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# Paradigms on Landfill Mining: From Dump Site Scavenging to Ecosystem Services Revitalization

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## Abstract

For the next century to come, one of the biggest challenges is to provide the mankind with relevant and sufficient resources. The recovery of secondary resources plays a significant role. The industrial processes developed for regaining minerals for production of commodities in a circular economy become ever more important in the European Union and worldwide. Landfill mining (LFM) constitutes an important technological toolset of processes that regain the resources and redistribute them with an accompanying diminishment of hazardous influence of environmental contamination and other threats for human health hidden in former dump sites and landfills. 'Classical LFM' is a useful technology to discover hidden resources and look at the big picture of resources in the local, regional and global perspective. Therefore, this paper considers development of paradigms and attitudes to LFM as the technology for regaining calorific value; the furthering of deposited material valuable to more advanced concepts of enhanced LFM (ELFM); the recovery of landfill space and land value, and, finally, the possibility of full ecosystem services revitalization. The future of our civilisation depends on our wise use of commodities. Thus, waste operations beyond the Zero waste concept must be applied if mankind is to conquer space and the abyssal plains to conduct mining in the deepest oceans on the Earth. Other research areas feasible for LFM in terms of the environmental rehabilitation are given in the review. This compilation summarises the previous, current and future trends of LFM technology regarding the paradigm developments that are influencing the attitude of scientists, industry and society to LFM as a complex tool for implementing the circular economy in practice. This review paper is based on a historical overview of global case studies and explores the methodology of waste management as regards the different tools for geochemical, geophysical and remote sensing that are used for field studies prior to the decisions whether LFM will be successful in an individual case. New technological developments of ELFM for the energy industry is described combined with a review of innovative material production. One chapter is dedicated to the Efficient Use of Resources and Optimal Production Economy (EUROPE) estimation model. The hazardous impacts of landfills, such as greenhouse gas emission and pollutants, are discussed. Throughout history, the major part of the 'LFM economy' has been viewed from a point of view of recovery of natural resources. Therefore, our main philosophy was to provide a historical experience linking with modern ideas of LFM to the increasingly relevant concept of a circular economy. The world is heading towards a restricted access to key resources. However, humanity should not limit itself to frame these restrictions but should also have a profound view on the global economy and life styles for future generations from an environmental and non-material resource standpoint. It is concluded that the big challenge is to adapt the relevant knowledge and find the right solutions and execute adequate decisions based on the economic feasibility and contingent valuation schemes to accomplish a full revitalization of the ecosystems considering different topics related to LFM.

**Key words:** landfill management, circular economy, ecosystem revitalization, resources recovery, recycling

## Highlights

- The shift towards a resource efficient circular economy is crucial due to global environmental challenges, climate change effects and resource shortages.
- Sufficient resources for mankind are dependent on the efficient use of secondary resources in the future.
- The paper considers the development of paradigms and attitudes to landfill mining from trivial 'hunting for valuables' approach up to the full ecosystem revitalization concept.
- Modern landfill mining approaches provide a holistic view as regards technical as well as strategic aspects.
- The sustainability growth in landfill mining projects is combined with an increase in the complexity of the valuation due to the addition of non-tangible benefits when performing calculations.

## Introduction

The shift towards a more resource efficient circular economy is becoming increasingly important as the world is facing severe global environmental challenges and climate change effects as well as resource shortages (Rockström et al. 2009, EC 2010). In order to overcome these challenges, the European Commission has adopted a new strategy of the European economy for a sustainable use of renewable resources. According to the European Commission's 'Roadmap to a Resource Efficient Europe', wastes should be managed as a 'resource' by 2020 rather than be seen as a 'get rid of' the material' issue (EU 2011).

Even though not directly mentioned in this roadmap, landfills are the prime candidates for resource recovery as landfills have been widely used as a final way to dispose, and store, residuals during the last decades. This waste is waiting to be picked up and utilized as a man-made resource from the past. However, as leachate and landfill gas is generated, landfills are mainly regarded as an environmental hazard. Old landfills, which generally lack modern environmental technology, are the sources of groundwater pollution due to hazardous substances leaching or long-term methane emissions contributing to the global warming. Countries having good environmental performance exhibit authorities which prefer to close these dumpsites to reduce risk and build new sanitary landfills. Neither, they attempt to harvest resources from landfills. This is considered the old-style paradigm that says old landfilled waste should remain in the ground.

Contrary to this, landfills should be seen as 'urban stocks' and be considered as resource reservoirs for future recovery, 'a bank account' for coming generations (Hogland 2001, Brunner and Rechberger 2004, Wittmer and Lichtensteiger 2007). The current enormous volumes of dumped waste in landfills could be regarded as potential resource reservoirs for metals, high quality recycled aggregates and waste derived fuels by LFM. The state of the art of LFM is the concept of ELFM which has been proposed as an improved practice of landfill mining (Jones et al. 2013). ELFM has been said to integrate the valorization of historic and future waste streams as both Waste-to-Material (WtM) and Waste-to-Energy (WtE) while considering stringent ecological and social criteria (Hogland et al. 2010, Jones et al. 2013).

150,000-500,000 old and still active landfills exist throughout EU representing an estimated total volume of 30-50 $Gm^3$ of waste (Hogland 2002, Hogland and Kriipsalu 2003, van der Zee et al. 2004, Hogland et al. 2008a, 2008b, van Vossen and Prent 2011). Thus, LFM should be emphasized as an approach to management of sustainable material that combines municipal waste management and material recycling. Accordingly, LFM has been adopted as a feasible technology for the ecological remediation of old landfills (Krook 2010, Krook and Baas, 2013).

Except for the purpose of resource recovery, LFM is crucial for the remediation of landfills to prevent local emissions, to create new potential landfill volumes in existing ones and create space for new infrastructure plus produce recyclable materials (Goeschl 2012). This new perspective of LFM is of interest from an economic point of view and in terms of mitigating climate change and reducing the pressure on scarce natural resources. EU promotes investment into waste management infrastructure. According to the EU legislation, only 10% of all wastes is planned to be landfilled by 2030 making investment in new landfills doubtful. Preferably, existing landfills should incorporate principles of LFM as the best available technology (BAT) in daily business operations. European and future targets are to abolish landfills in the way they were used in the past. Secondary raw materials strategies as well as the fact that only 10% of all wastes will be landfilled point in this direction. This development promotes the recycling industry but also the monopolising of the waste streams. Thus, large waste companies will analyse in depth supply *vs.* demand. Furthermore, the waste industry will learn how to efficiently obtain refuse derived fuel (RDF) from LFM waste and how to recover metals from the fine fractions. The discussion continues on how to mowing towards recovery of land and fully revitalize ecosystems when conducting LFM projects.

## Research approaches to landfill mining (LFM) projects

Certainly many LFM projects and studies have not been documented in the literature (Damigos et al. 2015). Possibly, the first cases occur when scavengers started to reuse and taking care of the discarded goods of the aristocracy and the wealthy. In ancient times, scavengers existed and they do exist in modern times, particularly in developing countries. This scavenging handles food waste as a response to poverty and collect construction materials for townships around megapolises, collect and sort plastic, glass, cardboard and metals to make a profit. The scavenging problem is disastrous when open burning is used for recovery of metals from electronic wastes and the collection of scrap becomes a national business for the poor in developing countries due to a low labour cost. Of course, these methods of extraction are far from sustainable from an environmental point of view. Another huge problem is ore mining waste; tailings and slugs make up approximately 80% of the waste generated worldwide (Sverdrup and Ragnarsdóttir 2014). However, this aspect could be disputed due to the complexity and the technological specifications that are different from MSW.

During the last 50 years, landfill remediation and rehabilitation appeared as a tool for sustainable landfilling. From this moment, the term LFM appeared widely denoting the process of excavating from operative or closed solid waste landfills and sorting the unearthed materials for recycling, processing or other dispositions. After the excavations, trivial sorting was performed mechanically and the soil amendment was separated for the use in citrus groves (Joseph et al. 2004, 2008). The discussion on methodological aspects for LFM started research such as several review compilations, for example, by Salerni (in Cossu et al. 1996). The 'Landfill Reclamation Manual' describes milestones and topics which initially are to be investigated like the operation history of dumps, the types of waste, the dimensions of landfill, the physical characteristics and the topography as well as aspects regarding equipment and material processing units, the organizing and managing of labour, and analytical methods and systemizing of the data collection. The crucial quantitative and qualitative analyses were highlighted by Hull et al. (2005), Joseph et al. (2008), Goeschl (2012) and Quaghebeur et al. (2013). Thereby, the health and safety are important and the selected operating machinery must be efficient with a balanced logistics for the waste and/or soil handling. Even weather aspects and the capacity of the labour should be considered when planning an excavation. The complexity of the LFM process drives the need to predict multiple iterations during operations.

Pilot studies were carried out in England, Italy, Sweden, Germany (Hogland et al. 1995, Cossu et al. 1996), China and India (Joseph et al. 2003, 2004). The latest works are performed by the Enhanced Landfill Mining group in the 'Draft Report on science and technology in Landfill Mining' (EURELCO, 2016) and the LIFE+ financial instrument of the European Community in the context of LIFE RECLAIM 'Landfill mining pilot application for recovery of invaluable metals, materials, land and energy' (Damigos et al. 2015) wherein the main methodological aspects are described that are necessity prior to and during LFM operations.

## Identifying waste in forgotten dumpsites and waste characterization

It is necessary to detect the environmentally problematic sites for a successful determination of the LFM sites that have a potential for recovery of energy, valuables or land etcetera if one lacks historical and well documented information. In the case of this lacking, the reverse forecast for the content in the past landfilled waste can be used by implementation of known waste prognostic tools and knowledge about changing of waste properties in the time (Blažaitytė et al. 2014). Remote sensing techniques usually cover large areas in a detailed and quick way. However, these might employ, for example special photogrammetry that observes smaller spatial objects as well. Platforms such as unmanned aerial vehicles (UAVs) or drones, airborne or space borne flying objects like airplanes or satellites can be used with limited spatial resolution properties. Yan et al. (2014) showed that LANDSAT images are informative on the lateral delineation of landfills by observing the land surface temperature. Dumps usually have an increased temperature comparatively to the surrounding areas. Drones or UAVs collect high-resolution (0.2×0.2 m) pixel topographic information giving relevant information for the improved design and management of landfills (Lucero et al. 2015). Usually, aerophotography, satellite imaginary, laser scanning (LIDAR) and various spectral filtered data like infrared and mid-range wave images compile the main advantages of the BAT.

To overcome the limitations of remote sensing, proximal sensing techniques are to be used (Rossel et al. 2010) for active (creating its own signal) or passive (fixing an existing signal). Methods may be invasive (putting devices into the soil) or non-destructive. Some methods are static (sequences of inserted electrodes) while others can be used in a mobile way (pulled by vehicles). Most commonly used proximal sensing methods are geophysical (Everett 2013), electrical conductivity, resistivity, magnetic permeability and dielectric permittivity. Seismic refraction and microgravity can be used as well as induced polarisation and the self-potential can be measured. More and more ground penetrating radars are used, this method being sensitive to abrupt changes of media. More challenges in the near future are to be overcome and new ways of proximal sensing will be possible for field use. Geophysical methods can help to detect waste characteristics prior to excavation and locate hazardous waste or estimate the volume of waste or soil. Carpenter et al. (1990) used a resistivity technique to map the internal dump structure and the leachate levels and thickness of the covering material. Kobr and Linhart (1994) combined different frequencies electrical methods to describe properties of waste and the local geology. Cardarelli and Bernabini (1996) used electricity and refraction seismic to obtain spatial frames and geometry of dumps. Haker et al. (1997) used surface wave tests to check dynamic properties. Bernstone and Dahlin (1997) and Bernstone et al. (2000) applied direct current resistivity and magnetometry for estimation of metallic objects in dumps. Geophysical measurements are also important to identify fractures and erosion processes in capping material and isolation (Carpenter et al. 1991, Bergström 1997).

All landfills contain heterogeneous waste materials in organic and inorganic form coming from different waste sources in society. Commonly one lacks information about the composition, volume and physical-chemical properties (Hogland 2002, Kaartinen et al. 2013). An essential step in exploring the feasibility of any landfill mining project is to identify the wastes' composition and physical-chemical properties to find the possible methods for recycling and recovering the mined wastes. Thus, waste characterization is the process of analysing and specifying the composition and the physical-chemical properties of the landfilled wastes.

Modified geological techniques can be used. Sampling can be done either by drilling or excavation. Drilling is the technology used during the installation of landfill gas collection systems. This technique was used by different landfill mining characterization studies (Hull et al. 2005, Sormunen et al. 2008, Kaartinen et al. 2013, Denafas and Bučinskas 2014). Disadvantages of the drilling technique are the high operating cost and the reduction of the particle sizes of the mined wastes (Kaartinen et al. 2013). The excavation technique can be done by digging and removing a layer of specified length (usually 1 m) and size (usually 1 $m^3$) from a vertical waste wall. The main disadvantage of this technique is the low sampling depth up to 5 meters (Quaghebeur et al. 2013).

Common waste categories are: paper, soft plastics, rigid plastics, wood, textile, rubber, ferrous metals, nonferrous metals, ceramics, stones, glass and unidentified materials (the fines and the wastes that cannot be identified by visual inspection) (Hogland et al. 2004, Zuberi and Ali 2015).

## Probing the dump interior through geochemistry

Hardly all the geochemical methods which can be applied for landfill investigation can consider contaminated brownfields also as dumps, nor all the soil environmental techniques that can be used depending on the range of contaminants. Quantitative and qualitative analysis for tracing and major element analyses in landfill mass is the usual procedure. Detailed and rapid screening are analytical tools available for site exploration (Landis and Yu 2003, Burlakovs et al. 2013). Conventional analytical methodologies include spectroscopic techniques such as atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectroscopy (ICP-MS). Laser ablation ICP-MS can be a solution. However, reference materials are needed for such techniques are virtually absent due to the heterogeneity of the technogenic masses. Field portable X-ray fluorescence analysers (FPXRF) are referred to as applicable tools for inorganic contaminants (Mäkinen et al. 2005, Carr et al. 2008, West et al. 2011). Comparison of screening and laboratory techniques for analyses of landfill fine fractions was recently performed by Burlakovs et al. (2015). Although the use of spectroscopic techniques including chromatography for organic substances are widely recognized as highly precise and accurate methods, screening FPXRF devices can become a state of the art technology for recycling according to the 'Beyond zero waste concept' especially when needed for economic and environmental fast evaluation purposes (Burlakovs et al. 2015). Several scientific studies in the field of element speciation have been addressed to speciation analysis of polluted soils (Øygard et al. 2008). Assessment of the mobility of toxic metals in landfill waste fine fractions is shown in details by Burlakovs et al. (2016).

LFM operations do include a direct link to problems with contaminated surface water and groundwater. The composition of leachate depending on waste composition and environmental and geotechnical conditions are studied by including organic macrocomponents, heavy metals, xenobiotic organic compounds (Kjeldsen et al. 2002). Various organic contaminants as polycyclic aromatic hydrocarbons (PAH's), polychlorinated biphenyls (PCB's), phenols, phthalate esters and pesticides can pose synergistic and antagonistic toxicity, carcinogenicity or estrogenicity (Matejczyk et al. 2011). The genotoxicity of landfill leachate was studied by Deguchi et al. (2007) by performing comet and micro- nuclei tests in erythrocytes from peripheral blood and gill cells from goldfish (*Carassius auratus*). The effects of genotoxicity of organic contaminants and free radicals to heart, kidney, liver other organs of mice are described by Li et al. (2006 a, b). Cytogenetic effects research methodology can be found for *Allium cepa* (Srivastava et al. 2005), *Vicia faba* (Sang and Li 2004) and *Hordeum vulgare* (Sang et al. 2006) and for mammals by Ghosh et al. (2014). The decomposition of organic waste generates an unpleasant odour and methane is one of the major greenhouse gases (GHG). Principles of the modelling of emission behaviour and field studies are explained by Diaz (2006), Machado et al. (2009) and by Weng et al. (2009). Perspectives of reduction of GHG emissions in the future are analysed by Kumar et al. (2004) and Niskanen et al. (2013).

## Economic aspects of LFM

When studying LFM it is essential to clarify the preconditions for the market initiatives which possibly can be developed as regards, for example, which and how stakeholders should be involved (Krook et al. 2012). Since the beginning of the millennia, the real prices of minerals have doubled and globally the demand for minerals will double once more over the next 25 years (HCSS 2009). The Western civilization's consumption of mineral resources is driven by forces like technological development, innovation trends, the increased living standard and the population increase (Stenis and Hogland 2011). Therefore, the costs and benefits of LFM vary significantly depending on the objectives of each individual case such as the closure of the landfill, aftercare costs, remediation necessity, site-specific landfill characteristics including previously disposed material, waste decomposition speed, burial practices, age and depth of dumped material commodities and local economics, for example, the real estate value, the cost of remediation and the final capping (Cossu et al. 1996, van der Zee et al. 2004, Rosendal 2015). The most potential economic benefits associated with landfill reclamation are hence indirect. However, LFM projects can generate income if markets exist for recovered materials such as recyclable and reusable materials, for example, ferrous metals, aluminium, plastic and glass, combustible waste sold as RDF, reclaimed soil that can be reused again as cover materials and sold as construction fill and last, but not least, revitalized land value or new landfill capacity. Analysis of case studies such as in Collier County in USA (von Stein and Savage1993) and the Filborna landfill in Sweden in 1994 have shown that 33% of the project costs was associated with excavation and trommeling operations at the landfill, but logistics of the reclaimed waste to resource recovery facilities and residue brought back to the landfill demanded 30% of the cost. Generally, the feasibility of LFM was dependent on the depth of the waste and the ratio of wastes to soil (Hogland et al. 1995, Cossu et al. 1996, Hogland 2002). The presence of hazardous materials will strongly negatively affect the economic feasibility. Environmental costs and benefits are to be added to the project expenditures and benefits prior to applying decision criteria as Net-Present Value, Benefit-Cost Ratio, or the Internal Rate of Return. Proper estimation of environmental costs and benefits is a main challenge (Rosendal 2014a, 2014b, 2015). Unlike tangible costs and benefits, the evaluation of environmental costs and benefits is problematic and hardly monetized. On the other hand, LFM projects will have global environmental benefits such as methane emission control that contributes to a reduction of the global warming impact. The rehabilitation of a dumpsite should be foregone by a relevant cost–benefit analysis if re-using the area for new waste cell building or new real estate project developments, remediation followed by phytoremediation or if simply recovery of materials etcetera are planned. Some conclusions can be sketched concerning dumpsite revitalization scenarios and potential, especially in Asia. For example, observations debated in the Joseph et al. (2008) 'Dumpsite Rehabilitation Manual' indicates that partial closure of dumpsites by scientific rehabilitation and the effective use of the site can improve MSWM in India. Separate storing of newly added construction and demolition wastes and other sorts of waste can significantly enhance the long-run economic effects. Communities mining their landfills may burn, compost, or recycle the waste, provide new cells for extra waste streams or, like in Hague, New York, close these dumps forever or, if the legislation allows it, sell it for private recyclers. One of the major difficulties is the appropriate marketing of excavated LFM material due to its various qualities. Dumpsites demand remediation and revitalization, especially in densely populated and environmentally sensitive areas where there is a lack of space and the price of land is substantial. It is hard to target state tax incentives and properly define the excavated material; do the owner of the landfill get the landfill tax back, what are the legislation norms for mining in 'contaminated' areas and is it allowed to provide the newly developed cells for future use of economically failed fractions of landfill and mined waste when the new technology appears for recovery, as a sort of bank account? Even Bill Gates, founder of the Microsoft Company, now enters the recycling business of metals from sewage. Examples exist on mining companies that earlier worked with mining and then started a recycling business (Sverdrup and Ragnarsdóttir 2014). More research is required to make this new type of mining successful in both economic and environmental terms.

- The model for Efficient Use of Resources and Optimal Production Economy (EUROPE) (Stenis and Hogland 2011) is the mathematical expression for the novel equality principle that can be used when economics of LFM has to be evaluated on a wider scale. The equality principle ensures a viable resource economy (Stenis 2002, 2005) in extended forms of landfill mining also in space (Stenis and Hogland 2014a, 2014b). This principle emphasizes an economic equality between regular products and the connected wastes in strictly financial terms. Thus, Stenis proposed a new waste management paradigm based on economic incentives for source reduction and recycling and/or recovery. The equality principle namely per definition is an economic instrument model and has for decades successfully been tested on, for example, the producing industry, the construction sector, recycling and recirculation and ore, landfill and urban mining plus the banking sector. This versatile innovation has been shown to enable a better economy, a more advanced technology and an improved environment when applied (Komerath et al. 2007, Stenis and Hogland 2014a). The EUROPE model is suitable for increasing the profitability, raising the technological level and improving the quality of the environment when mining is performed both on land and off shore. It is equally important to reduce the poisonous wastes at the source for ore mining as it is when metals and minerals are exploited at the bottom of the sea. The principles for landfill mining on land can preferably be applied on deep sea mining if the slag heaps from mining is regarded as common waste dumps in the outskirts of the cities all over the globe. In the future, off shore mining will increase in importance as the natural resources on land become ever more expensive to exploit. In that context, the equality principle has a crucial role to play in order to ensure an environment that is clean enough for people, the animals and other living creatures on this planet (Stenis 2002, 2005, Stenis and Hogland 2011, 2014a, 2014b, 2015).

## Brief history of LFM case studies and development of paradigms

There have been various trials of LFM projects for recovery of energy, material and space for landfills waste, including full scale and experimental research projects with the idea to later upscale the pilot studies. The numbers of such cases are summarized in Fig. 1.

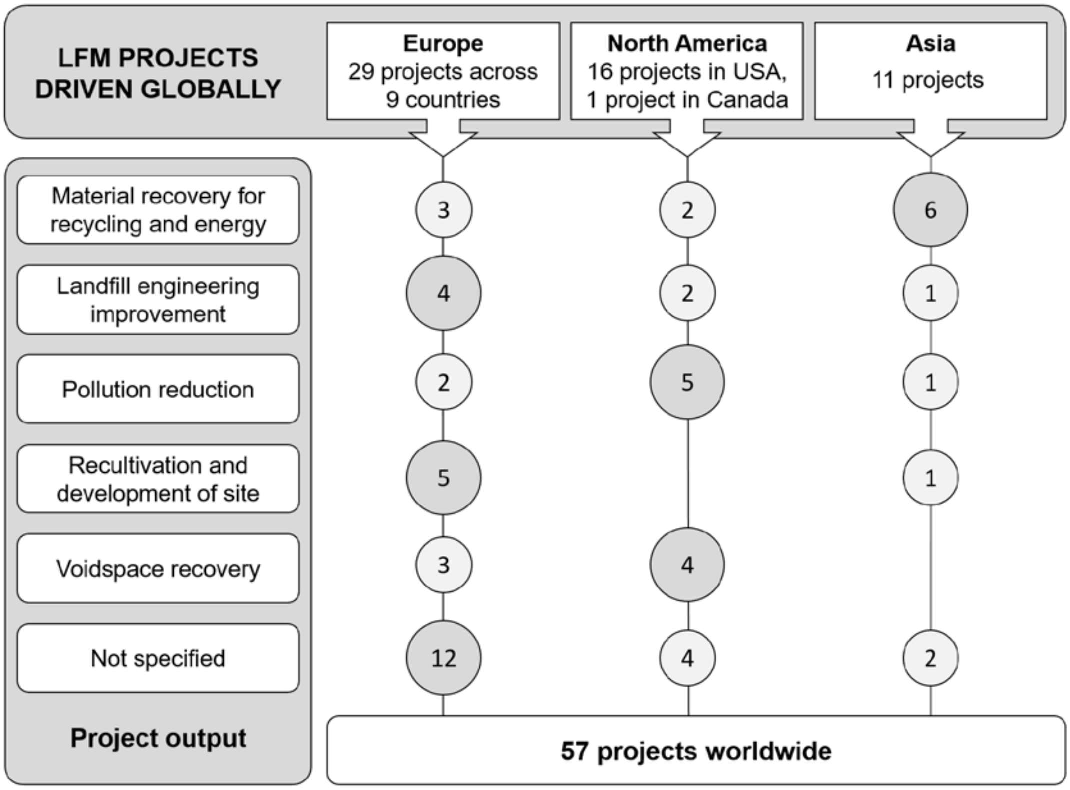


**Figure 1.** The main LFM drivers and case studies known (authors' workout, after Ford et al. 2013)

The first reported landfill mining action was organized in Tel Aviv in Israel in 1953 (Shual and Hillel 1958, Joseph et al. 2004, 2008). After several decades, ideas for deriving fuel for incineration and energy recovery appeared in the United States of America (USA) (Cossu et al. 1996, Hogland 1996, US EPA 1997). Two developments took place in USA from the 50s and 80s that impacted LFM. One was elaborated for recovery of steel containers, but the second development took place in the late 1960s and early 1970s and dealt with the assessment of the technical feasibility of composting landfilled MSW in situ (Joseph et al. 2008). The project was not implemented in full scale because of technical infeasibility. However, valuable information was gained on the degradation of organic matter in a landfill and the importance of providing multi-cell structure in sanitary landfills (Joseph et al. 2008). Afterwards, six landfill mining projects in the USA (Lee and Jones 1990, Murphy 1993) reported different aspects of MSW aerobic digestion and reclamation processes. LFM has been a method of waste management and planned or implemented in many developed and developing countries (Foster 1995, Murphy 1993, Nelson 1995, Hull et al. 2001). Dumps in Asian countries are similar and characterized by stochastically disposed heaps of open-air waste. There prevail open burning actions, stinky pools of stagnant contaminated water, scavenging of animals and poor people promoted by the absence of cover and primitive safety measures (Rushbrook 2001). Tremendously are needed improvement of infrastructure, management, monitoring for leachate, safety (fences against scavengers and control), and sustainable planning (Joseph et al. 2003, 2004, Hogland and Joseph 2008).

Landfill mining in Europe has been performed mostly for experimental purposes with linked ideas to perform environmental remediation with partial recovery of materials and energy (see Table 1)

**Table 1.** Chronological list of the main LFM case studies worldwide.

| Site | Year | Objective | Paradigm | Reference |
|---|---|---|---|---|
| Tel Aviv, Israel | 1953 | Soil for greenhouses | Material recovery | Shual and Hillel 1958, Savage et al. 1993, Joseph et al. 2004, 2008 |
| Naples, Collier, USA | 1986 | Remediation and energy recovery | Remediation<br>Energy | Lee and Jones 1990, von Stein and Savage1993, US EPA 1997, Joseph et al. 2008 |
| Thompson, Connecticut, USA | 1988 | Remediation, space for waste, energy recovery | Remediation<br>Energy<br>Space in landfill | Steuteville 1996, Joseph et al. 2008 |
| Lancaster County, USA | 1990 | Remediation, energy | Remediation<br>Energy | Nelson 1995, US EPA 1997 |
| Burghof, Germany | 1993 | Remediation, experimental knowledge | Remediation<br>Space in landfill | Schneider et al. 1995, Cossu et al. 1996, Hogland et al. 1997 |
| Mc Dougal project, USA | 1994 | Experimental remediation with injection of air | Remediation<br>Space in landfill | Nelson 1995, US EPA 1997 |
| Sardinia, Italy | 1994 | Environmental with research objectives | Remediation<br>Material recovery | Cossu et al. 1996 |
| Filborna, Sweden | 1994 | Environmental with research objectives | Remediation<br>Material recovery<br>Energy<br>Space in landfill | Hogland et al. 1995 |
| Deonar, near Mumbai, India | 1995 | Reuse as soil | Material recovery | Scheu and Bhattacharya 1997 |
| San Lin, China | 1997 | Soil for horticulture | Material recovery | Howlett 1997 |
| Live Oak, Atlanta, USA | 1997 | Remediation, space for waste | Remediation<br>Space in landfill | Joseph et al. 2008 |
| Måsalycke and Gladsaxe, Sweden | 1998 | Remediation, research, testing machinery | Remediation<br>Material recovery | Carius et al. 1999, Hogland 2002, Hogland et al. 2008a, 2008b, 2009 |
| Veenendaal, Netherlands | 2001 | Experimental material reuse | Material recovery | Geusebroek 2001 |
| Kudjape, Estonia | 2013 | Cover material as GHG degradation layer. Experimental material recovery and material-to-energy | Remediation<br>Material recovery<br>Energy<br>Land recovery | Burlakovs et al. 2013, 2015, 2016 |

In the early 1980s, New Jersey environmental officials started to talk about that ‘Recycling Pays’ and scepticism arose as profits from the sale of recycled materials seemingly were unrealistic. Recycling is a SWM option and whether to prevent and provide source reduction, continue landfilling, incinerate waste or do composting were debated. The critical question was provided: ‘Did your recycling program cost the residents money?’ as cost is unavoidable and must be expected (Morris 1996, E-Waste 2016). At some point ‘recycling of household waste should not be expected to make money’ was suggested. However, recycling is a modern reality for newly born waste and is feasible if complex approaches, such as recovery of space for creating new cells for waste, can be combined with recycling of LFM waste for biogas production (Hogland and Marques 1998). During the 1990s it was popular to construct biocells at landfills for biogas production. In Sweden, as well as in many other EU countries, former dumps are capped and monitored, but sometimes this is not an efficient solution as some of them needs to be exhumed, an example being Ringstorp. The value of the land commonly exceeds the value of the content

(Hogland and Kriipsalu 2001, van der Zee et al. 2004). Projects proved that landfills in the form of mines can serve wider policy concerns (Johansson et al. 2012) and that landfill mining can create jobs (Jones et al. 2013), reduce carbon emissions (Frändegård et al. 2012), prevent future leakage, postpone metal scarcity and increase autonomy of governments. Last but not least, a full scale project was performed 2011-2013 in Kudjape, Saaremaa Island in Estonia. Here an experimental attitude was implemented and the main objective was to remediate and recover the land of a public park. Additional experiments on material and energy recovery were successfully performed (Burlakovs et al. 2013). In 2015 the same research group performed test excavations at the Torma landfill in Estonia where the first landfill according to the EU Landfill Directive was constructed and analytical studies are in progress.

An extensive debate continues regarding incineration *vs.* material recovery. Incinerating waste can destroy the plans of waste reduction and recycling requires contracts with authorities to supply waste to burn over a long time although incinerators produce energy. It is a tiny fraction of the energy that is needed to make products from raw resources. For example, producing newsprint requires more than 2.5 more energy generated than by incinerating it. Glass requires 30 times more and aluminium 350 times (Morris 2010, ZeroWaste 2016). Recycling also reduces the energy consumption associated with extraction and the initial processing of raw resources. The recycling process typically is more energy efficient than production from new materials. In ten out of eleven studies, recycling is more energy efficient than incineration (Leach et al. 1997). The LFM debate occurred on a larger scale in USA in the 1970s as the construction of new incinerators for waste had expanded too much and problems to use the capacity occurred. A similar development took place in Sweden after the establishment of the EU directives in 1999 and in 2008 (EU CD 1999, EU CD 2008). In the 90s an increase from 21 to 34 incinerators was noticeable in Sweden. Annually, 500,000 tons/year are imported. This amount is expected to increase. Recycling incentives hence promote the import of waste and this is the problem for several ‘incinerator countries’ in EU. Several conferences on these hot debates were organized before the 90s in USA (Cossu et al. 1996, Hogland 1996, Hogland and Marques 1998).

In 2008, the interest for landfill technology increased due to the Global Landfill Mining Conference in London. On several occasions LFM has been discussed at the Linnaeus University Eco-tech conferences. Later on large international projects such as ‘Closing the Life Cycle of Landfills, Landfill Mining in the Baltic Sea Region for Future’ was promoted for the landfill in Estonia. See how to create an experimental soil capping layer for GHG emission degradation the natural way (Burlakovs et al. 2013).

LFM coupled with the concept of urban mining and, glass mining is described by Jani et al. (2014) and harbour mining by Fathollahzadeh et al. (2014, 2015). The research group ‘Resources 2.0, urban and landfill mining’ works on LFM issues in different scientific directions, for example, the economy of LFM (Krook 2010, Krook et al. 2012, Krook and Bass 2013). These projects exhibit the flows of material in society and urban and landfill mining in an emerging global perspective.

The recent trials on reuse of material from oil-shale bings (urban mining) in Scotland demonstrated that recovery of material for construction needs is both technically and economically justified. But it is generally used as low grade fill material, of which there exist other sources, both virgin and secondary, in the surrounding area and the rest of Scotland (Ford et al. 2013).

ELFM adds the option of processing plasma gasification and vitrification that is industrially operated in a number of facilities in Japan but nowhere in Europe due to the EU legislation. This can become a landfilling method at a relatively low cost (Spooren 2013). More holistic, integrated processes can be linked to ‘zero-waste’ cycles and would incorporate recycling, recovery and upgrade of materials, besides from energy production that are investigated and described by Jones et al. (2013). A significant state of the art work was recently added where incineration, gasification, pyrolysis, plasma technologies and combinations are critically analysed and compared (Bosmans et al. 2013). Japanese experiences are outlined by Themelis (2007) and Heberlein and Murphy (2008). In Europe, EUROPLASMA is currently under commissioning starting up a 12 MW gasification plant for solid waste treatment in Morcenx, France (EUROPLASMA 2016, EURELCO 2016).

Asteroids have been mentioned as threats (Massonnet and Meyssignac 2006) and at the same time as useful mining polygons for precious metals. Similarly, the comets and the moons can supply water, helium can be extracted from their rocks and radioactive minerals from asteroids could be used as fuel in fusion reactors to explore space. Innovative but basic methods are needed that managers on the UN and OECD levels can use to obtain a more cost-efficient mining, also in the solar system. A promoted equity of the distribution of natural resources and commodities can reduce the presence of profit-reducing residuals in space. To survive, we would be helped by an abundance of material and energy sources, also in space (Ball 2014). When talking about material and energy resources and their limitation we refer to our own planet and not the possibilities outside its atmosphere. When talking about landfill mining we do not include the waste heaps and their dams with slurry and sludge that the ore mining industry has generated and still is generating. In the future, LFM must encapsulate the ore mining research in order to recover valuable metals that are lost in the first simple, primitive and low cost extraction by drilling and extraction direct from the bedrock. Thus, the landfill mining paradigm must include ore mining, ordinary landfill mining from MSW landfills and industrial landfills including the metal recovery from fine fractions, glass mining, harbour and sediment mining, metal recovery from wastewater sludge and ocean sediments. It should also include future deep sea mining and asteroid mining in space but from a zero waste concept point of view. In 50 years, the world's population is expected to exceed nine billion people. Our three major fulfilment problems that we must solve in order to survive are: energy; mineral resources, and: food, including water. Living on platforms in space must encompass the total closure of the water and material loops (Lewis 1997, Sonter 1997, Tilton 2003, Simpson et al. 2005, Klotz 2012, Lendon and Hanna 2012).

## The Emerging Picture

Nowadays, environmental awareness of the changing environment and the development of modern contingent valuation concepts regarding ecosystem services and its revitalization on a global scale become more and more pronounced and vivid among the scientists in sustainable development.

## Global awareness on adaptation to climate change and LFM

Landfills and wastes are in focus of the present discussion on climate change impacts, the need in mitigation and adaptation activities (Monni 2012). Landfills are a significant source of greenhouse gasses (GHG) due to the presence of organic material and nitrogen compounds. In commonly anaerobic environments both carbon containing GHG ($CO_2$, CO, $CH_4$) as well as $N_2O$ are formed, besides of other groups of pollutants as emissions to air as well waters, subsoil environment (Chen and Lo 2016). Nevertheless, landfills are a significant source of uncontrolled GHG emissions. Not much specific studies have been performed on the role of LFM in diminishing them and on how much GHG are produced during the LFM action itself. Landfills is a hot topic for climate change mitigation activities and mitigation funding could hence motivate to consider LFM options as it has been demonstrated on several options (Weng et al. 2015).

Climate change can pose major risks of landfills. The change of precipitation intensity can result in a significant increase of the infiltrate leaking and an increased risk of extreme weather events that can influence accidental leakage of contaminants from the landfills. Thus, landfills should be considered as high risk objects and be included into the list of adaptation activities.

## Emerging pollutants as nano-scale threat to the environment

The concept of emerging pollutants includes many groups of materials and substances produced in industrial amounts after World War II and may impact humans and the environment. Common examples of such pollutants are pharmaceuticals, nanomaterials and other groups of substances and materials (Masion et al. 2015). Nano-sized materials can be found in textiles, sunscreens, cosmetics, personal care products and cleaning agents, paints and coatings, plastics and polymers, in the food sector: additives, supplements, containers and packaging, in the energy sector, fuels and catalysts, in consumer electronics and semiconductors and in many other fields (Bottero et al. 2015). Thus, it is critical to evaluate human and environmental risks posed by environmental nanomaterials, especially those with a high production volume. The reasons are that nanomaterials are materials that combine nano-sizes and high chemical reactivity. Thus the impacts on the environment and humans can be found even if the concentrations of nanomaterials in the environmental medium are very low The transformations of the nanomaterials due to their reactivity can influence their transfer to other environmental media such as soils, sediments and surface water and further association with natural colloids such as organic or minerals and accumulation in some compartments. These properties govern the hazard that strongly depends on the exposure and speciation. This field has received a lot of attention from researchers and regulators (Klaine et al. 2012). There is an urgent need for broad and integrated studies that address the risks of engineered nanomaterials and other emerging pollutants, including their impacts on the waste composition, to consider them for landfill mining and recovery of valuables (Tolaymat et al. 2015) as well as the recovery potential of nanomaterials itself. In the context of assessing potential risks of engineered nanoparticles, life cycle thinking can represent a holistic view on the impacts of nanomaterials through the entire value chain of nanoparticles containing products from production, through use, and finally to disposal (Mitrano et al. 2015).

An example of life cycle analysis perspective application to study the fate of nanomaterials in the environment is their fate in the construction industry waste where the source of nano-sized materials is paint and cement containing nano-$TiO_2$, nano-$SiO_2$, nano-ZnO, and nano-Ag (Hincapié et al. 2015). At the same time the problem of emerging pollutants is relevant not only in respect to possibly coming threats but also to already existing waste materials. A good example in this respect is nano-silica, as its production started in the 1950s and has a worldwide production of several million tons (Wang et al. 2016). Modelling of possible nano-silica concentrations in the surface water for the EU and Switzerland is predicted to be 0.12 μg/L. Also waste tire rubber and rubber ash contain nano-sized material and can influence environmental quality (Moghaddasi et al. 2015). As a prospective approach to use automotive waste tyres as resources for synthesis of $SiC/Si_3N_4$ nanocomposite has been reported by using simultaneous pyrolytic reduction and nitridation reaction using pyrolysed waste automotive tyre char as carbon source and silicon dioxide as silica source (Rajarao et al. 2015). Such innovative approaches of using automotive tyres as carbon source for synthesising nanocomposites could be used to reduce the volume of wastes in landfills, decrease the risk of health concerns and also recover valuable carbon resources. Many studies exist on possibilities to use nanomaterials for remediation of wastes, for example, it is described in the review written by Patil et al. (2016).

## Ecosystem services revitalization through landfill mining

The capacity of the global ecosystems is under increasing pressure. This is especially important in urban regions (Elmqvist et al. 2013). Due to urbanization and urban sprawl, cities often suffer from poor provision of ecosystem services (ESS), which is directly linked to the quality of life of the urban population (Boone et al. 2014). Soil sealing and land consumption are severely increasing in European urban areas (Scalenghe and Marsan 2009). Air pollution and water contamination from traffic, industrial production and habitat extinction are challenging urban areas (Elmqvist et al. 2013). The 1960s produced the books such as 'Silent Spring' (Carson 1965) and 'The Tragedy of the Commons' (Hardin 1968) establishing a huge change in environmental philosophy, a development that has to be based on environmental and industrial coexistence.

Often urban land consumption is accompanied by a reduction of green spaces such as parks, forests and allotment gardens and blue spaces such as lakes, rivers and wetlands (Nuissl and Rink 2005). This in turn alters the cities' ability to sustain functioning ecosystems and to provide ESS. At the same time, humanity faces increasing urbanization. Currently, 50% of all the population live in cities. In the near future it will increase to 75% and is predicted to reach some 90% by the end of the 21$^{st}$ century (UN 2014). The global urban land area is expected to grow at a faster rate up to 2030 as 60% of the urban spaces have not yet been exploited for building purposes (Seto et al. 2011, Elmqvist et al. 2013). As urban land-use and the built fabric increase, reducing the amount of space for urban nature and ecosystems induce more people depending on precisely those urban environments and ecosystems to provide drinking water, clean air, food and green spaces for recreation. To maintain suitable conditions for human health and welfare in cities, additional knowledge about the function of, and demand for, green and blue spaces and ESS provisions are needed. Although the pressure on urban ecosystems is disproportionately high, the value that nature offers urban citizens should not be ignored (TEEB 2011).

ESS are conditions and processes by which natural ecosystems and species that they represent sustain and fulfil the human life (Daily 1997). In 2005, The Millennium Ecosystem Assessment explored links among welfare of people, status of ecosystems and sustainable use (Sarukhán and Whyte, 2005). Half a million sites of potential contamination are reported by the US Environmental Protection Agency. According to the European Commission, more than 3 million potentially contaminated and 500,000 approved contaminated sites exist in Europe (Vanheusden 2009): The term 'contaminated site' refers to a specific spatial area which is defined as contaminated (US EPA 2016). 'Contaminated site, polluted site, degraded site and brownfield' are the terms that frequently are used as synonyms, but they do not have the same meaning. Stressors or contaminants in these sites include landfills that pose threats to the natural environment at densities, concentrations or levels that are high enough to disrupt the ecosystems (NZWS 2016). For example, The Canadian Environmental Protection Act (CEPA 1999a) declares that pollution prevention is a cornerstone of the national efforts to reduce releases of toxic substances in the environment, but risky sites are included in the registry (CEPA 1999b) and thus restore the functions of ecosystem services provided by the process of revitalization. This is a good example how the LFM projects in the above mentioned areas become revitalized and gain back functions they had before being degraded and contaminated. However, there are several drivers for fulfilling such operations as depicted in Fig. 2.

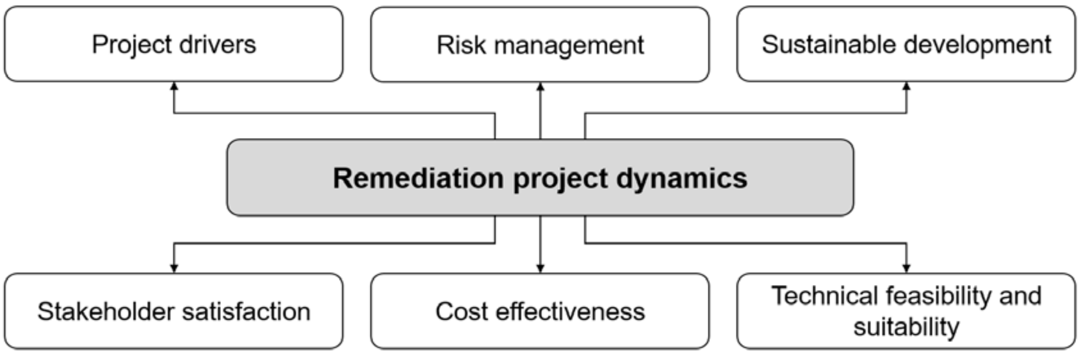


**Figure 2.** Dynamic system of decision support for landfill mining as a full scale remediation project for environmental revitalization (authors' workout, after Vik and Bardos 2002)

Cost effectiveness of remedial LFM actions can be assessed by using several environmental economy methods. One is the net environmental benefit analysis (NEBA) approach to study the impact of remedial actions on resources itself (Efroymson et al. 2004). It is defined as a risk-benefit analysis for environmental management options and quantifies as well as compares impacts to ESS that occur as a result of an action. The benefits of distinct alternatives can be analysed from the economic perspective, e.g., biodiversity, recreation potential etc. Comprehensive study on habitat analysis is used to quantify ecological services and is reported by Favara et al. (2008).

Usually, environmental efficiency of the LFM process varies from project to project and depends on the type of materials recovered, the method of mining process applied and the possibilities to extract methane. Frändegård et al. (2012) described the environmental evaluation of LFM with LCA and Monte Carlo simulations and performed analysis of three scenarios: 1) relating only remediation of landfill; 2) dealing with the excavation and recovery of materials at a mobile plant located at a landfill, and; 3) considering the transportation of the excavated waste to a stationary plant. The authors concluded that the environmental impact of LFM depends on: a) the efficiency of the waste sorting technology, weather conditions, electricity consumed for its operation as well as composition and quality of the recovered materials; b) the transportation distance between the different facilities constituting a great part of the photochemical oxidation effects, and; c) the final use of the recovered materials as combustion or reuse of recovered plastics and hence the avoidance of greenhouse gases. Van Passel et al. (2013) discovered the high potential of 'Closing the Circle' concept in LFM to reduce the greenhouse gas emissions where most of the reduction is achieved by the emission savings from material recovery.

Plethora of aspects should be considered in selecting a proper remedial solution for contaminated land problem. This is the case of landfills that can be objects for LFM. The core objectives must be considered, e.g., costs and benefits, technical suitability, efficiency and feasibility, risk management, aesthetic and environmental aspects as well as the social and economic conditions. Some services are quantified using economic models, such as the revealed preference, e.g., the travel cost and any random utility or the benefit transfer. NEBA approaches are used by several state environmental regulatory agencies in US such as the Texas Commission on Environmental Quality, the State of Florida Department of Environmental Protection, and regulated by Washington State Model Toxics Control Act (Efroymson et al. 2004). In general trends, the necessity to supply recovered valuables, energy, clean land and/or ESS is initial spark for taking the decision to fulfil the projects of LFM: it means that the more complex is the necessity, the more specific and complex approach is needed to evaluate the market from economic point of view (Fig. 3).

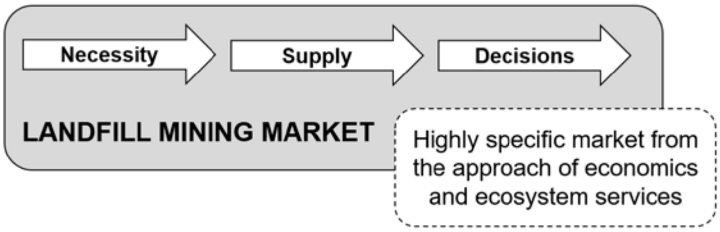


**Figure 3.** Initial drivers for LFM market (authors' workout)

Marella and Raga (2014) stressed the importance of evaluation of landfill mining projects through such social and environmental benefits as:

- reduction of environmental footprints;
- negative effects to air, soil, surface and groundwater;
- decrease of imported energy and materials;
- restoration of nature and development of recreational areas, and;
- social benefits from the urban development in the recovered area (increased land value).

The approach for implementing an ESS revitalization project as we see in literature is complex and demand a multi-criteria decision analysis (MCDA) to choose options for resolving the problem or a set of problems that are hardly quantifiable. According to Asafu-Adjaye (2007), problem solution through the MCDA must be done in following steps: 1) identification of the problem; 2) identification of the alternatives; 3) identification of the criteria; 4) scoring of the alternatives; 5) assignment of weights to the criteria; 6) evaluation of the alternatives, and; 7) sensitivity and risk analysis (Triantaphyllou 2000, Asafu-Adjaye 2007, Geldermann and Rentz 2007, Böttle 2011).

LFM decision support systems include standard steps that must be followed by MCDA for evaluation of each project if LFM projects for various purposes are planned for design. The Landfill Mining Austria project (LAMIS) included comprehensive economic and ecological assessment as well as decision-making procedure for landfill owners whether to keep landfills in after-care or to start-up an environmentally sustainable reuse or clean-up (Nispel and Gäth 2014). There are no universal tools for a comprehensive multi-criteria assessment that could include decision-making situations, criteria and available information to perfectly resolve the complex problem. Therefore, mainly economic feasibility discussions have been published so far and presented as cost and revenue calculations (Gäth and Nispel 2010, Bernhard et al. 2011, Bölte and Geiping 2011, van Vossen and Prent 2011, Nispel 2012, Rettenberger 2012). When focusing only on economic variables, it leads to discarding benefits as avoided after-care and compliance costs, taxes on extra landfilling activities, fair market value of cleaned-up sites on the real-estate market or potential revenue from added landfill capacity regained due to LFM (Nispel 2012). Problems with ecological, organisational or social economic criteria are also often neglected. The risk of wrong decisions is reduced if all of those criteria are included in the development of such an assessment and decision-making procedure (see Fig. 4). Relevant parameters and system boundaries in space and time have been executed by Hermann et al. (2014a) that has to include various qualitative and quantitative criteria. Single-criterion decision-making (SCDM) procedures are hardly useful (Schuh 2001), but assessment and decision-making procedures have to meet specific requirements in case of LFM operations (Hermann et al. 2014b).

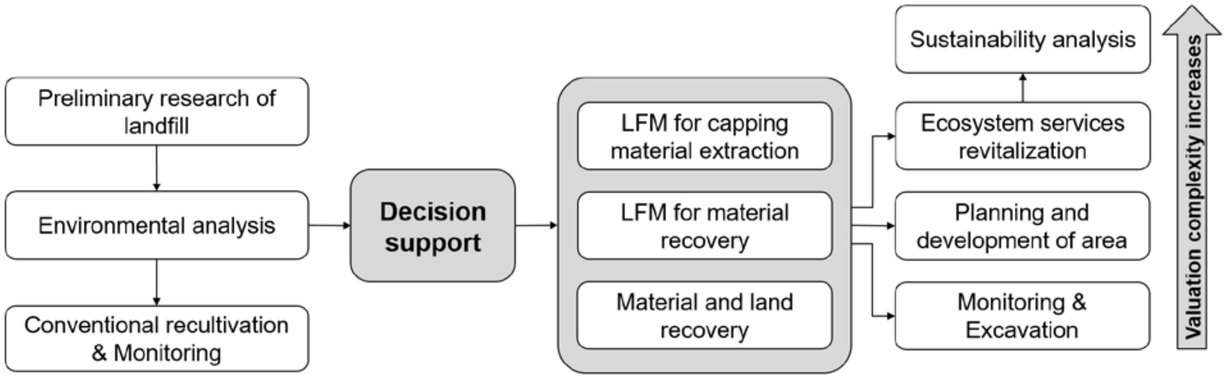


**Figure 4.** Trivialized decision support system combined with LFM operations purpose (authors' workout)

To trade waste for energy is the easiest way to avoid the problem with waste. Incineration of materials as valuables produces far less energy than what is required if one wants to produce the incinerated valuables again. Mainly materials for recovery are feasible for large fractions of waste at least nowadays - ore mining tailings and industrial mono-landfills will compete with old mixed dumps that seemingly never will be economically viable if only first two aspects in Fig. 5 will be considered. The main concepts that have evolved during the last 60 years regarding LFM paradigms of 'how to perform LFM' are displayed in Fig. 5.

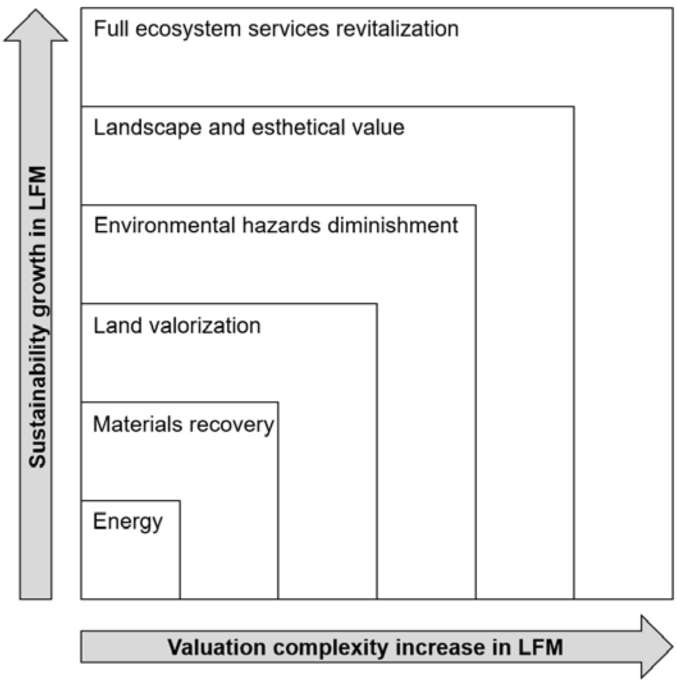

**Figure 5.** Simplified diagram of the LFM paradigm approach revealing how the increase of sustainability drives the valuation complexity that increases simultaneously (figure not in scale; authors' workout)

The next step after 'hunting for valuables and energy' is the land valorization that can be divided in two mainstreams: a) valorization for depositing new waste to prevent the formation of new dumps, and b) valorization of the land as real estate. Legislatory issues about the landfill tax paradox problem give rise to discussions if one is eliminating the waste from landfills that have been paid for already. It seems that real estate regaining can be very feasible if the landfill is situated in active urban areas since cities occasionally grow around these former dumps that become several magnitudes more expensive due to the real estate prices growth which are driven by the market and urbanization level. The more developed and environmentally awared is society the more attention this society will pay to the environmental hazards diminishment programs. Thus, LFM operations supported by legislation will in some way neglect costs and quantify environmental and societal benefits through MCDA with higher coefficients at the expense of cost-benefit aspects. Aesthetic landscape values and the cost of biodiversity can be quantified using additional contingent valuation schemes for, e.g., recreation such as swimming and bird-watching and/or commercial fishing. Full ecosystem revitalization can summarize the full cost of everything that can be included if LFM operations are performed with an environmental benefit valuation approach. The complexity increases as one must move away from the anthropocentric view and become eco-centric. This leads to extreme complexity of the evaluation process for most funding or investing bodies. From a holistic point of view, a shift of paradigms in LFM is ever more important as awareness and ESS evaluation comes into environmental strategies as a response to the disastrous impacts of residuals and contaminants in biogeochemical cycles that can be returned to the circular economy and close the loops.

## Conclusions

This review consists of the historical experiences of LFM and focuses on paradigm attitudes. It starts with the recovery – 'the hunting for valuables and energy' – and explores components such as land valorization and, finally, presents different advanced concepts of full revitalization of ecosystem services. The emphasis in the review is on additional aspects of such emerging practices that have a major potential to improve the recycling and valorization of residuals from dumps and contaminated areas and the GHG emissions from landfills and the emerging pollutants. When doing so, the reasons are given for why LFM should be considered as a valuable tool for adding beneficial aspects of LFM such as reduction of environmental hazards and the revitalization of a full ESS.

The evaluation of LFM projects from social and environmental points of view must, except from economic assessments, absolutely include aspects such as: the reduction of environmental footprints; the reduction of negative air, soil, surface and groundwater effects by dumps and contaminated areas; the efficiency of the use of secondary sources of material and energy; the restoration of nature; the provision of recreational needs through contingency evaluation; the social benefits from urban development in the recovered areas including the increased property value, the regaining of landfilled areas, and; a full ESS revitalization being regarded as the foremost holistic paradigm to promote the environmental practices from an eco-centric point of view.

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