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Development of a Sustainable Copper Scrap Management Model

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Abstract

A copper scrap management model at a country level is proposed, taking into account every collected copper scrap stream, with its associated environmental impact and cost. The method is applied on the treatment of printed wiring boards (PWB) in France. Considering the initial physical properties and composition of this scrap, seven flowsheets are constructed to produce refined copper. Then, depending on the ratio of PWB treated in each processing chain, the production rate, energy consumption, operating cost and environmental impact are evaluated. Three bi-objective optimizations are conducted based on a multi-objective genetic algorithm of NSGA II version: production versus energy consumption, production versus operating cost and production versus environmental impact. Pareto fronts are obtained for each optimization that gives the set of non-dominated solutions.

Keywords: Recycling, Resource Management, Copper, Waste, Multi-objective Optimization.

1. Introduction

The purpose of this investigation is to propose a copper scrap management model in order to analyze information on market trends and policy drivers affecting the copper supply chain, within the context of sustainable development. Indeed, copper, which is the third metal used in the world after iron and aluminum (Muchova et al., 2011), covers a wide range of applications and is 100% recyclable indefinitely, without any alteration or property loss. Moreover, according to Ayres et al. (2002), copper production peak should be achieved within two decades, while demand should continue to grow for several decades. Furthermore, emissions of copper lead to important concerns because of its known bioactivity.

In order to identify more deeply sustainability concerns and foster mutually beneficial relationships throughout the copper supply chain, it is important to improve copper recycling. In this study, the case of France serves as an illustration: France does not mine any copper ore but is a large copper consumer and thus a large refined copper importer. However, in a previous study (Bonnin et al., 2012), the material flow analysis of French copper cycle was presented and showed that only about 25% of secondary copper is used for the production of copper products in France against 40% in the rest of the world. Only 3.5% of collected copper is recycled in France, the rest being exported (Gie et al., 2010). From a technical point of view, many different processes have been developed for metal recycling with quite efficient technologies. However, an efficient

recycling system does not only involve efficient processes, but also requires an optimized management loop. This study lies in this perspective and takes into account copper scrap collection and different recycling processes together with the possibility of importing or exporting scrap.

2. Methodology

The methodology proposed here is divided into three steps: the first step aims at identifying the scrap deposit and the refined copper needs: this has been the core of another study (Bonnin et al., 2012). The second step is the construction of the flowsheets that can transform scrap into refined copper. The last section of the methodology is devoted to the selection of the best methodology via multi-objective optimization.

2.1. Flowsheet construction

2.1.1. Overview on copper recycling processes

The classical copper production process is constituted of six steps: mining, smelting, converting, fire refining, electro-refining and smelting for form casting (Figure 1). The recycling of copper scrap follows approximately the same processing, but depending on their concentration, it is not necessary to pass through all the processes.

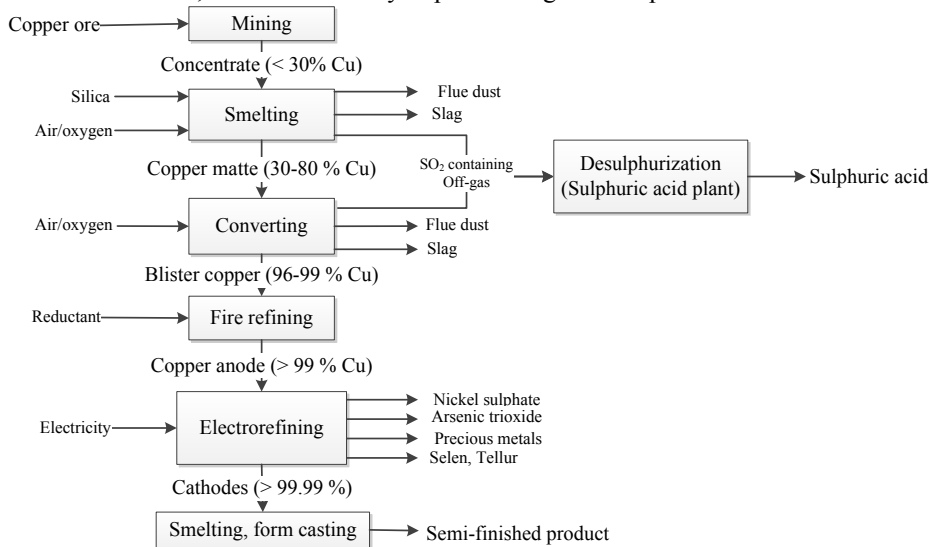


Figure 1: Primary copper production route

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 containing between 10 and 80% copper and alloy scrap. If they are well sorted, No.1 scrap and alloys can be melted and transformed into 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 again into finished products.

For each step, different processes are used in the primary copper transformation industry. Most of these processes can also be used for the second transformation industry, but operating conditions are slightly different. Indeed, unlike copper scrap, copper ore contains sulfides that generate heat when oxidized, thus allowing energy savings in the processes.

2.1.2. Inventory analysis

To cover the panel of scrap treatment, an inventory of every existing copper scrap treatment process has to be performed. For all identified processes, the operating conditions, energy and raw materials consumption, efficiency (among other parameters) have to be estimated. For each registered process, data is presented as described in Table 1 for the example of the Noranda furnace, as it will be further used in the calculation method.

Table 1: Typical process characteristics: the case of the Noranda furnace (Suljada, 2001 and US congress, 1998)

Process: Noranda furnace					
Compositional properties (%)					
Components	T _{c_min}	T _{c_max}	SF _{product}	SF _{waste1}	SF _{waste2}
Copper	0.2	0.35	0.940	0.125	0.200
Iron	0	0.45	0.060	0.750	0.300
Zinc	0	1	0.000	0.125	0.500
Lead	0	1	0.190	0.200	0.200
Tin	0	1	0.810	0.300	0.700
Balance	0	1	0.000	0.500	0.100
Physical properties					
Characteristics	T _{p_min}	T _{p_max}	T _{p_out}		
Size (m)	0	0.05	0		
Moisture (%)	0	0.14	0		
Energy and material consumption (kWh/t_{Cu})					
Electricity	369				
Fuel	1 562				
Water	0				
Oxygen	929				
Silica	190				
T _{c_min} , T _{c_max}	Minimal and maximal input stream composition acceptance				
SF _{product} , SF _{waste1} , SF _{waste2}	Split Factor: percentage of component that goes into the main output stream (product), the solid and liquid waste stream (waste 1) and the gaseous waste stream (waste 2)				
T _{p_min} , T _{p_max}	Minimal and maximal input physical acceptance				
T _{p_out}	Output physical characteristics				

A wide variety of processes (10) is proposed for smelting to produce copper matte from concentrate. Five processes for conversion and for fire and electro-refining have also been identified.

2.1.3. Flowsheet construction methodology

The identified processes are then used to construct acceptable flowsheets to produce copper cathodes (99.99%_{Cu}). The design of the flowsheet is based on a vector method proposed by Suljada (2001): the scrap flowrate, composition and physical properties are given and a series of operations is performed to obtain the flowsheets:

1. The scrap composition is compared with No.1 scrap and with every common alloy compositions: if it is a No.1 scrap or an alloy, no flowsheet is needed, the scrap only has to be melted for form casting;
2. If the scrap is neither No.1 or alloy, its characteristics are compared with all the processes characteristics (T_{c_min}, T_{c_max}, T_{p_min} and T_{p_max});
3. The scrap is transformed by every process that accepts it as an intermediate product: the Split Factors are used to determine each product and waste streams composition, flowrate and characteristics;
4. When one intermediate product reaches copper cathode purity, its flowsheet is finalized. Each other intermediate product is tested: if its composition is such that it

cannot be treated by any process, it is stored in a so-called “unprocessable product” matrix; otherwise it is processed again by every process that “accepts” it: steps 1 to 3 are used again until every intermediate product is transformed into cathodes.

As a result, a set of flowsheets is obtained giving the flowrate and composition of the final products and of the solid, liquid and gaseous wastes.

2.2. Multi-objective optimization

Once the processing schemes are designed, their associated energy consumption (EC), energy cost and environmental impacts (EI) are calculated. The environmental impacts are evaluated using a Life Cycle Assessment methodology. Moreover, cost and EI are allocated to the importation and exportation of both scrap and refined copper. Taking into account scrap deposit as input and copper demand (estimated via utilization) as a constraint to be satisfied, a superstructure is proposed that encompasses all the possible scrap management options as illustrated in Figure 2.

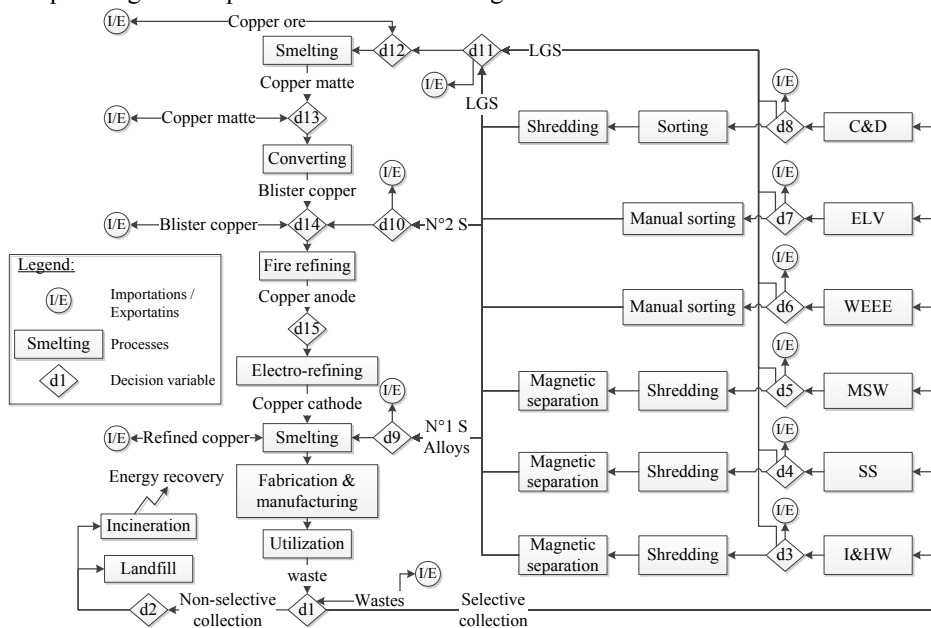


Figure 2: Superstructure of the copper scrap treatment pathways

First, refined products are produced with refined copper (that can be either imported, or produced directly from ore or scrap). Then, these products come to their end of life and are collected either selectively or not (d1). If they are not collected selectively, they can be either landfilled or incinerated (d2); if they are collected selectively, six independent streams containing copper are obtained: construction and demolition waste (C&D), end-of-life vehicles (ELV), waste from electrical and electronic equipment (WEEE), municipal solid waste (MSW), industrial and hazardous waste (I&HW) and sewage sludge (SS). These streams can be either processed as a whole, be reordered to separate alloy, No.1, No.2 and low grade scrap or be exported (d3 to d8). The exportation can concern a fraction or a whole of the average stream, or a specific fraction, for instance the fraction with the lowest copper concentration (d9 to d11). Afterwards, each obtained stream is processed separately but according to the same methodology: possible flowsheets are constructed (d12 to d15), their EC, operating cost and EI are calculated and multi-objective optimization is performed via a genetic algorithm (Gomez et al.,

2010) to obtain the set of best flowsheets. The objective functions that have been considered involve the minimization of cost, environmental impacts and energy consumption as well as the maximization of the refined copper production, while the decision variables are the copper ratios allocated to each pathway every time that a possible choice occurs (represented by the variable di in Figure 2).

3. Application on Printed Wiring Boards management

The methodology has been applied on an example derived from the work presented in Suljada (2001), i.e., the case of printed wiring boards (PWB) recycling in France.

3.1. Data collection

To illustrate the two steps of the method that are described in this study (flowsheets construction and multi-objective optimization), some simplifying assumptions have been made: it was considered that the scrap has been sorted and that PWB have been isolated for specific processing. Moreover, it was decided that the integrality of scrap is treated, without any import or export. Scrap characteristics are given in Table 2.

Table 2: PWB scrap characteristics (Suljada, 2001)

PWB	Cu	Fe	Zn	Pb	Sn	Balance	Flowrate	Size	Moisture
	22%	3.6%	0%	1.55%	2.6%	70.25%	50 t/day	0.1mm	0%

Under these assumptions, the first step of flowsheet design involves ten technologies: Pierce Smith converter (P), anode furnace (A), Outokumpu flash smelter (O), direct-to-blister flash smelter (D), electric furnace (E), SKS bath furnace (S), Teniente furnace (T), Noranda furnace (N), leach-solvent extraction-electrowin (L), electrolytic refinery (ER). The characteristics of each technology were taken from Suljada (2001), Giurco (2005) and a US Congress report (1998).

3.2. Flowsheet construction

A Matlab® program based on Suljada (2001) methodology has been implemented that determines all the possible combinations of processes that can transform a specified copper scrap into refined copper, considering the aforementioned technical acceptability of each process. For PWB scrap, seven flowsheets have been obtained (see Table 3) giving seven products associated with liquid, solid and gaseous waste streams, as well as thirteen flowsheets that give “unprocessable” products with a copper concentration ranging between 99.73 and 99.89%.

Table 3: Flowsheets obtained with the used technologies and flowrate of refined copper (t/day)

Flowsheet	Technologies	Flowrate	Flowsheet	Technologies	Flowrate
1	L	7.15	5	E*5+A	9.36
2	E+P+A	10.15	6	T+E*4+A	8.33
3	T+P+A+ER	8.93	7	N+E*3+A+ER	9.25
4	N+D+E+A	7.16			

3.3. Multi-objective optimization

For each of the seven products, EC, operating cost and EI have been determined. Energy consumption has been calculated considering, as it is generally assumed, that a part of the consumption is fixed (arbitrarily set at 20%), while the rest depends on the amount processed; the operating cost is calculated according to French market prices for electricity, fuel, etc. taking into account subscribed power and subscription cost; the environmental impacts are determined with SimaPro® software (mid-point method CML) taking into account only the energy and materials consumption, the emissions to

the environment (gaseous waste stream) and the solid and liquid waste treatment (landfilled); only global warming potential impact has been retained for this example. Then, three bi-objective optimizations have been carried out, each one targeting to minimize one of the three criteria described above while maximizing the quantity of refined copper obtained, the variables being the scrap ratio that goes into each flowsheet. The three corresponding Pareto fronts are represented in Figure 3.

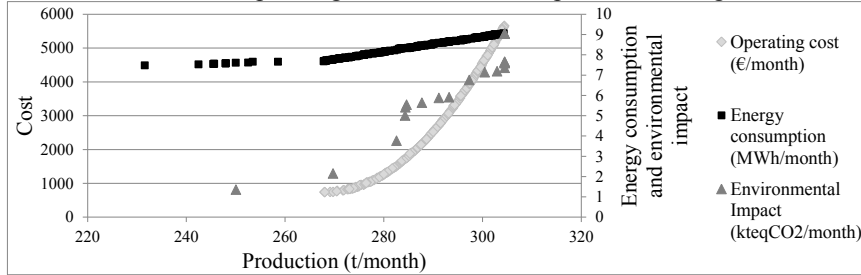


Figure 3: Results of the three bi-objective optimizations: Pareto fronts

Figure 3 shows that the best compromises seem to be obtained for a production between 260 and 300 t/month of refined copper. Looking at the decision variables, the flowsheets that seem the most interesting are No. 2, 5 and 7 regarding the GWP, No. 1, 2 and 3 regarding the EC and No. 2, 3, 5 and 7 regarding the operating cost.

4. Conclusion and Perspectives

A global framework of end-of-life product management has been proposed and implemented on the example of PWB scrap recycling. This application shows the interest to consider waste management at a large area scale. The main perspective is now to apply the model on a more realistic and also more complex issue that is related to the choice of technologies that could be used to optimize waste management in France, taking into account multiple streams. Moreover, the typical results generated by the multi-objective genetic algorithm are a set of non-dominated solutions: a next step could be to choose the best solution by use of a multiple criteria decision aid method. A further investigation would be to challenge the systematic production of such high grade refined copper, since a so high level of purity is not required for all the applications. The consideration of processes leading to degraded properties will extend the search space for optimization.

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