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Multicriteria optimization of copper scrap management strategy

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ABSTRACT

A model of copper scrap management at country level is proposed, taking all copper scrap collection streams into account, with their associated environmental impacts and costs. The method is applied to the treatment of printed wiring boards (PWB) in France. Considering the initial physical properties and composition of this scrap, seven flowsheets are constructed for the production of refined copper. Then, depending on the number of PWB treated in each processing chain, the production rate, energy consumption, operating cost and environmental impacts are evaluated. Three bi-objective optimizations are conducted based on the NSGA II multi-objective genetic algorithm: production versus energy consumption, production versus operating cost and production versus environmental impacts. Pareto fronts are obtained for each optimization, giving the set of non-dominated solutions. Then the decision support tool TOPSIS is used to find the best compromise solution for waste management.

1. Introduction

In many “developed” countries, and notably in France, much of the copper contained in waste is either exported or lost (Bonnin et al., 2013) even though a large proportion of the copper in question is not degraded during its use and could, therefore, be recycled. It is estimated that 85% of the copper in circulation is recoverable and that its average utilization time is 30 years (ranging from a few years in electronics applications to over 100 years in the construction industry) (SCF, 2012). Recycled copper is either refined or reused directly (in the case of electric cables, certain alloys, and new manufacturing scrap). The problem of copper recycling is an important issue as copper ranks third by mass in the metals used in the world, after iron and aluminium (Muchova et al., 2011), and has a wide range of applications. Moreover, pure copper is 100% recyclable, indefinitely, without any alteration or property loss.

In 2008, for a worldwide annual consumption of 24 Mt of refined copper, 6 Mt came from copper recycled by simple melting and 2.7 Mt from copper waste that had been refined. In other words, the total percentage of recycled copper in worldwide consumption was 36.2%. The proportion of recycled copper was 41.4% in Europe, 33.5% in Asia and 29.5% in North America.

France is absent from much of the copper cycle, particularly in metallurgy and refining, unlike Germany and Belgium for example. In contrast, it has an important industry for the first transformation of refined copper. In 2008, the production of semi-finished products was 387,000 t (−9.6% relative to 2007), half of which was in the form of wires and cables, made using imported cathodes or recycled copper (SCF, 2012).

From a technological point of view, many different processes have been developed for recycling metals with fairly efficient technologies. According to the Bureau of International Recycling (BIR, 2013), copper recycling reduces energy expenditure by 85% and reduces greenhouse gas emissions by 65% in comparison with primary copper production. Various works are in progress to improve recycling efficiency in specific processing systems, notably concerning WEEE (Johansson and Luttropp, 2009; Yamane et al., 2011; Zhang and Forssberg, 1998), the category of waste that contains the largest fraction of copper scrap.

However, according to Ayres et al. (2002), a peak in copper production is likely to be reached before the end of the 2020s, whereas demand should continue to grow for several more decades. Thus, according to Graedel et al. (1499), depletion should occur no later than the 2050s and, according to Jamet et al. (2009), the world's copper reserves will be exhausted by 2030. More recently, Sverdrup et al. (2014) developed a model at the whole world scale showing that the peak production should arrive between 2031 and 2042. Furthermore, copper emissions give rise to serious concerns because of its known bioactivity.

To study the possibility of setting up a strategy for large-scale recycling in France, it is first necessary to assess the performance of recycling processes in terms of cost and impact on the environment. A literature review shows that many different processes have been developed for metal recycling with quite efficient technologies.

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A	anode (furnace)
DTB	direct-to-blister (flash smelter)
EC	energy cost
Elec	electric (furnace)
EI	environmental impact
ELV	end-of-life vehicles
ER	electrolytic refinery
GWP	global warming potential
LGS	low grade scrap
LSXEW	Leach-Solvent eXtraction-ElectroWin
MILP	mixed-integer linear programming
NOR	Noranda (furnace)
OUT	Outukumpu (flash smelter)
PS	Pierce Smith (converter)
PWB	printed wiring board
SKS	Shuikoushan (bath furnace)
SS	sewage sludge
TEN	Teniente (furnace)
TOPSIS	technique for order preference by similarity to ideal solution
WEEE	waste from electrical and electronic equipment

According to the Bureau of International Recycling (BIR, 2013), recycling of copper allows 85% energy saving and a reduction of 65% of greenhouse gas emissions compared to primary copper production. Different works are being conducted to improve the recycling efficiency of specific processing chains, especially concerning the recycling of WEEE (Johansson and Luttropp, 2009; Yamane et al., 2011; Zhang and Forssberg, 1998; Das et al., 2009; Ruhrberg, 2006), which is the waste category that contains most copper scrap.

However, an efficient recycling system not only involves efficient processes but also requires an optimized management loop. For instance, Giurco and Petrie (2007) showed that innovative technologies will play a limited role in reducing the carbon footprint of copper and that the whole cycle has to be studied if the environmental impacts of the metal are to be reduced. Meanwhile, Agrawal and Sahu (2010) propose an interesting study concerning copper primary production and recycling in India, with an overview of the available processes and their characteristics, but also of the waste collect and deposit management.

Moreover, Ahluwalia and Nema (2007) present a model which aims to give the best possible configuration of computer waste management facilities to minimize cost, perceived risk and environmental impact, or a compromise between these three objectives, in a life cycle perspective. In a slightly more comprehensive approach, Minoglou and Komilis (2013) worked on the optimization of the treatment and disposal of municipal solid wastes: they used a non-linear mathematical programming to minimize both the costs and the equivalent carbon dioxide emissions.

From the reported works, it can be highlighted that the studies are related to different scales and focus on a specific kind of copper scrap or in contrast consider larger waste categories, the need of a comprehensive model for copper management optimization is clearly apparent. This work aims at developing a generic methodology combining these two considerations – choice of the recycling process and optimization of waste management strategy using mathematical programming – to help government or other decision makers to make decision concerning copper-containing waste treatment at national or other large area scale. Thus, the model developed here intends to help determining the best compromise solution between minimization of costs, environmental impacts, energy consumption and resource losses. More precisely, the questions that are addressed for any specific kind of copper scrap can be formulated as follows:

- is it better to eliminate or recycle a specific scrap?
- which is the best elimination strategy?
- which are the best recycling processes?
- how much copper, and of which purity, has to be imported/exported?

To address these issues, a framework combining a multicriteria optimization method with an aid decision making technique is proposed. The methodology is described in part 2, along with the definition of the system. It is then applied in Section 3 to a simplified example, i.e., the treatment of printed wiring boards.

2. Methodology

The production of refined copper, from ore as well as from scrap, is performed with a series of steps that concentrate gradually the raw material to reach the desired purity. Each step can be performed through different processes, the complete series of processes forming the refined copper production flowsheet. The underlying objective is to find the best treatment for a specific kind of scrap, i.e., the best recycling flowsheet. The proposed methodology is divided into two steps: the former involves the design of all possible flowsheets for the transformation of scrap into refined copper; the latter is devoted to the selection of the best management option via multi-objective optimization. This study focuses on the implementation of these two steps.

2.1. Flowsheet construction

2.1.1. Overview of copper recycling processes

Conventional pyrometallurgical copper production process includes seven steps: mining, preprocessing, smelting, converting, fire refining, electro-refining and smelting for form casting. The recycling of copper scrap follows approximately the same process but, depending on the concentration of copper in the scrap, it is not necessary to pass through all the unit processes (Fig. 1). Nowadays, about 80% of primary copper and almost all recycled copper is processed according to this method (SCF, 2012). However a hydrometallurgical method also exists, called solvent extraction and electrowinning (SX-EW) technology, which is mainly used for oxide ores but is starting to be studied for copper recycling (Oishi et al., 2008).

Copper scrap can be divided into four categories: No.1 scrap, containing more than 99% copper; No.2 scrap, containing between 88% and 99% copper; low grade scrap (LGS) containing between 10% and 88% copper; and alloy scrap (Giurco et al., 2001). If they are well sorted, No.1 scrap and alloys can be melted and transformed into a finished product without any other processing. No.2 scrap has to be refined, and low grade scrap has to be smelted, converted and refined before being transformed into finished products. The remaining copper scrap, i.e. scrap containing less than 10% copper, is generally discarded but, in the model developed here, it will be possible to choose between discarding and processing.

For each step, different processes are used in the primary copper transformation industry. Most of these processes can also be used for the secondary transformation industry but operating conditions are slightly different. Unlike copper scraps, copper ore contains sulfides that generate heat when oxidized, thus allowing energy to be saved in the processes (traditional copper concentrate from ore is mainly composed of $CuFeS_2$, FeS and FeS_2). The best example of this is the Teniente process, which is known as an autogenous smelting