider. The earlier stakeholders are involved in the implementation of a project the lesser the risk for public opposition. Nonetheless, there is a trade-off to be considered: with growing stakeholder awareness, also opposing voices might be raised as information is distributed. Additionally, the remaining project runtime can have a strong influence on LFM-project acceptance. LFM projects can last up to twenty years. Societal revenues at the end of a project have to be discounted and similarly, societal benefits that lay in the distant future are often perceived as less important than immediate societal burdens through LFM operations. Thus, demographic factors like age and income distributions throughout the affected communities also play a role, in addition to living circumstances, e.g. is the community dominated by renters or house owners (c.f. Section 3.2). Since demographic aspects are context-dependent the causal relation has no polarity and has to be further expanded and determined specifically for each LFM project.

Fig. 7 shows the dynamics of LFM-project acceptance. Within the system, it is important to build up a good relationship with all stakeholders involved at an early stage to be able to benefit from the reinforcing dynamics rather than be trapped in a downwards spiral. If political support is given to the project the realization of the LFM project can be influenced directly, getting it started quickly with all stakeholders on board (R1a). This can also lead to investment support in form of tax exemptions or subsidy schemes (c.f. Section 3.2), again driving the realization of an LFM project (R1b). At the same time, political support can decrease regulatory uncertainty, and with it the risk for penalties and fees and drive a project by lowering its potential costs (R1c).

With the realization of an LFM project, societal impacts accumulate and burdens turn into benefits along the way. This also increases the perceived societal impact, thus increasing LFM-project acceptance (R2a), also by lowering societal uncertainty (R2b). If, however, LFM-project acceptance is low or decreasing, the risk for project opposition increases, driving up costs of an LFM project by increasing the risk for penalties and fees due to a higher regulatory uncertainty (R3a). With it, permitting time could increase, resulting in a delay of implementation (R3b).

Whether these reinforcing loops work in favor of the project or against it depends highly on the perceived societal impact by the stakeholders, which again is dependent on exogenous variables. Do the involved stakeholders focus on short- and mid-term risks, will they perceive more burdens than benefits and are thus likely to lower LFM-project acceptance and consequently raise the risk for project opposition. On the other hand, if their focus lies on long-term risks they are more likely to support an LFM project (c.f. Section 3.2).

3.4. The dynamics of market acceptance of LFM products

Three main clusters of variables play a significant role regarding the market acceptance of LFM products. Fig. 8 shows these clusters and their dynamics. Variables referring to the (private) economic dimension of LFM are displayed as underlined for variables affecting the project profitability and project investment, and in bold for variables affecting LFM production and technology choices. Variables displayed in italics show factors referring to LFM product quality aspects and market uncertainty.

Market acceptance of LFM products is essentially driven by three key variables: market uncertainty, LFM product quality, and LFM product prices. Market uncertainty highly depends on exogenous variables, i.e. regulatory and customer quality demands, and the prices of LFM product alternatives like primary resources. Regulatory uncertainty is the only exception and can be influenced by LFM practitioners and stakeholders to some extent (c.f. Section 3.3). The product quality depends on the employed technology level, which can lower costs by increasing efficiency, for example, lowering LFM product prices, and consequently increasing market acceptance (R3) but at the same time increasing project costs and thus lowering market acceptance through increasing product prices (B2). However, through project investment in technology, the product quality can also increase driving up market acceptance, and with it, sales, thus increasing project profitability and investment (R1). This reinforcing loop (R1) is balanced by a decrease of the difference between customer quality demands and product quality through the increase in product quality, by increasing LFM product prices and therefore lowering their market acceptance (B1). Over time learning effects will set in reducing technological uncertainty, and also driving project investments to increase the technology levels, likewise increasing LFM product quality, and driving market acceptance (R2). The main leverage points to influence market acceptance lay within the (private) economic dimension of LFM. Industrial actors can make decisions about LFM product prices as well as technological choices affecting the technology level. Institutional and governmental actors can influence market acceptance indirectly to some extent by granting investment support, thus either increasing technology levels or lowering LFM project costs and with it LFM product prices. However, these societal actors have to keep in mind that by granting investment support they are also lowering the societal impact of LFM, which could affect LFM-project acceptance negatively (c.f. Section 3.3).

4. Discussion

The discussion takes a closer look at the underlying hypotheses from which we have derived our four essential research questions (c.f. Section 2). We have assumed that LFM projects overall bring potential societal benefits that could justify public investment support. Moreover, we also hypothesized that stakeholder involvement is a key element to drive public LFM-project acceptance and that potential leverage points are mainly influenced by industrial actors rather than societal ones.

The contextualization and conceptualization of the societal dimension of an LFM project have not only shown its vast complexity but also its interrelations with the other two dimensions of sustainability. The societal burdens, as well as the benefits of avoided impacts through the mitigation of primary resource production, are closely related to the environmental dimension of LFM, while most leverage points to influence the societal impact lay within the economic dimension of an LFM project. The important exception is the after-use utility, which can be influenced by societal actors to some extent but mostly on a systemic scale, affecting a broader context than only LFM. When influencing the societal impact, trade-offs have to be considered and more research is needed to guide decision-makers to sensible solutions. However, in this section, we will give the reader some quantitative context to get an idea about the extent of the societal impact, as well as discuss how stakeholders have been integrated into former LFM projects and research.

Several studies show a net environmental benefit from LFM operations in several environmental impact categories (Danthurebandara et al., 2015a; Laner et al., 2016; Maheshi et al., 2015; Van Passel et al., 2013). Winterstetter et al. (2015), for example, estimate net greenhouse gas (GHG) emission savings from avoided steel production. The monetization of environmental impacts, i.e. GHG emissions at a hypothetical CO_2 price of 10 € per t CO_2 showed a significant change in the net present value (NPV) of LFM projects even at previously negative NPVs (Winterstetter et al.,

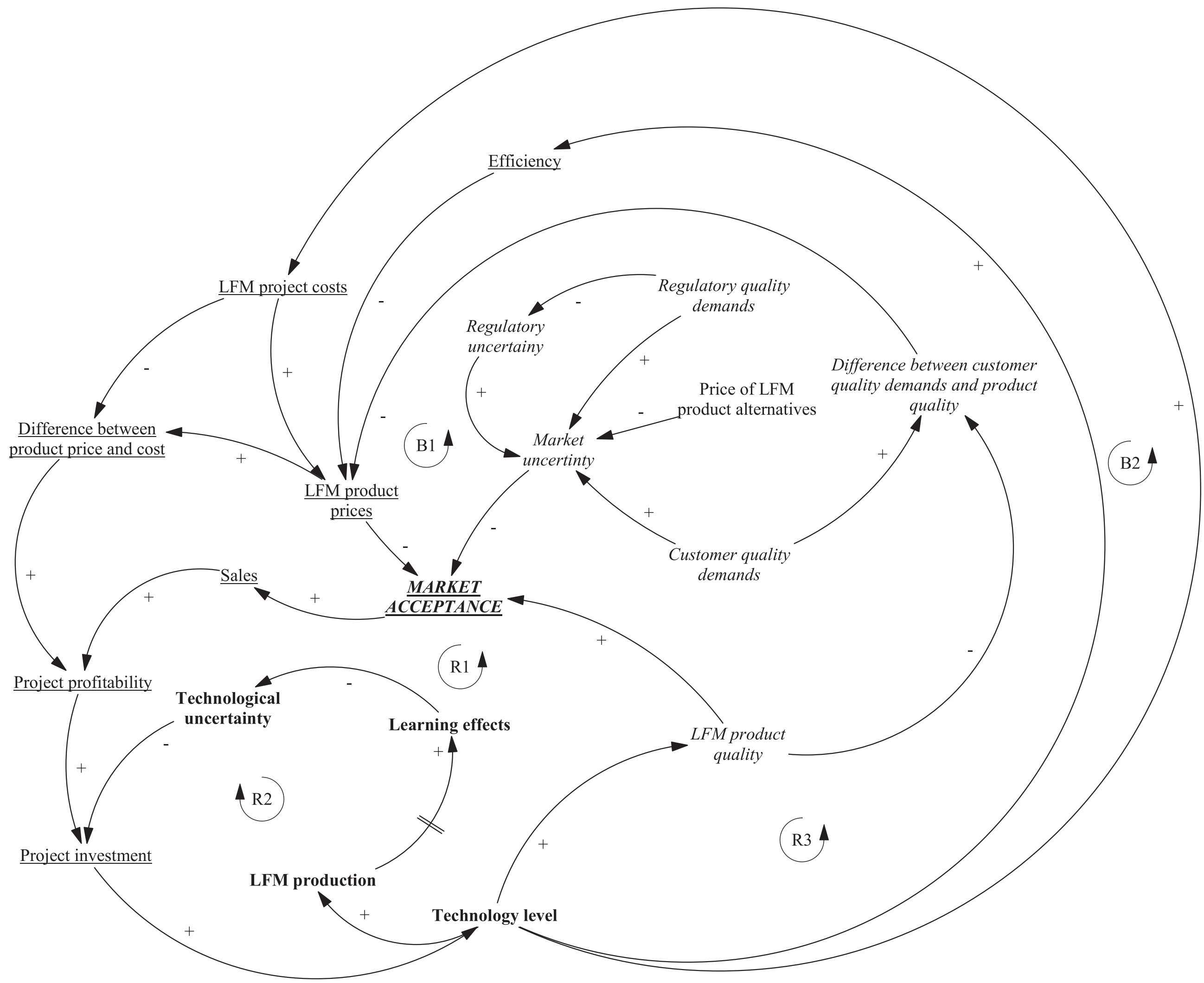

Fig. 8. The dynamics of market acceptance of LFM products. Variables referring to pricing and profitability are displayed as underlined variables. Variables in bold display factors with regards to LFM production and technology, while italic variables refer to quality aspects.

2015). Nonetheless, long-term effects of landfill leachate and LFG leakage still have to be investigated and environmental risk assessments setting timeframes of up to 100 years are still to be performed (Sauve and Van Acker, 2018).

According to expert opinions, LFG leakage continues even in relatively modern landfills longer than expected driving up costs for LFG collection systems that have to be renewed and maintained. Similarly, sewage treatment is expected to continue much longer than planned. The removal of a landfill could prevent future costs that are usually outsourced to communal waste fees, adding to the long-term societal benefit. Throughout the literature, the after-care or post-closure phase of a landfill is usually considered to be 30 years (e.g. Kieckhäfer et al., 2017). The interviewed experts, however, stated invariably that this is a vast underestimation. Institutional and industrial actors experience the necessity for water and LFG treatment far beyond the 30 years and are assuming a timeframe closer to 100 or 150 years and longer. Benefits and burdens of LFM always have to be set in relation to alternative scenarios, one of them being the "business as usual" '(BAU) scenario, i.e. keeping the landfill management as it is. If we consider these expanded timeframes in our analysis, it is likely that LFM projects rather quickly become beneficial from a societal point of view.

Fewer studies estimate the monetary benefits of the after-use of a landfill. Marella and Raga (2014) determine the economic value of LFM, including the benefit of creating a park, to approximately 1 Mio. €, using a contingent valuation method. Results show further a willingness to pay (WTP) of about 196 € p. p. for the LFM project (Marella and Raga, 2014). But also in other studies does land reclamation play an important role to drive LFM projects also for private investors (e.g. Zhou et al., 2015). Van Passel et al. (2013) identify substantial societal benefits from the reduction of air emissions, land reclamation, and lower import dependency and conclude that LFM support of about 108 €/MWh in form of green energy certificates is needed to reach a target internal rate of return (IRR) of 15%.

The most important factor to influence GHG emissions is the choice of WtE technology (Danthurebandara et al., 2015b; Laner et al., 2016), which is a decision to be made by the landfill operator and/or the LFM investors. Looking at the avoided impacts, the assumed CO_2 price plays an important role in the evaluation and can make all the difference (Danthurebandara et al., 2015a; Van Passel et al., 2013). Moreover, tax exemptions (Johansson et al., 2012) and avoided landfill management costs can drive the economic performance of LFM (Laner et al., 2019). All in all, it shows that policymakers might have a reason to, and can influence LFM performance by setting up specific regulations for such projects.

However, currently, no specific LFM regulations are in place, as the European Commission rejected an enhanced landfill mining (ELFM) Amendment in 2017 (Jones et al., 2018). Although most LFM experts on the institutional side stated that specific LFM regulations are not needed to implement a project and there are currently no regulations in place that hinder LFM, there are also no regulations in place that foster it. Moreover, causal relations exist at the systemic scale of LFM implementation, i.e. the implementation of multiple LFM projects creating an LFM industry. These are considered out of scope for this study but are worth investigating in the future. At a systemic scale, LFM could influence market prices of secondary raw materials and/or foster technological development, for example. While these systemic effects are not immediately affecting a single project, they still bear considerable potential for higher societal benefits and may justify broader political support and the implementation of LFM regulations.

Considering the perceived societal impact by LFM stakeholders it could be shown that it highly depends on the stakeholder perspective. A focus on short- and mid-term impacts would lead to rejection of an LFM project and potential project opposition, whereas a focus on the long-term benefits would have the opposite effect. When considering a holistic sustainability assessment of an LFM project, perspectives become even more complex and diverse (Einhäupl et al., 2019b). Are private economic benefits preferred over societal ones? Should the focus lie on the reduction of environmental burdens and risks or material valorization? Throughout this study, we could show that important intradimensional trade-offs have to be considered by decision-makers. Other than considering the long- or short-term perspective, questions of equity and demographic distributions have to be taken into account, where often no win-win situation can be reached. Looking at all sustainability dimensions the number and complexity of these trade-offs increases and subjectivity cannot be ignored in the assessment. We propose to integrate the subjectivity into the analysis by designing weighting factors based on previously developed stakeholder archetypes (c.f. Einhäupl et al., 2019b). Decision-makers are then presented with more detailed and transparent information as a basis for their actions. An integration of monetary and non-monetary societal impacts cannot be perspective-independent, and the monetization of societal impacts itself already carries a certain extent of opinions, viewpoints, and assumptions.

Finally, some limitations of the study should be mentioned that also open up possibilities for future research. The number of participants in this study is rather limited but the relevance of this limiting factor is difficult to assess since other interview studies in the field do not state the number of participants (e.g. Hölzle, 2019; Johansson et al., 2012). Other studies using questionnaires usually involve a larger number of participants (e.g. Damigos et al., 2016) but are also less time-consuming than interview studies. Higher stakeholder participation would strengthen the representativeness of the research but would also bring new limitations. During our research, we are aiming to integrate stakeholders with a high degree of practical experience in LFM to avoid hypothetical bias. As LFM is a rather less-practiced industrial activity, finding those participants is not an easy task. Moreover, we decided to conduct time-intensive in-depth interviews, mini-workshops, and focus groups to elicit knowledge and opinions about LFM. Alternatively, questionnaires could have been created and broadly distributed but this limits our possibility to dive deeper into relevant themes as they come up during the semi-structured interviews. It is also important to note that this study is part of ongoing research and more work is needed before we can move towards the quantitative modeling of societal impacts. This includes investigating the formerly mentioned implementation of LFM at a systemic scale and resulting societal impacts as well as their relations to the project level. Additionally, studies with larger samples of the general public are needed to increase the representativeness and validate the findings of this study. Hence, this study can be considered a step forward in LFM research but more steps are needed to complete the bigger picture.

5. Conclusion and outlook

LFM projects are embedded in a broader societal context. Through the use of system dynamics tools, we were able to make this context visible and have conceptualized three core societal themes identified by the relevant literature and stakeholder interviews. These include the composition of the societal impact of an LFM project, the dynamics of the public acceptance of an LFM project, as well as the dynamics of the market acceptance of LFM products. Institutional and industrial actors are able to influence market acceptance of LFM products to a certain extent by adapting to changing quality standards or differentiating prices, respectively. To fill a current research gap, we have, for the first time, designed a comprehensive composition of the societal impact of an LFM project and could show that intra- and interdimensional conflicts arise when sustainably implementing LFM (c.f. Section 4). A decision to foster LFM implementation by granting a project tax exemption, for example, also decreases the societal impacts of the project and can affect LFM-project acceptance negatively. As many societal impacts derive from environmental ones, a key variable for their determination is the avoided primary resource consumption as well as the mitigation of long-term risks and related costs. One essential leverage point to affect the net societal impact of LFM is, therefore, the applied WtE and WtM technology as well as the considerations about the trade-off between material and energy recuperation.

Moreover, the after-use has a strong effect on the net societal impact as well as on the project's acceptance. To gain the trust and support of the relevant societal stakeholders, i.e. community members, institutional, and governmental actors, it is important to get a broad spectrum and a large number of stakeholders involved at an early stage of a project's implementation. This can generate political support and create an upward spiral towards a successful implementation. However, in case of miscommunication and public project opposition, this effect can turn around into a downwards spiral and ultimately prevent the implementation of LFM.

The use of CLDs has proven to be a valid method to conceptualize societal impacts and mechanisms and presents a first step towards quantitative modeling. The visualizations identified trade-offs as well as dynamic processes that can enable policy- and decision-makers to reinforce positive and avoid negative change, or, if necessary, find the right balance of effects. To do so we recommend a factorial approach based on Laner et al. (2019, 2016). The identified variables have to be combined into sensible factors and filled with data. Data collection might turn out to be a crucial bottleneck for the actual evaluation of societal impacts of LFM due to data availability and diversity. Discrete choice experiments could help identify relative relations between different societal impacts. Contextual data like demographic structures could play an important role similar to stakeholder perspectives to normalize societal impacts to monetary units, for example. While we can tackle subjectivity through the introduction of weighing factors, unavailable data has to be estimated and thus increases model uncertainty. Last but not least, there is a strong need for the integration of societal impacts with economic and environmental ones to establish a holistic view of the burdens and benefits of LFM.

CRediT authorship contribution statement

Paul Einhäupl: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Karel Van Acker:** Resources, Supervision, Funding acquisition, Conceptualization, Methodology, Investigation. **Herbert Peremans:** Resources, Visualization, Conceptualization, Methodology, Formal analysis, Investigation. **Steven Van Passel:** Resources, Supervision, Funding acquisition, Conceptualization, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126351.

Appendix A

Interview guide for the development of causal loop diagrams

This guide is to be used for interviews with key stakeholders of landfill mining (LFM) projects to refine and enhance previously designed causal loop diagrams (CLDs). Moreover, the CLDs will be presented to and discussed with the interviewee to get a better understanding of various LFM processes and their interrelations. The stakeholder selection process is defined by the quadruple helix approach and respond driven sampling and will include community members, governmental and non-governmental institutional participants, industry representatives as well as academic actors.

Interview guide

1. Could you please describe your role in landfill management?
a. What are your professional activities and responsibilities?
b. Please describe the processes and workflow you are involved in.
c. Are you satisfied with your profession?
d. What goes very well in your (daily) workflow?
e. Where do you see room for improvement in your (daily) workflow?
2. What experiences have you made with LFM projects?
a. Which processes seemed to go effortless?
b. What were the challenges you encountered?
c. What surprised you?
d. (How) did you integrate a broad stakeholder environment?
3. Why do you think LFM projects are/should (not) be carried out?
a. What are the main drivers and barriers for LFM projects you can identify?
b. How are they related to each other and to LFM processes?
4. Where do you see the largest public benefit/cost of LFM projects?
a. In your experience, is LFM generally positively or rather negatively accepted?
5. What external factors can hinder/delay an LFM project?
a. What are regulatory drivers and barriers for LFM projects and how do they influence LFM processes?
b. Do you have any experience with public resistance to an LFM project?
c. If yes, how did you encounter this challenge? What strategies did and did not work?
6. What uncertain/unforeseeable variables can influence an LFM project?
a. In what way/how?
7. According to you, which are the most influential actors when it comes to the planning and realization of LFM projects?
a. What are their roles and responsibilities?
8. Where do you see room/need for change to improve the facilitation of LFM projects?
a. Regulatory, financial, technological, public challenges?

Questions to refine CLDs

1. What are the missing variables?
2. What is the magnitude of different effects?
3. What is the timescale of different effects?
4. Where in the processes do delays happen?
5. What units could be used to express the different variables?

Variables table

Table A.1
Variables from which the first CLD drafts were created

Variables	Endogenous	Exogenous
Site	- Quality of waste composition - Landfill size - Landfill location/transport distances - Safety - Material recuperation (WtM) - Energy recuperation (WtE) - Land reclamation - Landfill airspace recovery - Employment	- After-use

(continued on next page)

Table A.1 (*continued*)

Variables	Endogenous	Exogenous
Project	- Level of technology - Disamenities - Site potential - Site purpose - Operational learning effects - Stakeholder involvement - Planning - Permitting - Risk for project opposition - Direct environmental impacts - Employment - Disamenities (traffic, noise, odor, dust) - Profits - Product quality - Flexibility of valorization routes - Risk for disamenities - Resource potential - Project acceptance - Project opposition - Project runtime - Project investment	-Subsidies (received)/public investment support - Taxes (paid) - Pilot projects - Technological uncertainty - Environmental uncertainty - Social uncertainty - Public acceptance - Permitting time - Public costs - Public benefits (financial) - Regulations

Table A.2
Continuation of Table A.1 listing the variables from which the first CLD drafts were created.

Variables	Endogenous	Exogenous
Project	- Regulative learning effects - Profits - Product costs - Production - Product quality - Product price - Penalties, fees and taxes - Communal benefits	
System	-Environmental risks (connect to climate change, e.g. flooding fire, etc.) - Subsidies - Taxes and fees - Public benefits - Investment support - Number of ELFM projects - ELFM implementation - Industrial exploration - ELFM reserves - Avoided impacts - Emissions - Resource recovery - Public acceptance - Stakeholder awareness - Investment incentive, Investment actually happen on a project basis	- Market prices - Market instruments - Tariffs - Resource scarcity - Material demand - Material supply - Energy demand - Energy supply - Avoided impacts - Market acceptance - Resource independence - Economic growth - Environmental pressures/changes - Resource competition - Regulatory uncertainty - Market uncertainty - Background energy system performance - Quality of background social system - Profitability LFM (is in between) - Technological development

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