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Sustainability and the circular economy: A theoretical approach focused on e-waste urban mining

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ABSTRACT

Reuse and recirculation of products and materials are the basis of the concept of the circular economy (CE). The CE is an innovative proposal that can result in positive impacts such as reduced demand for raw materials, reduced consumption of basic resources, and job creation, as well as preventing negative impacts resulting from the exploitation and processing of natural resources. Mining is infamous for its potential environmental impact, but mining waste from traditional mining (in the linear economy) may recover material through upcycling techniques, as can urban mining of industrial and post-consumer waste categories (in the circular economy). Urban mining, a form of closed-loop supply chain management, offers an attractive alternative to the management of waste electrical and electronic equipment (e-waste) and, at the same time, as a sustainable way to exploit mineral resources, reduces primary material intake and stimulates the circularity in the supply chain. The present study reviews the main CE solutions for e-waste management, highlighting the importance of recovering and classifying mineral material according to urban mining procedures.

1. Introduction

The movement of hazardous waste across frontiers between developed and developing countries is among the most contentious of waste management policies (Milovantseva and Fitzpatrick, 2015). The limits seem to be not effectively established despite the Basel Convention guidelines promulgated in 1989, which came into force in 1992, for the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (Nnorom, 2008; Ogunseitan, 2014). This convention covers the hazardous components from Waste Electrical and Electronic Equipment (WEEE or e-waste). According to this convention, the movement (import/export) of hazardous waste and other wastes between countries is prohibited or restricted (Albers, 2015; Lepawsky, 2017). Kummer (1995), based on Basel Convention, emphasizes that “wastes should be disposed as close as possible to the source of generation”, endorsing the restrictions on movement proposed and also specifying liability.

E–waste is one of the fastest growing categories of waste (Awasthi et al., 2018). The hazardous potential of post-consumer electronic equipment is raising concerns about the significant volume of e-waste generated in the world, estimated at 44.7 million metric tonnes in 2016 (Baldé et al., 2017).

Part of mining sector waste generation can be included in the analysis of the e-waste life cycle, since the electrical and electronic devices are mainly produced from mineral raw materials. Disasters in the mining sector have had a long-term impact on environmental sustainability. This has focused public attention on mining procedures for waste management and sustainable solutions for e-waste life cycle management (Talsen, 2017).

Some of the impacts of electrical and electronic equipment disposal are also observed in mining waste management, which means that contamination by metals and hazardous substances must be avoided in both sectors: production/consumption/disposal of electronic devices and mining activities.

The waste management strategies necessary for a transition from a linear to a circular model are not always consistent with the basic principles of economics. This is evident in developing countries where the economic value of materials for the waste-pickers is less than the financial value to a recycler or reverse manufacturer (Rebehy et al., 2017). A case study of two developing countries (Indonesia and Brazil) found that waste-pickers’ cooperatives are not a solution for this category of waste management (Colombijn and Morbidini, 2017).

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Some authors propose an analogy between the organization of cooperatives for waste management by waste pickers and the formation of cooperatives by artisanal gold miners (Lee, 2005; De Theije and Bal, 2010). They suggest waste pickers and goldminers, “have embraced the general principle that people who willingly forfeit protective bonds can reach new levels of freedom” (Lee, 2005).

There are huge differences in e-waste management approaches in developing countries. A classic case of a developing country's effort to manage the huge volume of e-waste that comes from developed countries was presented by Ongondo et al. (2011). Sothun (2012) makes an important contribution analyzing e-waste import and management procedures in Cambodia with the support of the Secretariat of the Basel Convention (SBC). Although Cambodia has no specific regulation for e-waste management, the Ministry of Environment developed, together with Korea's Ministry of Environment, a guideline for Cambodian e-waste management with seven principles, as follows:

- Reuse e-waste as far as possible prior to disposal;
- Reduce e-waste from its sources, e.g. householders, retailers, repairing and dismantling units;
- Repair electronic and electric equipment for reusing rather than keeping it or disposing of it;
- Recycle e-waste prior to disposal: “Waste is Money”;
- Manage e-waste throughout its life cycle, e.g. generating process, storage, transportation, treatment and disposal based on environmentally sound principles;
- Identify, establish and operate a safe dumpsite for hazardous waste, including e-waste from selected urban areas;
- Comply with national and international laws, regulations, conventions, and protocols.

The Basel Convention addresses the poverty and vulnerability of developing countries related to waste management, related to the value and efficiency, though not always fair, flows of post-consumer e-waste products and materials. The post-consumer and disposal phases may bring cumulative environmental and social impacts.

Waste management methods have been discussed for more than four decades and in recent years a new paradigm has been proposed: the transition from a linear to a circular model (Wang, 2005; Ellen MacArthur Foundation, 2013; Cobo et al., 2017; Davis and Hall, 2017). Although it is relatively easy to understand the importance of this transition, it is challenging to implement it in countries with different economic and technological status. According to the Ellen MacArthur Foundation (2013), the Circular Economy (CE) is defined as an industrial system that aims to avoid waste through design of optimized cycles of products, components and materials by keeping them at their highest utility and value. In other words, it is desirable to maintain products in use as long as possible, to incentivize repair, refurbishing and reuse techniques, and promote the use of secondary raw material, creating new growth and job opportunities.

Some specific approaches, such as reverse logistic and urban mining, are part of the Circular Economy and may contribute to reducing environmental impact. Wider analysis of the entire life cycle is needed, to promote reinsertion of co- and by-products, as well as secondary raw materials, in a closed-loop supply chain, instead of the classical linear produce-consume-disposal model.

In a recent report for the United Nations University, Baldé et al. (2015) stated that e-waste recycling worldwide has been “limited due to lack of incentives from legal frameworks, awareness of pollution control during recycling as well as the lack of training opportunities for certification”. The importance of circularity in the e-waste sector is reinforced by the abundant workforce, advanced solid waste regulation, and access to knowledge about the reuse of waste, (Baldé et al., 2017).

This article analyses some aspects of the mining sector and recycling segment to reflect on potential changes to the CE concept, and how to improve sustainability of those practices and increase the chance of mutual feedback.

This paper is divided into four sections. This opening section introduces the state of the art and theoretical background of the sustainability and CE concepts, together with their development over time. In the second section the methodological approach is presented and in the third section the results are presented. The fourth section provides discussion and conclusions.

2. Conceptual background

Mining is a basic industry that provides raw materials for the manufacturing industry to produce essential goods. All society benefits from the results of this activity. Over the centuries, mining activity has evolved into businesses that today seek to conform to international sustainability guidelines. We propose a historical approach to the main concepts related to sustainability in mining and urban mining. In this article, the term “urban mining” is applied exclusively to the recovery of secondary raw material from waste under the 3Rs concept, which means to reduce, reuse and recycle. The main premise is that valuable materials may be recovered from waste in a way that is analogous mining, to produce high value and sustainable secondary raw material, so that industrial products can be supplied cheaper. In other words, the e-waste management can result in profitable urban mining.

2.1. Early concepts

The carrying capacity is the most popular ecological concept linked to sustainability and conveys a sense of precision that the sustainability concept lacks (Sayre, 2008). Odum (1953) was one of the ecologists who first proposed and discussed carrying capacity, which he described as saturation level of the resources and environmental conditions related to public welfare.

Hardin (1968) summarized the ecological carrying capacity concept as, “A finite world can support only a finite population …” This is a rich sentence that introduces the understanding of finiteness and also provides tools to rethink the exploitation of natural resources. Industrial ecology (Erkman, 1997) was proposed in the 1970s, to show the potential symbiosis between the productive processes and the ecosystem of cities, through the pioneering reuse of waste in the form of raw material. Industrial metabolism (Ayres, 1989) proposes a similar approach inside industrial ecosystems. Some authors argue for a potential interaction between industrial metabolism and CE and propose some case studies related to metal recovery (Octave and Thomas, 2009; Han et al., 2016; Gómez et al., 2017).

In the early 1980s, the British Standards Institute, especially in BS 7750, proposed the basis for environmental management from an organizational point of view. This may be regarded as a basis for sustainability presented in the report, Limits to Growth, published in 1972 by the Club of Rome. The Brundtland Report (1987) also reinforced the sustainability movement and the concept of sustainable development (Strong, 1992).

As Stahel (2017) pointed out, the Club of Rome considered the transition to this model as a way to reduce greenhouse gas emissions by 70% and to grow demand for labor force by 4%. We believe the CE may facilitate the achievement of United Nations’ Sustainable Development Goals (SDG), potentially bringing more pragmatism to actions, as it includes businesses as relevant players. The current production and consumption models, as well as business models, need to be completely rethought, to align with the changes that the CE model embodies.

With the emergence of technological and strategic tools in reverse logistics, urban mining can provide the best solution for e-waste management. Cossu and Williams (2015) argue that e-waste is the backbone of urban mining, that can recover secondary raw material that is of critical industrial interest.

Previous approaches of *Closing the Loop*, or, earlier, of *Cradle to Cradle*, were conceived in the early 1980s to combine biological and technical cycles (McDonough and Braungart, 2013), as proposed by the 3Rs concept. While *Cradle to Cradle* is related to a circular approach, the *Cradle to Grave* approach is related to a linear conception of the product life cycle. McDonough and Braungart (2013) noted that there was a "downcycling" (i.e., lowering value) of some products and material instead of "upcycling" (i.e., increasing value) during recycling processes. In addition, they remarked that closing the loop is not a positive event when the reprocessed material or product is toxic, for example.

2.2. Sustainable mining

Many experts have suggested that mining is an inherently unsustainable activity, since it is based on the exploitation of non-renewable resources (Lins and Horwitz, 2007). However, some initiatives may reduce or mitigate the impact. As there are potential impacts on the environment, health, communities and economies of neighboring areas where mining takes place, society requires sound sustainable development actions. However, improving sustainability in the resources industry can be a challenge, especially to address the three dimensions of the sustainability concept: environmental, social and economic aspects. The concept of sustainability implies the use of resources without compromising their potential use for future generations, and as mineral resources are finite, some authors consider that there is no place for sustainability in the mining industry. Mudd (2010) clarifies this argument: since, "mineral resources are widely interpreted to be finite or non-renewable; to consider sustainability in mining would constitute a paradox.

Other authors believe that the net of benefits of extractive resources industry can be balanced (Villas-Bôas and Beinhoff, 2002; Jenkins and Yakovleva, 2006; Shields and Solar, 2007). Machado et al. (2011) emphasized the importance of sustainable mining through a legal framework and administrative procedures for environmental protection of mining sites.

Mudd (2010) also argues for considering the benefits of the mining industry as a whole and not only one segment of the sector: "It is the sum of all individual mines over time and space and their respective resources, impacts and benefits, which should be considered in ascribing sustainability to mining". Sustainable mining needs to be addressed not only to obtain social license to operate – given the relevance of the issue for investors and consumers – but for economic growth (Ellen MacArthur Foundation, 2013), and economically sustainable development (Robeyns, 2005; Ayres, 2008; UNDP, 2015).

In general, sustainable mining seeks to combine social responsibility and environmental preservation with the financial objectives of mining operations, as has been attempted in countries with a tradition of mining such as Australia, Canada and US (Solomon et al., 2008). More recently, developing countries have also invested in better and sustainable mining practices, such as China (Zeng et al., 2016); Burkina Faso (Ouoba, 2017); Ghana (Essah and Andrews, 2016); Greenland (Tiainen, 2016); Poland (Pactwa and Woźniak, 2017); and Brazil (Carmo et al., 2017; Aires et al., 2018).

Brown et al. (2007) highlight the 1992 UN Environment Conference in Rio as a turning point in the discussions of shared responsibilities among governments, non-governmental organizations, global corporations and society. Environmental, social and economic impacts – the triple bottom line of sustainability – frame discussions about private corporations having an active role, not as part of the environmental problem but as part of the solution. The CE model makes it feasible to include businesses as part of the solution. The following section analyses products and materials from e-waste according to CE requirements in different countries.

2.3. To infinity and beyond

Investments for a transition towards a CE have been made by the European Union, the US, Australia and China. Sweden had a pioneer initiative to reduce by 50% the tax on repaired products, as well as removing taxes on workers employed in repairing services (Stahel, 2017). In Australia the project, Wealth from Waste, was created among its main universities and the CSIRO to optimize the reuse of waste and also mapping urban mining using Proxy and GIS tools (CSIRO, 2015). Initial studies recognize the importance of metal reuse and recycling, but some authors remark the need to find technical solutions, as well as appropriate policies, to make mineral reuse feasible and suggested the need to solve the overlap of the life cycle of minerals in different industrial sectors to avoid the over-taxation in a CE (Golev et al., 2016).

The European Union has discussed the possibility of providing economic incentives for production including the principles of CE, and to reduce the price of products in proportion to the length of their life cycle.

Companies in the US have developed robots to extract materials from cell phones, with the capacity to recover minerals such as aluminum, copper, gold, platinum group metals, silver, tin, rare earth elements, cobalt, tungsten, and tantalum. Those metals can be reused in new gadgets and the pilot plant – developed in 2016 with the capacity to process 24 million gadgets per year – is approved (CEC, 2017).

Given some of the outcomes listed above, it can be seen that, the focus on CE is on more tangible results for the environment, businesses and communities. In the traditional linear approach, economic growth was indicated by only the increase of gross domestic product (GDP), and is interpreted as an absolute sign of well-being and quality of life, assuming a direct correlation between access to consumer goods and quality of life (Mishan, 1967; Robeyns, 2003). However, some schools of economics have questioned this mainstream assumption that growth indicated by GDP assures quality of life (Boulding, 1966; Atkinson, 1970).

Moreover, the linear model does not take into account the costs and impacts on the environment and to public health because of the way it treats goods and resources as disposable and inexhaustible. In this model, the costs of natural resources are not taken into account (Hardin, 1968; Ayres, 2008). As Mudd (2010) highlighted, sustainability in the mining sector can be interpreted as an oxymoron as "mineral resources are widely known to be finite". In fact, the mining industry was conceived in the paradigm of the linear model – in contrast with the CE - so there are some obstacles to achieving sound sustainability approaches in the sector, although the International Council on Mining and Metals claims it to be possible in regard to the SDGs (ICMM, 2014).

While sustainability initiatives have been progressively introduced and put on the agenda of enterprises and organizations, the CE model has the potential to bring about a long list of amendments, corrections, changes, and new developments that may significantly improve sustainability outcomes, and that can benefit the planet.

While the traditional linear model does not consider that natural resources are finite, and the sustainability approach is required to address its impacts, the circular model tries to integrate the finiteness of resources into the model and proposes the reintroduction of materials from secondary sources in a regenerative system (Braungart and Lovins, 2014). The value of products, materials and resources should remain in the economy for as long as possible, since they should be designed to return to the production cycle or to the services system, even if in other loops.

The scarcity of natural resources may compromise some technological and sustainable products through lack of supply or the rising price of critical raw materials such as rare earth or valuable metals (Pavel et al., 2017). It is possible to reduce the demand for resources by efficiency improvements, design for environment and substitution strategies for material. The concept of the circular economy provides more direct solutions to address ecological footprints. According to the Ellen MacArthur Foundation, the adoption of a "more restorative approach" would save "more than USD 600 billion p.a. by 2025, net of material costs incurred during reverse-cycle activities" (Ellen MacArthur

Foundation, 2013).

According to Luthra et al. (2015), in their remarkable contribution to Green Supply Chain Management (GSCM), the scarcity of natural resources has been identified as the main Critical Success Factor (CSF) to guarantee business sustainability.

The circular model is thus “an industrial system that is restorative or regenerative by intention and design” (Ellen MacArthur Foundation, 2013), which aims to reduce the need for primary resource extraction and it targets zero waste generation (WRAP, 2016). In fact, waste is considered in the CE model as “a failure of design” (Ellen MacArthur Foundation, 2013). According to the Ellen MacArthur Foundation, more thought should be given to a “restorative use of non-renewable resources” (Ellen MacArthur Foundation, 2013), as businesses could invest on “an industrial model that decouples revenues from material input” (Ellen MacArthur Foundation, 2013), as is envisaged in the CE model. As a result of this view, the acquisition of a new product is not seen in the CE paradigm as *the good option*. It is implicit that a transition towards a CE model will require changes in organizational culture, leading to changes in the production processes in general, mining included, as well as consumer behavior and marketing practices, to reduce the impact of obsolescence.

The CE is based on a “make-and-remake /use-and-reuse” model (Ellen MacArthur Foundation, 2013) where resources and products in the production system run in more efficient and innovative ways, as highlighted by the European Commission in the European Union Action Plan for the Economic and Social Committee (COM, 2015). This model does not rule out profit but seeks to find economic outlets for the “long-term effect of having not considered the finiteness of natural resources at the starting point of the industrialization process, whose costs need to be addressed for the planet sustainability” (Ribeiro-Duthie and Lins, 2017).

Although reprocessing residual waste could be interpreted as a sort of reuse of resources, for some authors the waste reprocessing undertaken in the mining industry cannot be considered a CE initiative, even if it is in line with sustainability in the industry. According to Lèbre et al. (2017), “reprocessing mine waste in order to recover further minerals is classified as primary extraction rather than a case of metal recycling”. However, if reprocessing mineral waste is not recycling, such processes still make it feasible to re-use minerals. How the classic mining industry can integrate CE principles is still a road untraveled. In the case of urban mining, CE model seems to motivate and reinforce the activity.

The use of the CE terminology is incipient in the mining sector. Some mining or industry-related experiments or organizations, both internationally and nationally, may be in tune with the CE paradigm. In this context, in 2018 was created the Technical Committee from the International Organization for Standardization ISO TC 323 on Circular Economy, secretariat by the Association Française de Normalisation (AFNOR) and with 68 countries taking part in the scope of the establishment of requirements for circular economy projects.

2.4. Mining and urban mining

The application of the principles of sustainable development to the mining sector has been extensively discussed (Lins and Horwitz, 2007; Gomes et al., 2014; Giurco et al., 2014; Vintró et al., 2014; Zvarivadza, 2018). Mining is one of the oldest and most traditional economic activities, responsible for providing raw material for different supply chains.

China is responsible for around 90% of the world's supply of rare earth elements (REE), and these elements are critical for the countries that use them in different applications, for example: permanent magnets (20%), polishing (15%), fluid-cracking catalysts (13%), other metallurgy (10%), batteries (8%), glass (7%), phosphors (7%), autocatalysts (6%), ceramics (5%), and other (8%) (García et al., 2017).The natural reserves of REE are concentrated inafew countries: China, Brazil, Canada, US, Russia and Congo (Massari and Ruberti, 2013; Paulick and Machacek, 2017).

Brazil has the fourth largest mining sector in the world. The country is internationally considered a global player for its exports of niobium (1st), iron ore (3rd), manganese (5th), tantalum (2nd), graphite (3rd), bauxite (3rd) and large stones (4th). However, Brazil is an import-dependent country for metallurgical coal, sulfur, potassium, phosphate rock and rare earths (KPMG, 2015; IBRAM, 2017). Materials are classified into strategic or critical according to the trade-off between availability and lack of these materials. In the case mentioned above, for example, niobium is strategic for Brazil, but it is critical for those countries that do not have their own ore.

Despite the different motivations, environmental regulations are the basis for the sustainable management of natural resources and consolidation of the CE by promoting the closed loop of products and material. The main goal is to coordinate economic, social and environmental targets in order to attain mutual benefits. As the demand for high tech products increases and the strategic or critical raw materials become scarce, the e-waste emerges as an important supply of secondary resources (Tansel, 2017; Marra et al., 2018). In 2016 it was estimated that Latin American countries generated 4.2 Mt of electronic waste. Brazil is the second major e-waste generator among American countries, with 1.5 Mt tons per year, behind United States (6.3 Mt) and followed by México (1Mt) and Argentina (0.4Mt) (Baldé et al., 2017). This strategic position of Brazil in the volume of e-waste generation in Latin America has been exacerbated by the economic growth experienced by the country in the last decade, as well as by the strong legal framework related to e-waste management. Impact mitigation resulting from e-waste urban mining can also be interpreted as an economic solution for social and environmental issues.

The transition from a linear to a circular economy model demands the integration of different areas of knowledge. This flux can be exemplified through the comparison between the traditional mining processes and the new urban mining possibilities. In this conceptual background, inspired by the current scenario of e-waste management, we presented the original concepts that led to the consolidation of the circular economy concept, presented some challenges for a sustainable mining, and introduced some innovative processes for material recovering as secondary raw material.

3. Methodology

This section is structured as follows. After a literature review on the concepts of sustainable mining, e-waste urban mining and CE, to produce the conceptual framework, we present the specifics of e-waste urban mining, highlighting the linear and circular economy trade-off, and classify the secondary raw materials according to the criteria for economic, environmental and social aspects.

3.1. Conceptual framework

This is a theoretical study of sustainability and CE, and of the related set of concepts, their interactions, and the contribution of e-waste urban mining. The methodology consists of reviewing literature and regulations on CE and sustainability in different countries and identifying the importance of recovering critical and strategic materials from post-consumer electrical and electronic devices.

The bibliographical research analyses traditional mining (linear economy) to urban mining (circular economy) and CE concept, to provide elements of the conceptual framework, linking the key-concepts.

3.2. Secondary raw-material classification

Since the traditional mining has well defined phases, it was necessary to identify the urban mining stages. There are not specific definitions in the literature in this specific area, but some details are provided according to the category of input material in the traditional supply chain and this base was considered as start point in this classification. The secondary raw materials resulting from e-waste urban mining are classified according to economic and environmental characteristics. The evolution of CE and related practices in different countries was highlighted as the basis of the discussion.

The material classification took into account the specificities of the secondary raw material from different technological processes. The definition of each class was made by focusing in the circularity potential of those materials in the electronic equipment supply-chain.

4. Results and discussion

One straightforward piece of information obtained from the theoretical approach is the set of concepts that support sustainability and the CE approach. The coverage of e-waste highlighted the importance of urban mining and the importance of biotechnology for material recovery from e-waste. The results are presented according to the main topics covered in the theoretical approach.

4.1. Conceptual framework

The literature review revealed that the CE concept is not a disruptive innovation, but a set of concepts integrated so as to promote waste prevention, 3Rs incentives and sustainability practices. The CE concept has a strong legacy gathered from classical concepts such as carrying capacity, industrial ecology and industrial metabolism. But it also has important contributions from the environmental management regulations started in the 1980s. The following analysis is based on the chronological ordinance of these classic definitions (Fig. 1).

The chronological analysis depicted in Fig. 1 presents the main concepts of sustainability and the CE. All the concepts emerge from the concept of carrying capacity proposed by Odum (1953). This concept identifies a limit to the provision capability that is the main pillar of resource management. How to manage the available resources according to the present and future demand is still the main focus in sustainability and also in new concepts such as Extended Producer Responsibility (EPR) and the Integrated Policy Product (IPP). The IPP was introduced by the European Community regulation as a strategy to promote the development the market of greener products; while the EPR, adopted by several countries, is the producer responsibility and commitment on collect and recycle the products on its behalf in order to reduce the respective impact along the life cycle.

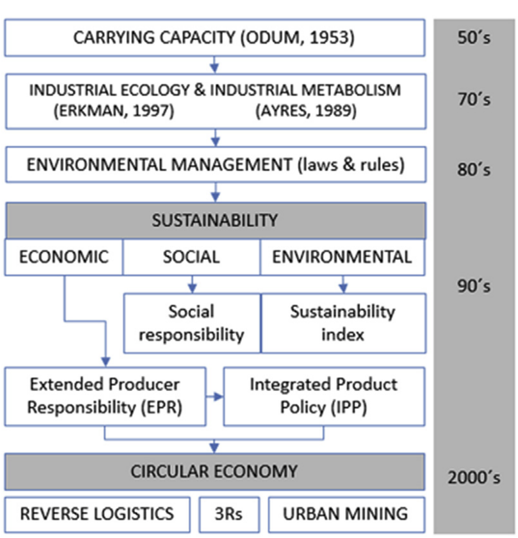

Fig. 1. Chronological analysis of sustainability and the circular economy.

In a nutshell, to promote a sustainable corporative image, the organizations are searching for reduce hazardous substances and recycle materials, while the consumers are been introduced to the reuse possibilities. Together, the 3Rs, reverse logistics and urban mining concepts are among the most important in the CE. Reduce, reuse and recycle are the main steps for reverse logistics and urban mining, both related to the CE concept.

The following evaluation focuses on e-waste management procedures in the most recent frontier of urban mining, regarding e-waste management as an opportunity to recover and upcycle materials as well as manage waste and energy efficiently.

4.2. E-waste urban mining

Open pit mines and piles of sterile material deposits are a reality of almost all mineral activities in mining. This aspect allied to failures in environmental restrictions and to costs to maintain tailings, contribute to the trend of disposing of open-pit mining waste on the surface and result in environmental impacts.

To minimize and solve these problems, it is important to promote the sustainable production of the sector with support for programs for the correct management of tailings and mine closure, as well as incentives to recycle and reuse products and reuse materials from mineral resources, in line with the concepts of the 3 Rs (reduce, reuse and recycle) from the development of the circular economy. A remarkable advantage of urban mining, i.e. mining from secondary sources, is that the proportion of valuable metals that can be recovered from e-waste is up to ten times greater than the amount extracted from primary mineral deposits (Szamałek and Galos, 2016). To extract ore from a mine site, it is necessary to undertake a geological study and a survey before mining operations start. Even then, the exact amount of the metal of interest in the site cannot be known. Therefore, urban mining appears, at first sight, to be a better option. For example, the recovery of gold from e-waste may represent 250–350 g per ton of scrap, while conventional gold mine extraction will yield only 1–5 g per ton of ore (Owens, 2013). High yields of precious metals and aid in reducing environmental impacts seem to be characteristics that the mineral sector needs to have social, political and economic support for important advances. This work goal contributes to paving the way for a more sustainable industry and to optimize the recovering and use of minerals and metals.

The European Union's Restriction of Hazardous Substances (RoHS) Directive was the first initiative to restrict the use of specific substances in electrical and electronic equipment, i.e. lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium (Cr^{6+}) and flame retardants. This established the parameters to guide the definition of toxic substances in e-waste.

The sustainable management of e-waste calls for the technologies of treatment of this waste to be based on innovation and sustainable practices. It is necessary to search for optimized and low-cost solutions for handling, extraction and recovery of metals of interest, both from the environmental liability that is already established, and new e-waste that will be generated in the coming years (Hunt et al., 2013).

E-waste basically consists of polymers, metals and ceramics, but the complexity of separating these types of materials requires the use of a differentiated set of unitary operations. Experts agree that investment in the development of state-of-the-art technologies for the manufacture of electrical and electronic equipment should equal investment for the proper management of waste and the complete recovery of mineral goods (Hunt et al., 2013; Khaliq et al., 2014).

Each possibility analyzed can reduce demand for primary raw materials, since they result in substitution of the entire product, its components or materials. They encourage the reduction of new material exploitation and support the urban mining, reducing energy consumption, lowering emissions and reinforcing sustainability standards. Recycling is the last step in the chain as a product reaches the end of its life. Recycling involves more cost and technical complexity to reintroduce the material in a service or production loop. The ideal procedure is to design for reuse and repair. Implementing the CE principles involves integrating some steps to reach the stage where all industries design with the CE model in their initial project conception.

The extent to which raw mineral extraction can be reduced is still to be evaluated, and the tools for applying the model in the mining industry need to be improved.

Among the materials that make up e-waste, the metallic resources are those that add more value and receive more attention in the recycling process. The metals in the electronic waste can be found in their native metallic form or in alloys embedded in non-metallic parts. The metals present in e-waste are commonly divided into precious metals, base metals and toxic metals (Ogushi et al., 2013). According to Işıldara et al. (in press), base, precious and REE are collectively termed as technology metals. This classification summarizes the technological potential inherent to the respective materials, as well as their economic potential.

Some metals have been characterized as critical, when their supply is much lower than increasing demand, including their rare geological occurrence. These minerals can be also considered strategic, as they do not have substitutes and often have been used for specific applications such as military equipment and hi-tech products (Bakas et al., 2014, 2016). The mineral raw materials commonly found in e-waste are illustrated in Fig. 2.

Precious metals and strategic minerals may account for about 80% of the intrinsic value of the equipment, but they do not amount to 1% of the total equipment weight. Despite their low recovery levels from e-waste recycling, there are some metals and minerals which are essential for the development of hi-tech products. Recycling of these strategic elements could contribute to reducing dependency on a permanent supply of essential resources, boosting recycling companies, minimizing environmental contamination and solving e-waste management (HYDROE-WASTE, 2014).

For example, antimony is currently produced from stibnite ore (Sb_2S_3) which is processed into antimony metal and antimony oxide (Sb_2O_3) and is applied as a flame retardant in plastics, coatings and electronics. This metal also has important applications in lead-acid batteries, as a catalyst for the production of PET plastic and in fluorescent lamps containing halophosphates. However, it is estimated that in about 10 years, or by 2050, antimony reserves will be scarce in the world. It will be the first mineral to have its production totally dependent on secondary sources, mainly from e-waste as batteries and passive fluorescent lamps containing halophosphates (Dupont and Binnemans, 2016).

Another group of strategic minerals which has attracted attention to recovery through the recycling of e-waste are the rare earth elements, 17 elements consisting of the 15 lanthanides plus scandium and yttrium. Rare earth elements are also considered strategic minerals due an increasing demand for new technology-based and innovative products that could lead to a scarcity of these resources in future and a dependency on a very few supply countries (Binnemans et al., 2013).

4.3. Urban biomining: innovations in e-waste recycling

Limitations on recovering precious and strategic minerals from e-waste are related to conventional approaches, such as pyrometallurgical and hydrometallurgical techniques, which are rapid and efficient, but cause secondary pollution and are often economically unviable (Prya and Hait, 2017). Biohydrometallurgical processes are one of the most promising technologies in metallurgy due the possibility of treating low-grade resources, easier control of waste, and lower energy consumption (Chauhan and Upadhyay, 2015).

Microbes have great potential for e-waste recycling, and integrated biohydrometallurgical processes have been developed for metal recovery mainly form waste printed circular boards (WPCBs) (Luda, 2011), phosphor lamps and cracking catalysts (Reed et al., 2016), waste liquid crystal display (WLCDs) (Higashi et al., 2011), computer gold finger motherboards (Madrigal-Arias et al., 2015), waste electric cables (Lambert et al., 2015). Urban biomining comprises mainly three unit operations based on the use of microorganisms as illustrated in Fig. 3.

The interactions between microbes, their metabolites and e-waste could promote selective or non-selective recovery of precious metals and other strategic elements such as rare earths. This characteristic is inherent in biohydrometallurgy and favors the use of a combination of different unit operations to dissolve, extract and recover the separation of valuable elements (Machado et al., 2011; Park et al., 2015). Urban biomining can achieve closed-loop recycling of the waste with significant efficiency.

Bioleaching has been successfully applied to recover precious metals and copper from ores, and recently from e-waste. In this bioprocess, some bacteria are able to withstand extreme conditions of pH, contributing to metal extraction by oxidizing e-waste with ferric ions generated from ferrous ion oxidation. With this process, in about 5 days, copper can be totally biosolubilized from waste PCBs (Xiang et al., 2010).

In minerals containing gold, these bacteria can catalyze oxidation of

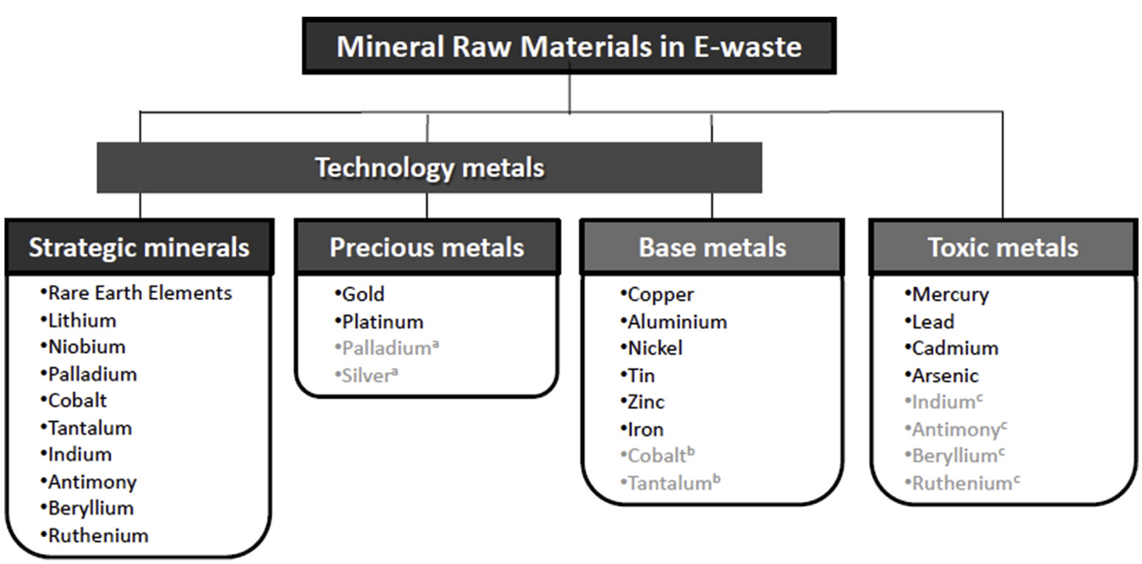

Fig. 2. Classification of mineral raw materials present in e-waste: [a]Precious metals, [b]Base metals and [c]Toxic metals.

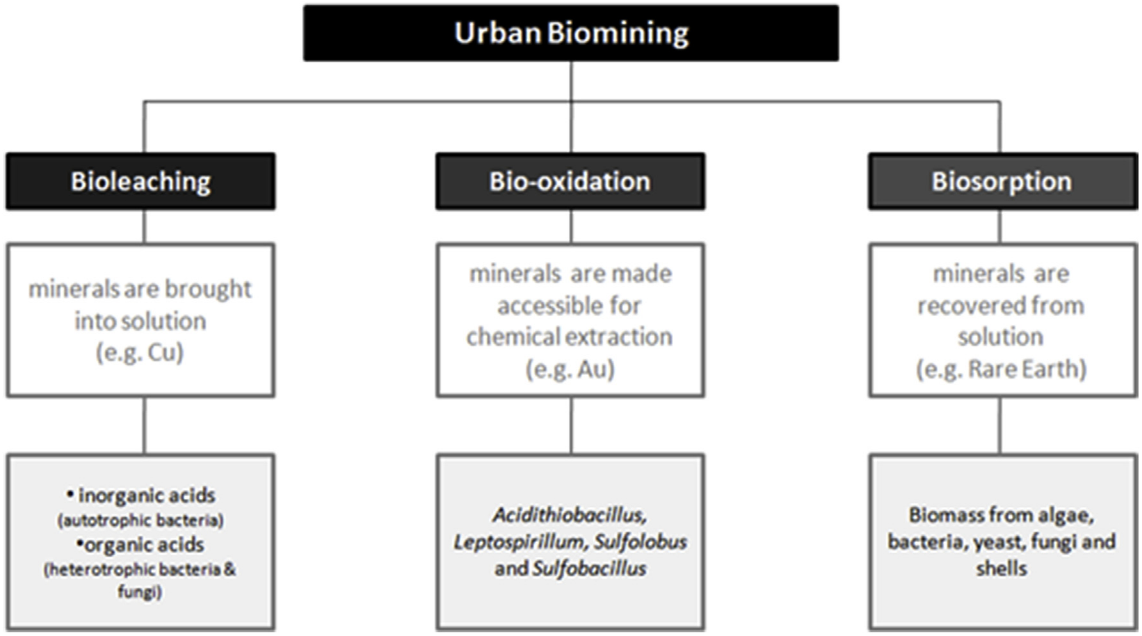

Fig. 3. Biohydrometallurgical processes used in urban biomining.

sulfide matrices making gold accessible for dissolution during cyanidation. This process is called bio-oxidation and is commonly used as a pre-treatment step. In a specific case of an e-waste containing gold and copper, bio-oxidation can result in the removal of in excess of 80% of the copper, increasing the gold/copper ratio in the residual solid and improving gold recovery by a posterior bioleaching (Pham and Ting, 2009).

Biosorption involves the ability of biosorbents to bind metal ions present in the external environment at the cell surface or to transport them into the cell for various intracellular functions depending on the specific properties of the biomass (alive, or dead, or as a derived product). The passive physicochemical interaction occurs between the charged surface groups of microorganisms and ions in solution and often the biosorption process is integrated with the processes of acid leaching or pyrometallurgy to recover and concentrate precious metals and strategic minerals (Luda, 2011).

Scientific efforts are made to develop hydrometallurgical techniques for the recovery of metal components from e-waste, especially by selective leaching (Silvas et al., 2015), selective precipitation (Provazi et al., 2011) and liquid-liquid extraction (Provazi et al., 2012). However, as the particularity of these approaches may be not environmentally friendly, some research groups have developed biohydrometallurgical strategies for recycling metal values from e-waste (Yamane et al., 2011, 2013). The development urban biomining techniques will be important to assist in the construction of an economic model of recovery of non-renewable values from secondary recycled resources, contributing to the insertion of CE concepts into e-waste management.

5. Discussion and conclusion

The urban mining of technological waste is an item on the political agenda of many countries. Since the Basel Convention proposed the prevention of waste import/export movements, many other initiatives were implemented in technical, economic and environmental approaches. Regulations that focus on the CE cover different dimensions according to the respective priority of each country. Sustainability in e-waste management can be achieved by promoting the 3Rs principle, while the closed-loop supply chain can contribute to CE efficiency. Carrying capacity can be regarded as the basis of the chronological analysis presented, from which derive important concepts such as industrial ecology, industrial metabolism and sustainability.

This paper proposes a theoretical approach to sustainability and the CE in e-waste management. From a robust literature review, the key-concepts are analyzed, and a chronological framework of sustainability and the circular economy is proposed. Recovery, reuse, classification and recirculation of e-waste material are important aspects of sustainability and the CE and can be supported by biotechnology. The main techniques available to material recovering are presented in order to provide a connection between managerial and technical requirements. The importance of international e-waste management and trading in different countries and the critical raw materials procedures were presented as basis for discussion regarding sustainability on CE framework. Thus, we propose the technological routes to recovering secondary raw material as one of the most important solutions to achieve the sustainability of e-waste urban mining.

The theoretical approach allowed an analysis of privileged strategic conditions in different countries due to both ownership of critical or strategic raw material reserves, the volume of e-waste generated annually and the consolidation of regulatory instruments on urban mining of e-waste. Urban mining can be seen as a multifaceted solution to social (through employment generation), environmental (to mitigate the environmental impact of e-waste and even traditional mining) and economic issues (making financial gains through innovation).

The classification of secondary raw materials from e-waste urban mining into strategic minerals, precious metals, base metals and toxic metals seems to meet an international demand for reverse logistics solutions, which means CE business models and a strategy for e-waste management. In future research, economic and social criteria should be considered in order to provide another analysis of sustainability and the CE of e-waste management.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://

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