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Getting serious about mining the technosphere: a review of recent landfill mining and urban mining research

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ABSTRACT

This study reviews the articles in a special volume of *Journal of Cleaner Production* on urban mining and landfill mining, identifying what is seen as relevant for exploring the feasibility of such approaches and which societal changes and research areas are essential for their further dissemination. In doing so, we put the articles in relation to previous research and a modified resilience model displaying dimensions of relevance for socio-ecological transitions, i.e., Metabolic flows, Governance & knowledge, Business dynamics and Infrastructure & markets. The main contributions of the articles in the special volume are in regards to metabolic issues (e.g. characterization of technospheric material stocks and societal impacts of landfill mining) and business dimensions (e.g. economics, organizational issues and management tools). Two articles also provide original contributions by conceptualizing these emerging approaches and defining what makes them different from existing recycling strategies and practices. We conclude that urban mining and landfill mining show high potential but that state-of-the-art is theoretical, implying a need for applied approaches to develop applicable methods and technology and to assess performance of such activities in practice. However, realization of these approaches faces interdisciplinary and long-term challenges, which apart from technology and facts also needs to address non-technical conditions in terms of governance, market dynamics and organizational structures and cultures.

1. Introduction

Our continuous need for materials and energy services has resulted in substantial accumulations of natural resources in buildings, infrastructure, products and waste deposits (Brunner and Rechberger, 2004; UNEP, 2010). The fact that such technospheric stocks of copper, for example, are now globally comparable in size to the amount remaining in known geological ores illustrates the magnitude of this ongoing relocation process of natural capital (Kapur and Graedel, 2006). Perhaps even more notable is that when it comes to base metals such as iron and copper, approximately half of the amounts extracted to date are no longer in use (Spatari et al., 2005; Müller et al., 2006; UNEP, 2010). These previously employed resources are not necessarily permanently lost but could be found in waste deposits (e.g. landfills, slag heaps and tailing ponds) or in out-of-date gadgets, buildings and infrastructure networks in the built environment.

In times of global environmental problems and concerns for long-term availability of natural resources, these so far often overlooked technospheric reservoirs might offer an opportunity for more sustainable development, or at least a complement to virgin production and recycling of annual waste flows in feeding market demand (Bergbäck and Lohm, 1997; Savage et al., 1993; Krook et al., 2011). This special volume pays attention to different aspects of two such emerging approaches, going beyond the end-of-life phase of landfills (landfill mining) and recycling of annual waste flows (urban mining). Before going into the details of this article, we believe it is first necessary to clarify what is meant by urban mining and landfill mining in the volume.

Recently, urban mining has come up in many forms and under different definitions in news reports, websites and conferences. It has frequently been used as a new, fancier term to describe different types of material recycling from annually generated waste flows, often in relation to coveted metals present in electr(on)ic waste (cf. Cossu et al., 2012). Although the resource potential of in-use metal stocks in terms of future waste flows often is specifically stressed, occurring definitions are vague, referring to more or less any recovery of metals (and other resources) from anthropogenic sources (Ayres et al., 2001; Brunner and Rechberger, 2004; Wittmer and Lichtensteiger, 2007; UNEP, 2010; Klinglmair and Fellner, 2010). Such a broad definition make urban mining largely similar to and entangled with other

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concepts already in use such as resource management, closing the loops, cradle to cradle and integrated waste management, especially since some authors also seem to include product design in the concept (Baccini and Brunner, 2012). In this volume, a more narrow understanding of urban mining is applied, in which "urban" means the area inside city borders and "mining" is understood as the extraction of secondary metal resources from obsolete, and in that sense accessible, reservoirs situated in these areas. This turns the focus somewhat away from in-use metal stocks currently fulfilling a function as well as "traditional" waste handling and recycling challenges – common focal points for several of the concepts outlined above. Instead, emphasis is on hibernating metal stocks which for several reasons have been halted from such ongoing anthropogenic material cycles, thereby not collected for waste management but abandoned in their current urban location (Bergbäck and Lohm, 1997; Krook et al., 2011; Milovantseva and Saphores, 2012).

In principle, landfill mining refers to the excavation, processing, treatment and recovery of deposited materials situated in informal waste dumps and in structured landfills (Savage et al., 1993). Although landfill mining at first glance might simply appear to be a subcategory of urban mining, it contains features making it somewhat different. While urban mining largely considers technospheric material stocks as potential assets, landfill mining originates from the waste sector in which such accumulations often have been considered a problem for various reasons. This perspective was also strongly reflected in many of the early landfill mining initiatives taking place during the 1980s and '90s, which commonly aimed at solving traditional landfill management issues such as lack of landfill void space, local pollution concerns and interference with urban expansion (Krook et al., 2012). Apart from some exceptions recovering landfill cover material and waste fuel (e.g. Dickinson, 1995; Reeves and Murray, 1996; EPA, 1997; Krogmann and Qu, 1997), the main driver of these reported landfill mining projects was seldom recovery of the deposited materials. Typically, simple excavation and screening equipment was therefore applied, demonstrating moderate performance in obtaining recyclables in terms of salable material and energy resources (Cossu et al., 1996; Krogmann and Qu, 1997; Hogland, 2002). Recently, however, several studies emphasizing resource recovery as a possible motivation for landfill mining have been conducted (e.g. Baas et al., 2010; Jones et al., 2010; Krook et al., 2012). In this volume, it is this emerging approach of landfill mining as a strategy to recover deposited materials and energy resources by employing more advanced, up-to-date material separation and processing technologies that is emphasized.

1.1. Aim and scope

This study aims at developing an umbrella article for the *Journal of Cleaner Production* volume on urban and landfill mining (Krook, 2010). In doing so, we review the main topics and research findings of the articles included and categorize them according to four main dimensions of a resilience model – dimensions believed to be of importance for any kind of socio-ecological transition. The contributions from the articles are then put in relation to previous research and transformation and resilience theories in order to identify essential areas for knowledge generation and further dissemination. Specifically, this study aims at addressing the following two research questions:

- What is currently seen as relevant in exploring the feasibility of urban mining and landfill mining?
- What transformations and research challenges are related to the further dissemination of these two emerging approaches?

Given the emerging phase of research regarding urban mining and landfill mining, as understood in this volume, the Call for Papers involved a broad approach inviting contributions dealing with issues ranging from policy and legislative matters, to economic, societal and environmental impacts down to details about technology and organizational issues (Krook, 2010). The response from the scientific community was moderate, however. In total, 21 articles were submitted. Approximately half were rejected because they involved topics beyond the scope of this volume, such as traditional management and recycling of different household and industrial waste flows or assessments of environmental impacts from landfills. Of the ten selected articles, eight dealt with landfill mining, making the contribution of this volume skewed towards resource recovery from waste deposits. Fortunately, however, one of the other two articles involved a review of a variety of concepts and initiatives for mining the technosphere, thereby bringing somewhat more balance between the two approaches addressed.

2. Resilience model: how did we work?

We see urban and landfill mining in a long-term perspective where material agglomerates excluded from ongoing anthropogenic cycles are brought back into societal systems again. As we have to cope with a complex system, we use a modified resilience model to indicate the complexity and multiple challenges facing urban and landfill mining.

Initially, the term "resilience" was utilized in ecosystem dynamics for a process of coping with severe changes, even shocks, in natural systems (Holling, 1973; Holling et al., 1995). However, recent interpretations of resilience are applied to social-ecological systems, defining it as "the capacity of a system to absorb disturbance and reorganize while undergoing change, so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al., 2004). Such a definition could be qualified as conservative by retaining the old features, but at the same time this research illuminates the need for interdisciplinary approaches for understanding how socio-ecological systems emerge, stabilize, transform and even decline (Westley et al., 2011). Emphasizing such dynamics between social, ecological and technological subsystems also prevents sub-optimization, as is the case in the assumption that new technologies will solve our environmental problems – an assumption already heavily criticized in the 1970s (cf. Ehrlich and Ehrlich, 1973; Schumacher, 1973).

In response to the trend of urbanization world-wide, urban socio-ecological systems have become the focal point of resilience research. The cooperation of three institutes resulted in a Resilience Alliance (RA) that provided a Research Prospectus involving four interconnected themes for prioritizing such research, Fig. 1 (CSIRO et al., 2007; Rose, 2007). This research goes beyond the traditional understanding of resilience by also linking it to the dynamics of system innovation and transformability (Walker et al., 2004; Westley et al., 2011). Urban systems can face disturbances that have the potential to create opportunities for doing entirely new things as innovations and new developments (Folke, 2006). In essence, this approach deals with how to turn problems in urban systems into innovation opportunities – something which in principle displays similarities to the emerging approaches of urban and landfill mining (cf. Baas et al., 2010; UNEP, 2010).

2.1. The modified resilience model for urban and landfill mining

The role of metabolic flows in sustaining urban functions, human well-being and quality of life is strongly linked with production, supply and consumption chains that neither start nor are complete within cities (CSIRO et al., 2007). Virgin production is the

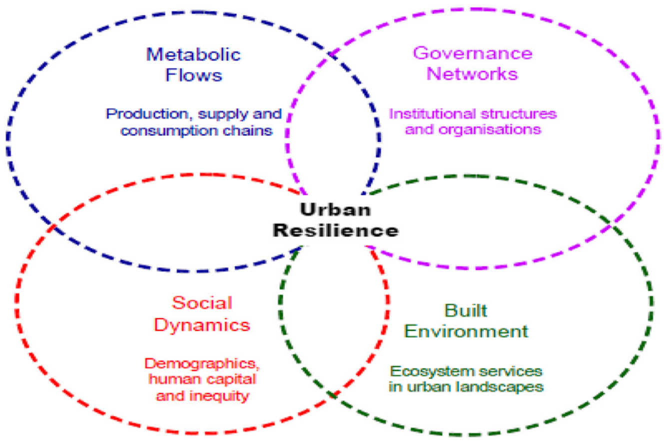

Fig. 1. The four interconnected research themes for prioritizing urban resilience research.

dominant source of such metabolic flows, although recycling of annually generated waste flows partially contributes to feeding the demand for some materials such as base metals (UNEP, 2012). In the modified resilience model, we fine-tune the dimension of metabolic flows as bringing obsolete and abandoned material stocks in waste deposits and hibernating products back into societal flows, Fig. 2. This involves development and application of methods for providing fundamentals regarding the magnitude, composition, location and accessibility of such obsolete stocks – knowledge which at present is largely limited (Van der Zee et al., 2004; UNEP, 2010; Krook et al., 2011, 2012). In addition, the resulting changes in physical resource and pollutant flows that exploitation of such non-traditional reservoirs cause are here seen in a systems perspective, aiming to keep track of environmental implications occurring on the global, regional and local scales (cf. Udo de Haes et al., 2000).

Governance networks face highly dynamic processes of human institutions and social organizations. In urban resilience research, the importance of a more fluid and responsive pattern of governance is commonly stressed (CSIRO et al., 2007). For sustainability innovations in general and urban and landfill mining in particular, decision-makers should thus be more concerned with adaptable and flexible management than prediction and control, given the complexity and uncertainty that follow such transformations (Loorbach, 2007; Baas et al., 2010). However, environmental policies and legislation are in many cases still adapted to controlling linear material flows. Improving the market conditions for urban and landfill mining will therefore most likely require new policies or at least removal or adaptation of counter-productive regulatory

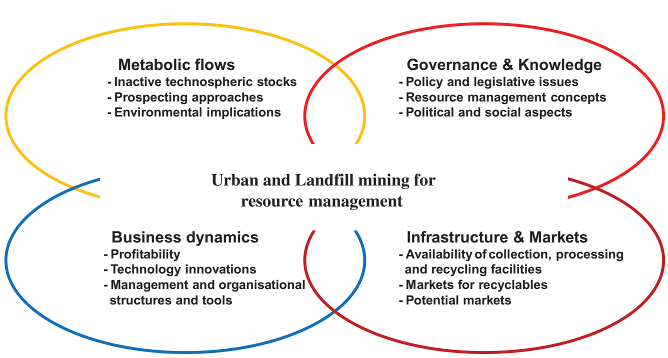

Fig. 2. The four themes of the modified resilience model "Urban and landfill mining for resource management."

relics (Strebel, 2004; Baas et al., 2010; Krook et al., 2012). Here, knowledge generation and dissemination processes seem essential in order to develop a common understanding about the specific challenges facing urban and landfill mining and whether these approaches deserve attention in terms of tactical policy-making (cf. Westley et al., 2011).

In the modified model, we specify the theme of social dynamics as business dynamics. The economic conditions for urban and landfill mining are not easily grasped, however, because they rely on case-specific conditions and perspectives, and on what societal scale such initiatives are evaluated (e.g. Van der Zee et al., 2004; Hull et al., 2005; Baas et al., 2010; Krook et al., 2011). Technospheric material stocks are also often owned by actors with limited or no experience and knowledge about resource extraction and recovery. Outsourcing and new forms of collaboration and business agreements might therefore be needed in order to facilitate implementation (Krook et al., 2012). In this context, technology is yet another critical parameter influencing the feasibility and incentives for realization, i.e., what useful resources can actually be extracted and transformed from such obsolete agglomerates and at what quality level? Overall, management innovations and tools making it possible to cope with uncertainty and risk seem essential for overcoming reluctance and resistance among actors to initiate such non-traditional activities (cf. Rogers, 2003; Baas, 2005).

In urban resilience, the built environment theme deals with the continuous changes in urban landscapes (CSIRO et al., 2007). In a way, people live in "yesterday's cities," since the structure of roads, buildings and green areas reflect decision-making processes in the past. This displays clear similarities to the theme of infrastructure and markets for secondary resources in our modified model. In industrial countries, emphasis so far has been to avoid landfilling, often through energy recovery of waste, which means that the capacity of the material recycling sector is still limited (Ayres, 1997; Loorbach, 2007; Corvellec and Hultman, 2012). For developing countries, material recycling is even more scarce, involving cherry picking of especially valuable materials such as metal and plastic bottles by scavengers and small-scale entrepreneurs (Rankokwane and Gwebu, 2006; Biswas, 2008). For urban and landfill mining, the issue of regionally available processing and recovery facilities for such supplementary materials is critical, because otherwise such initiatives risk causing new disposal problems (Fisher and Findlay, 1995; Krook et al., 2012).

In the next section, we work more in depth with the developed resilience model "Urban and Landfill mining for resource management" for categorizing and qualifying the articles of this volume. This is done by also relating their contributions to previous research. In the concluding section, resilience and transformation theories are introduced in order to identify what is important for further dissemination of urban and landfill mining. Emphasis is on knowledge generation and dissemination and how normative questions and competing value systems are not external, but rather integral to the development of these approaches (cf. Cote and Nightingale, 2012).

3. Main topics and contributions of the special volume articles

The contributions of the selected papers are spread across the four themes of the developed resilience model, Fig. 3. Most of them deal with issues belonging to the themes *metabolic flows* and *business dynamics*, which is not surprising given the fundamental character of such issues for displaying the potential of an emerging concept or strategy. When it comes to *governance and knowledge*, the articles are conceptual, attempting to define what urban mining and landfill mining are, assess their potential societal impacts and

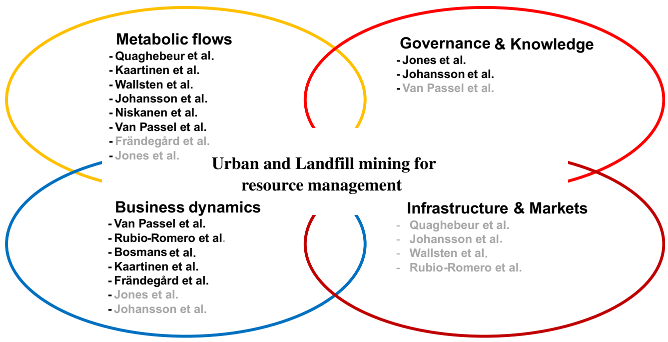

Fig. 3. Positioning of the special volume articles in the resilience model "Urban and Landfill mining for resource management." Author's surname in black font means main contribution and focal point of the article while light gray corresponds to sub-topics, which are only partly addressed. Some articles involve more than one main topic and/or sub-topic.

explain what makes them different from other existing landfill management and recycling strategies. None of the selected articles really focus on the theme *infrastructure and markets* for secondary resources, although several of them touch upon such issues, mostly in terms of potential markets.

3.1. Metabolic flows

Johansson et al. (2012) identify six main types of metal stocks in the technosphere and estimate their magnitude, location and concentration, two of them being of particular interest for this volume, i.e., landfills and hibernating products. Together with other waste deposits, i.e., tailing ponds and slag heaps, landfills constitute a significant reservoir for base metals (see also Kapur and Graedel, 2006; Müller et al., 2006). Globally, the amount of copper in such waste deposits is of a similar magnitude (390 million metric tons) as the current in-use stock of copper (350 million metric tons). More than two-thirds of this deposited copper is situated in landfills while the remainder is primarily found in tailing ponds (Kapur, 2006). This relation between in-use copper and obsolete copper in landfills is also likely to persist, although the magnitudes of both stocks will increase significantly in the years to come.

Although knowledge about hibernating stocks is scarce, they are often estimated to be small, comprising less than 10% of the in-use stock (Bergbäck and Lohm, 1997; Kapur and Graedel, 2006; Daigo et al., 2007). In this volume, Wallsten et al. (2012) assess a so far largely "invisible" hibernating stock situated in the subsurface of Swedish cities in the form of obsolete pipes and cables. The fact that such disconnected parts of infrastructure are continuously disconnected and left behind during maintenance and system upgrading has over time resulted in a significant underground metal reservoir. For Sweden, the amount of obsolete copper in this subsurface infrastructure mine can be estimated at 350,000–400,000 metric tons, to be compared with the copper stock in the yet operational parts of the networks of approximately 1.7 million metric tons (based on Wendell, 2005; Krook et al., 2011; Wallsten et al., 2012). In the near future, this hibernating copper stock will however increase significantly since most of the currently active, first-generation systems have already surpassed their lifetime expectancy. So, if the disconnect-and-leave-behind logic of subsurface infrastructure provision prevails, this obsolete copper stock buried in the ground will reach a magnitude similar to the current Swedish reserve in mountainous ores (1.8 million metric tons of copper), including Aitik, the largest copper mine in Europe (cf. Swedish Geological Survey, 2009).

Although useful from a policy perspective, this type of knowledge, obtained from material flow studies, aims to understand the overall patterns of the industrial metabolism rather than going into detail about certain reservoirs in specific locales (e.g. Spatari et al., 2005; Müller et al., 2006). For landfills in particular, data on the landfilled amounts of different materials in different regions often is scarce (UNEP, 2010). This means that fundamentals of mining are seldom addressed, such as precisely where in space specific resources are located and in what physical and chemical form they occur, i.e., how accessible they are for recovery. In real life, a region obviously does not contain a few uniform and easily localized metal stocks but rather a vast number of unique and diverse agglomerates scattered all over the landscape, in individual buildings and households, specific parts and sections of extensive infrastructure networks, local waste dumps, and so on. Hence, affordable and accurate prospecting methods are fundamental for the realization of urban mining and landfill mining.

There are some bottom-up and material flow analysis-based methods under development, which potentially could provide more detailed knowledge about technospheric "ores" (e.g. Lichtensteiger and Baccini, 2008). Such methods are however often still largely based on generic data and estimates and also fail to address the critical question regarding exactly where in an area the prospected resources are located. By performing a fine-grained bottom-up stock accounting, based on specific GIS information, maps and data from operators, Wallsten et al. (2012) go more into depth in their prospecting of metal resources situated in disconnected pipes and cables in the subsurface of the city of Norrköping, Sweden. This study implies that in order to provide readily applicable information for urban mining, detailed and spatial data of the specific locale is a necessity. Given the insufficiencies in map-based data on infrastructure, however, actual digging is plausibly still needed in order to validate the existence of such obsolete metal resources – or as a geologist would put it, to go from "probable" to "proved" resources (cf. Smil, 2003).

For specific landfills, even locally available statistics and log book data on deposited waste, if available, are often insufficient for obtaining a detailed understanding of the potential for mining. Jones et al. (2012) show that such data merely makes it possible to identify main waste categories (e.g. household waste, slag and industrial waste) occurring in the landfill while necessary information about the actual amount, position and condition of specific material resources (e.g. iron, non-ferrous metals, plastic, wood, and so on) are difficult to address.

These insufficiencies of available data on landfills and their interior can probably explain the numerous landfill mining field studies of recent decades, analyzing the composition and characteristics of excavated waste samples from specific sites (e.g. Cossu et al., 1996; Hogland et al., 2004; Hull et al., 2005). Two of the articles in this volume also involve such extensive field studies about the characterization of deposited household and industrial waste (Quaghebeur et al., 2012; Kaartinen et al., 2012). They add to the increasing amount of research demonstrating that both similarities and significant variations in material composition occur among different landfills (Krook et al., 2012). Apart from that, the study on the REMO landfill in Belgium includes some features making it especially interesting from a landfill mining prospecting perspective (Quaghebeur et al., 2012). In particular, the influence of time on the material composition due to changes in waste management and/or degradation processes in the landfill is thoroughly analyzed. Older parts of the landfill contain more recyclables in terms of metals and glass but also generally involve higher contamination levels, while more recent sections hold significantly larger amounts of potential waste fuel, primarily consisting of plastics and paper. Comparable age patterns have been identified previously for a municipal landfill in New Jersey, with the exception of metals which in that landfill seemed to remain on a fairly constant level of occurrence regardless of the age of deposited material (Hull et al., 2005).

Within the landfill mining literature, there is more or less consensus about the necessity of site-specific investigations for planning and execution of such projects (Quaghebeur et al., 2012; Kaartinen et al., 2012; Krook et al., 2012). Such excavation and analysis of waste samples are costly however, and thus only possible to realize on a limited number of landfills. The increasing number of landfill mining field studies, including the contributions in this volume, facilitates the identification of recurring patterns regarding the material composition of landfills of different types and age. Combining such generic knowledge with regionally and/or locally available data on landfills might make it possible to select the most promising sites for mining in a region for detailed field investigations, as suggested by Van der Zee et al. (2004).

Three of the articles in the volume apply a systems approach for simulating environmental implications of different types of resource recovery from landfills. Niskanen et al. (2012) quantify the potential of global warming mitigation through recovery of landfill gas from two Finnish deposits, displaying annual savings of several thousand metric tons of GHG emissions. An even greater potential is demonstrated for the planned landfill mining project at the REMO landfill in Belgium, aiming to more or less fully recover the 18 million metric tons of deposited resources, either as material or energy (Jones et al., 2012). Over a 20-year period, it is estimated that this project will result in approximately one million metric tons fewer of GHG emissions than business-as-usual involving combined heat and power recovery of generated landfill gas (Van Passel et al., 2012). The most important reason why landfill mining exhibits such a significantly larger environmental potential than landfill gas recovery is avoided primary production emissions caused by material recycling processes.

3.2. Business dynamics

Today, extraction of deposited resources from landfills alone often cannot justify such projects financially (Fisher and Findlay, 1995; Dickinson, 1995; Van der Zee et al., 2004). Instead, drivers of reported cases have been reclamation of valuable land in city regions, remediation or creation of new landfill space (Hull et al., 2005). In this volume, however, several articles assess the potential of applying more advanced, up-to-date separation technologies than were used in previously reported projects (Jones et al., 2012; Kaartinen et al., 2012). Based on pilot trials and expert estimates, they conclude that a significant share of deposited materials such as ferrous and non-ferrous metals, earth construction material and waste fuel is technically possible to extract into salable commodities, especially after further optimization of the tentative process schemes is done. One of these articles also presents an economic analysis of a planned landfill mining project at the REMO site in Belgium (Van Passel et al., 2012), in which the not yet commercially proven waste-to-energy technology Gasplasma will also be used (Gomez et al., 2009; Bosmans et al., 2012). However, despite assuming high efficiencies of separation technology and the Gasplasma plant, the economic incentives to engage in such a project still seem to rely on governmental intervention in terms of significant support through green energy certificates, tax breaks, investment support or the like. Given current market structures and material prices, the inherent problem is thus that costs for sorting, pre-treatment and energy recovery are still too high in comparison to revenues from the extracted commodities (Van Passel et al., 2012).

For extraction of hibernating subsurface infrastructure in cities just for the sake of metal recovery, the situation is similar. In most cases, revenues obtained from extracted metals simply cannot outweigh costs for excavation and site restoration (Krook et al., 2011). Extraction of such disconnected cables and pipes is thus rare and only happens when there is an immediate risk of pollution or a lack of space for installing new cables and pipes. Technology innovations in terms of modifying existing non-digging technologies for such urban mining purposes, thereby avoiding much of the excavation and site-restoration costs, thus appear essential for creating economic incentives for metal recovery (Krook et al., 2011; Wallsten et al., 2012).

It is not surprising that the economic feasibility of resource extraction from landfills and hibernating infrastructure is still largely questionable, given that no such full-scale projects have been realized. In contrast, the primary mining industry has through centuries of practice engaged in knowledge and learning processes, gradually developing more efficient prospecting methods and extraction technologies (Ayres, 1997; Johansson et al., 2012). Metal ores are also far more homogeneous and less distributed than technospheric metal stocks, which prohibits emerging fields such as urban mining and landfill mining to directly take advantage of these methods and technologies available within the primary mining industry.

However, as several articles in this volume state, implementation of urban mining and landfill mining relies on many things other than pure methods and technology. So far, for instance, urban and landfill mining have often been realized as rare, isolated events by actors with another core business (Van der Zee et al., 2004; Baas et al., 2010; Johansson et al., 2012). These actors, e.g. municipalities and infrastructure companies, then generally have to bear the extraction cost and risks while the main benefits may fall upon actors in other sectors, e.g. material and energy companies, or even occur on the societal level (Jones et al., 2012; Van Passel et al., 2012; Wallsten et al., 2012; Krook et al., 2012). In order to facilitate sharing of costs and benefits among such different actors, new forms of cross-sector collaboration might therefore be needed. This type of isolated and scattered initiative also means that long-term learning effects and processes stall – processes which within the virgin mining industry have resulted in an extensive knowledge base regarding how to prospect, organize and execute cost-effective metal extraction (Johansson et al., 2012). Such an understanding calls for specialized urban mining and landfill mining actors, ready to invest in fundamental and long-term learning processes, instead of as it is now when each project or initiative more or less starts from scratch.

Another important business dimension is how private actors should cope with any uncertainties surrounding the exploitation of landfills and hibernating resources. It is unlikely that companies will engage in such activities if the final outcome is vague or even impossible to foresee. There are, for instance, many possible landfill mining costs (e.g. prospecting, site preparation, regulatory compliance, gate fees, labor, transportation and equipment) and benefits (e.g. revenues for different recyclables, reclaimed land value, new landfill space and avoidance of future remediation costs) that may or may not appear dependent on how and for what purposes such projects are realized (Van der Zee et al., 2004; Van Passel et al., 2012; Jones et al., 2012). The same is true for environmental impacts where the characteristics of specific resource stocks, technology efficiencies, markets for recyclables, transportation needs and resource use of extraction and recycling processes are all examples of uncertainty parameters influencing performance (Frändegård et al., 2012; Krook et al., 2012). Again, there is a significant difference between these emerging approaches and primary metal extraction in that the latter can fall back on decades of experience and knowledge from previously exploited mines – a fact that drastically reduces business risks and uncertainties although they still may be significant.

Although assessment of complex, yet largely unproven approaches is indeed difficult, two of the articles in this volume provide such frameworks for environmental (Frändegård et al., 2012) and economic (Van Passel et al., 2012) evaluation of landfill mining projects. Both frameworks integrate a systems approach with the probabilistic method Monte Carlo simulations, making them capable of handling the large number of parameters and uncertainties that inherently will follow this type of non-traditional activity. Although more work is needed to finalize and validate these "prospecting tools," there is no question about their usefulness for learning more about critical conditions and breaking points for beneficial implementation of landfill mining. In the end, such knowledge is fundamental for being able to plan, organize and accurately optimize the performance of specific projects.

3.3. Governance & knowledge

Although emphasis is not on policy and legislation specifically, several of the articles in the volume include discussions about such implications in relation to their results. Both Van Passel et al. (2012) and Jones et al. (2012) show that the profitability of landfill mining relies on governmental intervention creating incentives for private actors to engage in such projects. By other words, extraction of material and energy resources through landfill mining cannot yet be realized solely on commercial grounds but is only an economic option if subsidies or other kinds of support are in place (Van Passel et al., 2012). External or let us say societal benefits of obtaining valuable material and energy resources through landfill mining instead of primary production (e.g. reduced carbon footprint and local pollution risks, improved regional material autonomy, conservation of strategically important materials such as metals, reclamation of valuable urban land, and so on) are arguments used to justify such support mechanisms in these studies. At present, however, such externalities normally are not internalized into private actors' returns (Jones et al., 2012).

Going down to legislative specifics, Jones et al. (2012) conclude that no specific barriers for mining old landfills occur in the European Waste Framework and Landfill Directives. On the other hand, current environmental legislation is still heavily adapted to linear material flows, which at least indirectly could influence the feasibility of and/or interest in urban and landfill mining (Johansson et al., 2012). For instance, the common way to deal with end-of-life landfills within the European Union is final closure involving capping and post-monitoring for decades, all in response to the Landfill Directive (European Council, 1999). Apart from taking away the limelight from alternative options such as landfill mining, such reinforced legislative documents probably make the owners of landfills resistant to opening them again for mining, especially given all the uncertainties that will follow such an endeavor. There are also several legislative uncertainties related to landfill mining. Johansson et al. (2012), for instance, raise the question if and how current landfill bans (i.e., for combustibles and organic waste) and taxes will apply to the inevitable re-deposition of non-recoverable materials from such projects.

The above discussions about policy and legislation strongly relate to knowledge dissemination and a common understanding of emerging approaches such as urban mining and landfill mining. However, as was already implied in the introduction, there are different opinions within academia and elsewhere about what these mining metaphors actually stand for. In particular, urban mining is indiscriminately used with largely different meanings within the fields of virgin mining (Dayani and Mohammad, 2010), traditional waste management and recycling (Cossu et al., 2012), holistic resource management approaches (Baccini and Brunner, 2012) as well as research dealing with the exploration of potential urban ores in terms of technospheric material stocks (Wallsten et al., 2012; Lichtensteiger and Baccini, 2008). As Johansson et al. (2012) argue, in its present indecisive form, the term "urban mining" fails to help us navigate in the complex technosphere. What secondary resources are we actually talking about: current or future waste flows, potential resources currently fulfilling a function in society or abandoned and hibernating resource reservoirs? Without such a fundamental understanding, policy-making becomes difficult and there is a risk that we even fail to identify the largely different potentials and challenges that are related to these different types of material flows and stocks in the technosphere.

In order to address this vocabulary confusion, Johansson et al. (2012) develop an umbrella concept entitled "Technospheric mining" describing six main types of initiatives for extraction and recovery of technospheric mineral stocks. The core of this concept is on extraction of minerals and metals directly from inactive technospheric stocks (e.g. landfills, tailing ponds, hibernating products) rather than handling the various forms of discards that annually are generated from in-use stocks (cf. Cossu et al., 2012), which is typically the focal point of existing strategies such as closing material loops and waste management and recycling. Although still rarely realized, except for recovery of gold, copper and iron from re-processing of tailings, this concept offers a more stringent vocabulary, which could facilitate the emergence of a new research field dealing with its own specific policy implications and challenges (Johansson et al., 2012). This is because there are such specific issues related to mining the technosphere, for instance, when it comes to the interdisciplinary challenge of identifying and facilitating extraction of such inactive or hibernating resources from their urban or rural locations (Wallsten et al., 2012; Jones et al., 2012).

The work on the enhanced landfill mining concept in several of the articles in this volume also appears useful for distinguishing between past and present approaches to landfill mining. This concept is defined as "*the safe conditioning, excavation and integrated valorization of (historic and/or future) landfilled waste streams as both materials and energy, using innovative transformation technologies and respecting the most stringent social and ecological criteria*" (Jones et al., 2012). As implied by this definition, enhanced landfill mining also considers future landfills as temporary storage sites for valuable resources, which cannot be recovered by existing technologies or display a potential for being recycled in a more efficient way in the near future.

3.4. Infrastructure & Markets

For obsolete products rich in metals such as disconnected infrastructure, once they are extracted from their subsurface location there will probably be a market in many industrial countries given the intrinsic value and demand for such strategically important materials. When it comes to materials extracted from landfills, the situation is somewhat different. Quaghebeur et al. (2012) conclude that fairly high levels of contamination in several of the deposited materials in the REMO landfill (e.g. in plastic, paper, fines, shredder residues) might in the end make material recovery technologically challenging.

Even in countries with sophisticated recycling systems in place, the treatment capacity of existing plants is limited. This means that supplementary materials extracted from inactive stocks in the technosphere such as landfills will, at least initially, compete with presumably "cleaner" materials obtained from source separation programs (Fisher and Findlay, 1995; Baas et al., 2010). In Sweden, for instance, several waste incinerators are currently experiencing overcapacity but for that reason are not looking at landfills as

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alternative sources for waste fuel. Instead, the common way to cope with such shortages is to import separated combustibles from other European countries suffering from insufficient waste treatment capacity (Profu, 2010). Securing a market for resources extracted from landfills and hibernating products therefore seems essential and another strong argument for developing long-term collaboration and agreements with recycling and energy companies (Baas et al., 2010). The approach by Jones et al. (2012) involving on-site processing and recovery plants solely constructed for taking care of extracted landfill mining materials might be yet another way to overcome such initial market limitation and competition.

Several of the articles in this volume identify potential markets or "windows of opportunity" for urban and landfill mining. Wallsten et al. (2012) argue that forthcoming city renewal and transformation projects offer an opportunity for recovery of subsurface infrastructure given that a large share of these areas will be dug up anyway, for installation of new infrastructure and sanitation purposes. In many regions of the world, there are also plenty of landfills that are in urgent need of remediation or need to be removed for city expansion and transformation reasons (Johansson et al., 2012). Adding a resource recovery aspect to such planned projects might thus offer an opportunity for landfill mining. Similarly, large-scale implementation of energy recovery of landfill gas, at least at larger sites, could be worthwhile given that EU legislation already demands gas collection systems with flaring as a minimum (Rubio-Romero et al., 2012).

4. Societal transformation and research challenges

What history tells us is that societal transformations take time, at least decades, and are the result of policy as much as of bottom-up societal movements and experimentation and exogenous sociocultural changes (Loorbach, 2007). The approach of mining deposited or hibernating resources from the technosphere could be seen as such a fundamental turn in perspective, involving its own specific potential and challenges (Jones et al., 2012; Johansson et al., 2012). At the same time, such a resource extraction system emerges within a larger whole consisting of a variety of systems and subsystems being more or less institutionalized and thereby resistant to change (Walker et al., 2004). There are, for instance, already two existing systems for resource extraction within which urban and landfill mining is entangled, i.e., primary production, the dominant mode, and recycling of annual waste flows. As indicated by several articles in this volume (e.g. Jones et al., 2012; Johansson et al., 2012; Van Passel et al., 2012), such interactions cause uncertainties and barriers but could also open up possibilities for synergies facilitating realization.

From transition research, we have learned that a breakthrough of any emerging system often means that the stability, i.e., resilience, of some already existing system has to decrease (Walker et al., 2004; Westley et al., 2011). In this case, urban and landfill mining are not necessarily disruptive to existing resource extraction systems but could even be catalytic by offering complementary sources for feeding the ever-increasing market demand for materials and energy. Metals are, for instance, fundamental for modern society and the anticipated scarcity is daunting. At the same time, we know that as long as there is a rapid growth in metal consumption, recycling of annual waste streams cannot replace a significant share of primary production (Graedel et al., 2004; Baccini and Brunner, 2012). Today, for instance, the global waste generation of copper is a few million metric tons while the annual consumption is approaching 20 million metric tons (U.S. Geological Survey, 2012). However, this kind of reasoning often neglects the significant agglomerates of previously employed metals which have been excluded or halted from ongoing material cycles (Kapur and Graedel, 2006; Müller et al., 2006). In time, extraction of the hundreds of million tons of obsolete copper that reside in landfills, tailing ponds and hibernating subsurface infrastructure could provide the recycling industry with substantial amounts of additional raw material, making it possible for this sector to take advantage of economy of scale (cf. Ayres, 1997). As has been argued in this volume and by others (e.g. Kapur, 2006), these obsolete technospheric stocks are also likely continue to grow rapidly in the years to come.

However, such non-traditional resource extraction is still in a pre-development phase involving scattered experimentation by informal constellations (e.g. academia, corporations and others) while little visible change occurs on the societal level. Within transition and innovation research, such "shadow networks" are often thought of as incubators for new ideas, working on alternatives to replace existing regimes if the right conditions occur (Westley et al., 2011). Despite difficulties in top-down management of societal transformations, governance could here play an important role by already in this early phase recognizing the work of these shadow networks. Tapping these constellations and putting their ideas on political and societal agendas will display a direction and create incentives for them to invest in technology development and long-term learning processes (Strebel, 2004; Loorbach, 2007) – an inevitable journey which the primary mining industry has largely already gone through. For urban and landfill mining such recognition by governments, NGOs and other opinion-makers has just started to appear. For instance, the UNEP Resource Panel, in their global report on metal stocks in society, has highlighted the importance of such strategies (UNEP, 2010). In Sweden, urban and landfill mining are now part of the national waste plan and soon, if the Swedish Environmental Protection Agency has its way, will also be incorporated into the upcoming Swedish mineral strategy (SEPA, 2012).

In this volume, the contributions of several articles imply that the environmental, economic and societal potential of urban and landfill mining is there but also that significant challenges remain in terms of how to initiate, prospect, organize and execute such projects cost-efficiently. More specifically, state-of-the-art is still largely theoretical, displaying a need for applied approaches developing applicable methods and technology and demonstrating feasibility and performance of such initiatives in practice. Some of the main challenges for facilitating further dissemination of urban and landfill mining are outlined below:

- *Metabolic Flows*
  - How can specific obsolete resource stocks be prospected in an affordable and accurate way?
  - What are the global, regional and local environmental impacts of such initiatives?
- *Business Dynamics*
  - Which technologies are capable of transforming inactive technospheric stocks into salable materials and energy carriers?
  - How can such projects be organized in order to obtain mutual benefits among involved actors and manage the inherent uncertainties and risks?
- *Governance & Knowledge*
  - From which perspectives and on what scale should urban and landfill mining projects be evaluated?
  - What are the societal impacts of urban and landfill mining and could such effects justify governmental intervention in terms of new or adapted regulations and policy instruments?
- *Infrastructure & Markets*
  - How can markets be secured for materials and energy resources extracted from landfills and hibernating products?

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- How can the resource recovery dimension be introduced to and become a natural part of ongoing planning processes for city and landfill transformations?

Learning from the past, it will presumably take decades before urban mining and landfill mining become common praxis even if significant investments in knowledge and technology development were made immediately (Loorbach, 2007). Such an understanding calls for immediate action given that the deposited and hibernating resource stocks, e.g. of metals, are of such an order of magnitude that we simply cannot afford neglecting them, at least not in a long-term perspective. The numerous planned landfill remediation and city transformation projects worldwide could in this respect serve as a foundation for thriving learning processes about such non-traditional resource extraction. Rapidly growing resource demands globally, increasing raw material prices and peak metal concerns are all examples of ongoing exogenous changes that over time might create strong enough incentives for such integrated initiatives, but we are not there yet. For now, landfill and city transformations are instead driven by other reasons, which largely neglect the resource recovery dimension of these reservoirs. Governmental intervention in terms of new or adapted policies and regulations might therefore be needed in order to create incentives even now for actors to initiate such a long-term journey on how to best exploit these urban and landfill ores.

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