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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. Recovery of secondary resources plays a significant role. Industrial processes developed to regain minerals for commodity production 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 resources and redistribute them with an accompanying reduction of hazardous influence of environmental contamination and other threats for human health hidden in former dump sites and landfills. This review paper is devoted to LFM problems, historical development and driving paradigms of LFM from 'classical hunting for valuables' to 'perspective in ecosystem revitalization'. The main goal is to provide a description of historical experience and link it to more advanced concept of a circular economy. The challenge is to adapt the existing knowledge to make decisions in accordance with both, economic feasibility and ecosystems revitalization aspects.

1. 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; Henckens et al., 2014; Walan et al., 2014; Reijnders 2014; Jin et al., 2016). 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. Nevertheless, they reject attempts to harvest resources from landfills. This is considered the old-style paradigm that says old landfilled waste should remain in the ground.

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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,b; 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.

First attempts to analyse results of LFM projects and reports were performed in 90-ties of the last century and beginning of 21st century by Cossu et al. (1996), Hogland et al. (1997) and Hogland and Joseph (2008). Asian projects were reported in project type reviews by Joseph et al. (2003, 2004, 2008). Later comprehensive reviews were compiled by Krook (2010), Krook, et al. (2012) and Krook and Baas (2013), specifically environmental questions were taken in account in review by Frändegård et al. (2012).

This paper was performed on literature basis of previously done reviews, case studies, project reports and takes in account additional literature on environmental aspects linked to performance of LFM that were not considered widely in previous studies. Authors take an insight in paradigm development from classical LFM and resource recovery ideas of enhanced LFM (ELFM) towards full ecosystem services revitalization concept.

2. 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.

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 50 s and 80 s 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 (Forster, 1995; Murphy, 1993; Nelson, 1995; Hull et al., 2001). Dumps in the countries of Asia are similar and characterized by stochastically disposed heaps of open-air waste with open burning actions, stinky pools of stagnant contaminated water, scavenging by animals and poor people. Additionally, the absence of cover and primitive safety measures is disregarded (Rushbrook, 2001). In these countries improvement of infrastructure, management, monitoring for leachate, safety (fences against scavengers and control), and sustainable planning is highly needed (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).

In the early 1980s, New Jersey environmental officials started to talk about that 'Recycling Pays' however cost was estimated higher than expected (Morris, 1996), this discussion has topicality until nowadays nevertheless of successful source separation from the raw waste (E-Waste, 2016). 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 mostly are capped and monitored. However, sometimes this is not an efficient solution as some of them needs to be exhumed, e.g., in Ringstorp (Hogland and Kriipsalu, 2001; Van der Zee et al., 2004). Experiments on material and energy recovery were successfully performed in Kudjape Landfill, Estonia during its remediation process through LFM (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 (comply with the requirements of Directive 1999/31/EC on the landfill of waste; hence old dump sites usually do not comply) and analytical studies are in progress.

There is on-going dispute how the primary generated waste (municipal, construction and other waste) should be treated; and recovery through LFM, also dominantly, are closely related to recycling, energy production or both. In fact, previously landfilled material could be processed to recover materials for recycling, and combustible materials for energy. However, not all countries have the possibility to use waste for energy, which actually could limit the feasibility of LFM projects in some cases. If there is the possibility to recover fuel besides recyclables, for some countries without incineration capacity appears opportunity to recover fuels and send them to countries which can utilize them. 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 mate-

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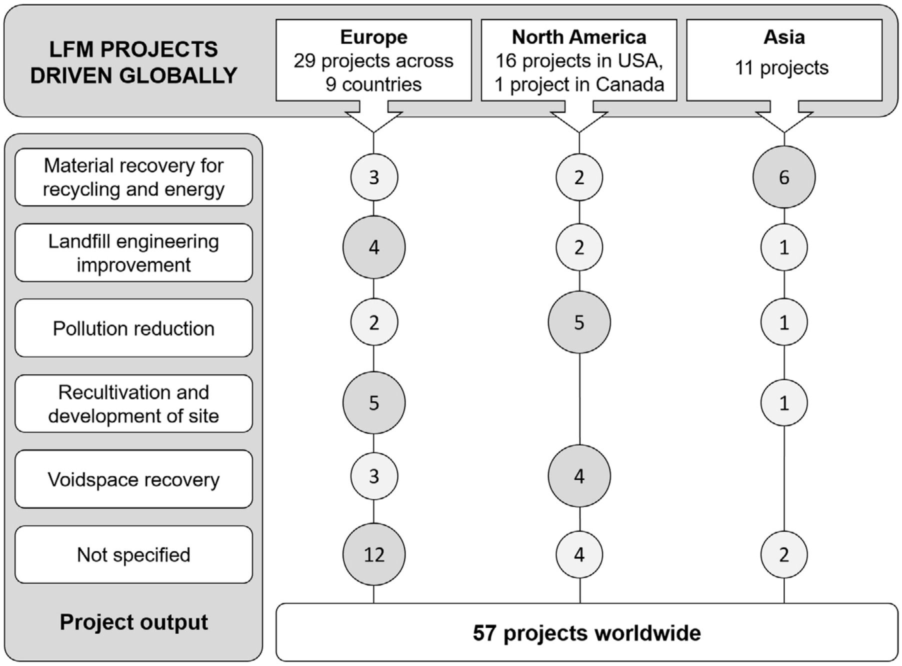

Fig. 1. The main known LFM drivers and case studies (authors' workout, after Ford et al., 2013).

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 Energy	Lee and Jones (1990), von Stein and Savage (1993), US EPA (1997), Joseph et al. (2008)
Thompson, Connecticut, USA	1988	Remediation, space for waste, energy recovery	Remediation Energy Space in landfill	Steuteville (1996), Joseph et al. (2008)
Lancaster County, USA	1990	Remediation, energy	Remediation Energy	Nelson (1995) and US EPA (1997)
Burghof, Germany	1993	Remediation, experimental knowledge	Remediation 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 Space in landfill	Nelson (1995) and US EPA (1997)
Sardinia, Italy	1994	Environmental with research objectives	Remediation Material recovery	Cossu et al. (1996)
Filborna, Sweden	1994	Environmental with research objectives	Remediation Material recovery Energy 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 Space in landfill	Joseph et al. (2008)
Måsalycke and Gladsaxe, Sweden	1998	Remediation, research, testing machinery	Remediation Material recovery	Carius et al. (1999), Hogland (2002), Hogland et al. (2008a,b, 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 Material recovery Energy Land recovery	Burlakovs et al. (2013, 2015, 2016)

rials. In ten out of eleven studies, recycling is more energy efficient than incineration (Leach et al., 1997). In USA in the 1970s the construction of new incinerators for waste had expanded and some 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 90 s 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 confer-

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ences were organized before the 90 s in USA (Cossu et al., 1996; Hogland, 1996; Hogland and Marques, 1998). At the same time there are a number of studies that have found that importing waste from countries of intense landfilling to countries like Sweden which incinerate the waste, is both environmentally and economically acceptable (Assessment of Increased Trade of Combustible Waste in the EU, 2012; Cimpan et al., 2015). The EU Waste Framework Directive promotes the efficient use of waste logistics and treatment at EU level as number of countries cannot afford to build expensive incineration plants (Sahlin et al., 2013).

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 LFM projects such as 'Closing the Life Cycle of Landfills, Landfill Mining in the Baltic Sea Region for Future' were promoted to create an experimental soil capping layer for GHG emission degradation in 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).

Recent research project 'TönsLM' in Germany has shown that there are still technical possibilities to create more valuable outputs within enhanced treatment processes when LFM or ELFM approaches in remediation are taken (Maul and Pretz, 2015).

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. 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) and Spooren 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). So far the general view is popular that performance of alternative thermal waste treatment (plasma and gasification) technologies is lower than for conventional energy-for-waste systems and the reason might be that exists less operational experience (Alternative Waste Conversion Technologies, 2013).

3. Methodological aspects

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 (Guerrero et al., 2013). 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 (Sepúlveda et al., 2010). These methods of extraction are far from sustainable from an environmental point of view. Another problem is ore mining waste; residual make up approximately 80% of the waste generated worldwide (Sverdrup and Ragnarsdóttir, 2014).

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 in Tel Aviv (Shual and Hillel, 1958; 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.

4. 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 and more if one lacks historical and well documented information. In this case past landfilled waste can be determined by using indirect means of survey: remote sensing and geophysics. Overview of the most important preliminary indirect research methods that are advised for the beginning stages of LFM operations are given in Table 2.

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 sur-

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Table 2
List of the main indirect landfill surveying methods.

The main indirect landfill surveying methods		Advantages	Disadvantages
Remote sensing	UAVs	Detection of unknown buried landfills	Limited spatial resolution properties
	LANDSAT	Informative on the lateral delineation of landfills	
	LIDAR	Spectral filtration possibilities	Vegetation and infrastructure create blind zones
	Aerial photography	Indicative on geomorphological details	
Proximal (Geophysical)	Electrical (conductivity, resistivity, dielectric permeability)	Help detection of waste characteristics prior to excavation and locate hazardous waste Estimate the volume of waste or soil, amount of waste with distinct physical properties Indirect opportunity for leachate study	Provide comprehensive indirect information about structure and properties of landfill masses, provide opportunities to estimate erosion risks and determination of capping fractures, however, without appropriate field and laboratory studies reliability on data is partial and uncertain
	Magnetic (permeability, anomalous field)		
	Seismic (refraction, microgravity)		
	GPR		

face 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 (see Table 2).

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), e.g., 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) (Table 2).

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 m (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). Source separation experiments from, e.g., excavations in Sweden show that in average for plastic, paper, wood and inert material it is 7–9% for each of a kind; 2–4% – textiles, organic waste and ferrous metals; less than 1% for each non-ferrous metals and hazardous waste; however, dominating fraction is soil – >50% (Cossu et al., 1996; Hogland et al., 2004; Hull et al., 2001, 2005; Sormunen et al., 2008; Frändegård et al., 2013). Nevertheless, there is no guarantee that such composition must apply to each and every LFM site – unique LFM project must consist of package of appropriate remote and proximal investigations, field drilling and sampling of waste and likely that must end up with the fine fraction analysis in laboratory as the fine fraction mainly consists of soil and its quality and contamination level is important when decisions through project implications are made (Burlakovs et al., 2015, 2016). Thus geochemical tools are important for having complete knowledge on site and these tools are described in chapter below.

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5. 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 might include a set of problems with contaminated surface water and groundwater flow changes, also chemical properties of inorganic and organic contaminants can be changed as environmental pH, moisture content, oxygen availability and other geochemical factors have influence on mobility of pollution. 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 estrogenic alike activity (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. (2006a,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).

6. Valorisation aspects

When studying LFM as an option 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). Globally the demand for minerals will increase as population and demand growth is unavoidable and it influences the volatility of primary resources (HCSS, 2009). The 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 Savage, 1993) 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,b, 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. Examples exist on mining companies that earlier worked with mining and then started a recycling business (Sverdrup and Ragnarsdóttir, 2014; Stenis and Hogland, 2015). More research is required to make this new type of mining successful in both economic and environmental terms.

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.,

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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 where the main objective was to remediate and recover the land for a public park.

It was revealed that capital and operational costs are very high, nevertheless in some cases the first were lower as equipment was leased or hired. The larger the scale of project, the less proportion the lease of techniques are taking. Literature usually reflects costs of operations limited to excavation, shredding and screening, typically using rented mobile equipment. Also, most of projects have been of relatively short duration and therefore full valorisation feasibility is hard to be calculated (Ford et al., 2013). All costs appear to have included metal separation, however seldom the primary interest for project implication is resource recovery (Hogland et al., 2011). Therefore, evaluation of full set of benefits (see Fig. 5) from diminishment of hazardous influence, valorisation potential for land (future public parks and industrial zones), gaining additional landfill space, recovery of aesthetic landscapes and revitalization of ecosystem services are not yet calculated with proper attention, therefore further comprehensive studies in this direction in future are necessary and it is more described in subsequent chapter.

7. Ecosystem services revitalization through landfill mining

The capacity of the global ecosystems is under increasing pressure and 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) affecting 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 21st 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). 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). Many of these sites are landfills and dumps where stressors or contaminants pose threats to the natural environment at densities, concentrations or levels that are high enough to disrupt the ecosystems (NZWS 2016; US EPA, 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 contaminated sites, including landfills through LFM projects can become revitalized and gain back functions they had before being degraded. However, there are several drivers for fulfilling such operations as depicted in Fig. 2.

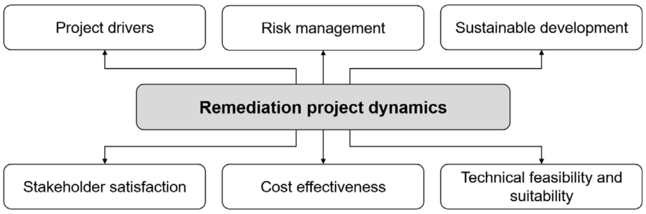

Fig. 2. Dynamic system of decision support for landfill mining as a full scale remediation project for environmental revitalization (authors’ workout, after Vik and Bardos, 2002).

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. The best available technical choice through decision trees have been explored by Laforest (2014), contingent valuation algorithms by Ferreira and Marques (2015). Profound study on defining if the potential hidden in landfills might be classified as ‘resource or reserve’ where the last are potentially extractable already today is provided by Winterstetter et al. (2015).

Many aspects are to 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,

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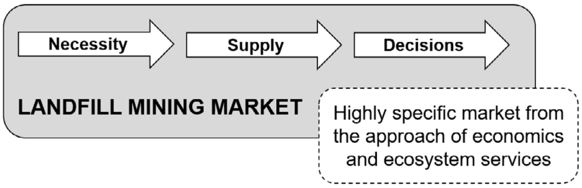

Fig. 3. Initial drivers for LFM market (authors' workout).

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).

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 methods like multi-criteria decision analysis (MCDA) might be used 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,

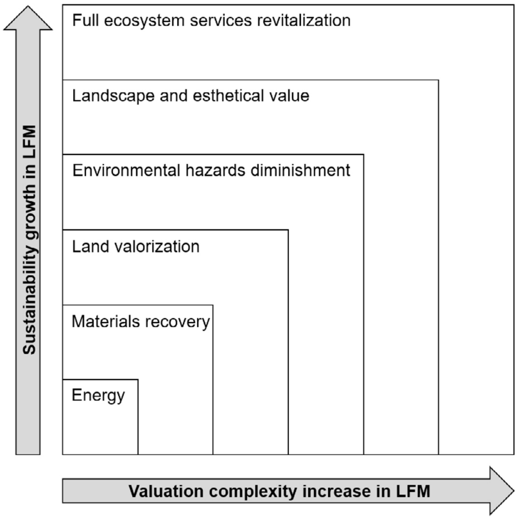

Fig. 5. Simplified diagram of the LFM paradigm approach revealing how the increase of sustainability drives the valuation complexity that increases simultaneously (figure not in scale; authors' workout).

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; Bonnin et al., 2015). 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).

The 'hunting for valuables and energy' is followed by 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. It seems that real estate regaining can be 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 driven by the market and urban-

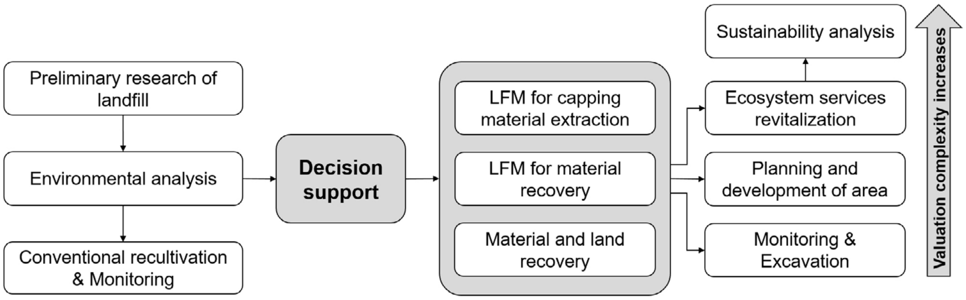

Fig. 4. Trivialized decision support system combined with LFM operations purpose (authors' workout).

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ization level. The more developed and environmentally anxious is society the more attention this society will pay to the environmental hazards diminishment. 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 valuation schemes for, e.g., recreation such as swimming and birdwatching 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 main concepts that have evolved during the last 60 years regarding LFM paradigms of 'how to perform LFM' are displayed in Fig. 5.

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.

It can be recognized that LFM project results, if taken in a holistic (environmental, social and economic) manner, might be analysed from different point of view. Thus, it might become more than just commonly cost-benefit judged item. Welfare of current and future generations (anthropocentric view) is important, however, the valuation of nature itself and biodiversity (eco-centric view) is more and more taken in consideration. The revitalization (land, ESS, biodiversity) under ethical considerations and societal attitudes is coming on the scene (willingness to pay for restoration and quantitative evaluation of environmental and ESS quality). Cost-benefit analysis might be not enough descriptive in order to give clear answers whether LFM projects are recommended and the performance would be approved or not—MCDA might be one of the tools that helps to broader evaluation of feasibility for consensus.

8. Conclusions

This review consists of analysis of the historical experience 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 various advanced concepts of full revitalization of ecosystem services. The emphasis in the review is placed on the additional aspects of such emerging practices that have the major potential to improve the valorization, diminish negative environmental hazards, look upon methodologies of additional benefits by estimating social and environmental aspects.

The future of LFM projects from social and environmental points of view is highly dependent on social attitudes, environmental and energy policies in general. ESS revitalization in the circular economy perspective is being regarded as the foremost holistic paradigm to promote the environmental practices from both, anthropocentric and eco-centric points of view.

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