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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

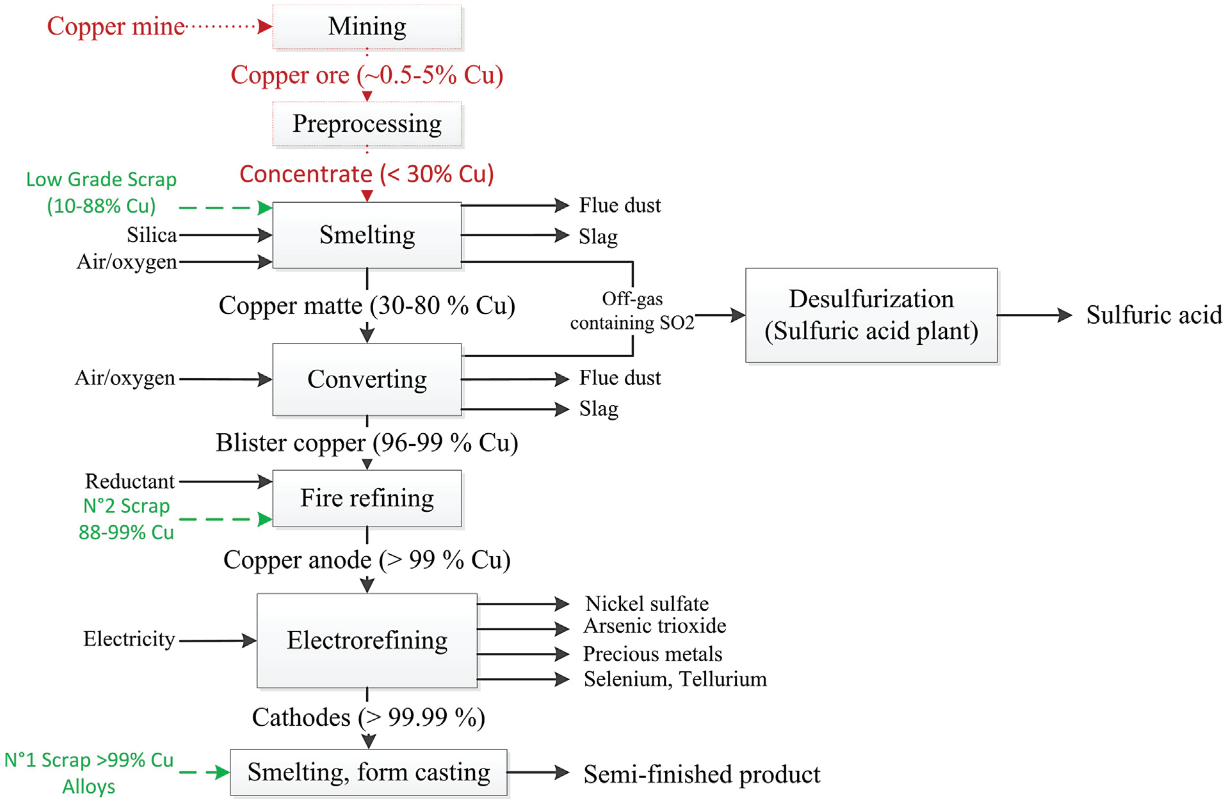


Fig. 1. Pyrometallurgical copper production route. In red with dotted lines: steps that are specific to primary processing, and in green with dashed lines: steps linked to copper recycling. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

process because no external heat is supplied: exothermic oxidation reactions supply enough heat for the endothermic decomposition of the copper concentrate. However, copper in low grade scraps is often mixed with impurities such as Fe, Zn, Pb, Sn, Ni, As, Sb and some precious metals (Au, etc.).

The flowsheet construction step is intended to review every existing combination of unit processes, i.e. every flowsheet that can be used to transform one specific type of scrap into refined copper, together with the associated impacts (cost, environmental impacts, energy consumption, copper losses, etc.). Thus, to construct the flowsheets, it is necessary to know not only the process characteristics together with the possible composition concerned and the physical range of acceptance, but also the energy and material consumption. This information is retrieved through an inventory analysis, described in Section 2.1.2.

2.1.2. *Inventory analysis*

As previously mentioned, to cover the current range of scrap treatment, an inventory of all existing copper scrap treatment processes had to be drawn up. For each process identified, the operating conditions, energy and raw material consumption, and efficiency (among other parameters) had to be estimated. A literature review revealed a great variety of unit processes, especially for the smelting and converting steps, but only a few of them are widely used around the world: about ten unit processes were identified for the smelting step (which produces copper matte from concentrate), and five processes for conversion and for fire- and electro-refining. However, by considering the data available and taking account of Suljada (2001) findings, ten technologies were selected for this work: one hydrometallurgical process (Leach-Solvent Extraction-Electrowin (1 = LSXEW)) and nine pyrometallurgical processes, described below:

- For the smelting step
  - Flash smelters
    - * Outukumpu flash smelter (2 = OUT)
    - * Direct-To-Blister flash smelter (3 = DTB)
  - Furnace
    - * Electric furnace (4 = ELEC)
  - Bath smelting
    - * Noranda furnace (5 = NOR)
    - * Teniente furnace (6 = TEN)
    - * SKS bath furnace (7 = SKS)
- For the converting step
  - Pierce Smith converter (8 = PS)
- For the fire-refining step
  - Anode furnace (9 = ANODE)
- For the electro-refining step
  - Electrolytic Refinery (10 = ER)

The characteristics of each technology were taken from Suljada (2001), Giurco (2005) and a U.S. Congress (1988) report.

For each registered process, data are presented as shown in Table 1 for the example of the Noranda furnace, in the form most convenient for use in the calculation method (data used for the other processes are available in Appendix A): Tc_{min} and Tc_{max} give the minimum and maximum fractions of each component that can be accepted by the process; the Split Factor (*SF*) matrix gives the fraction of each component that goes into the manufactured product (SF_{product}), the solid and liquid waste stream (SF_{waste1}) and the gaseous waste stream (SF_{waste2}); and Tp_{min}, Tp_{max} and Tp_{out} give the minimal and maximal physical properties that the process can accept in the input stream and indicate the output stream physical properties. Data concerning energy and material consumption are all given in kWh/t_{Cu} and thus can be aggregated into one criterion for optimization purposes.

Table 1
Typical process characteristics: the case of the Noranda furnace (Suljada, 2001; U.S. Congress, 1988).

Process	Noranda furnace				
Compositional properties (%)					
Components	$Tc_{\min}$	$Tc_{\max}$	SF_{product}	SF_{waste1}	SF_{waste2}
Copper	0.2	0.35	0.94	0.06	0
Iron	0	0.45	0.19	0.81	0
Zinc	0	1	0.125	0.75	0.125
Lead	0	1	0.2	0.3	0.5
Tin	0	1	0.2	0.3	0.5
Balance	0	1	0.2	0.7	0.1
Physical properties					
Characteristics	$Tp_{\min}$	$Tp_{\max}$	Tp_{out}		
Size (m)	0	0.05	0		
Moisture (%)	0	0.14	0		
Energy and material consumption (kWh/t_{Cu})					
Electricity	369				
Fuel	1562				
Water	0				
Oxygen	929				
Silica	190				
$Tc_{\min}$, $Tc_{\max}$	Minimum and maximum fractions acceptable in input stream composition				
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)				
$Tp_{\min}$, $Tp_{\max}$	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

2.1.3. Flowsheet construction methodology

The processes identified were then used to construct acceptable flowsheets for the production of copper cathodes (99.99%Cu). The flowsheet construction was based on a vector method proposed by Suljada (2001), illustrated in Fig. 2. The scrap flowrate, composition (Sc_0) and physical properties (Sp_0) were given and the following operations were performed to obtain the flowsheets:

1. Compare the scrap composition with No.1 scrap and with the compositions of all common alloys (brass, bronze, etc.): if it is 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 nor an alloy, compare its characteristics with all the process characteristics ($Tc_{\min}$, $Tc_{\max}$, $Tp_{\min}$ and $Tp_{\max}$);
3. If compositional characteristics are not in the range $Tc_{\min} - Tc_{\max}$ of a process, the scrap cannot be processed by that method. If physical characteristics are not in the range $Tp_{\min} - Tp_{\max}$, prescribe scrap preprocessing to adapt its physical properties to the process in question;
4. Transform the scrap into an intermediate product (PI) by every process that accepts it: use the Split Factors to determine each output product and waste stream composition, flowrate and characteristics;
5. When one intermediate product reaches copper cathode purity, finalize its flowsheet. Test each other intermediate product: if its composition is such that it cannot be treated by any process, store it in an “unprocessable product” matrix (U_f); otherwise process it again by every process that accepts it: repeat steps 1–3 until every intermediate product has been transformed into copper cathodes (P_f) or classified as an unprocessable product.

The resulting set of flowsheets gives the flowrate and composition of the final products and of the solid, liquid and gaseous wastes, together with an “energy consumption” matrix showing, for each flowsheet, the various energy consumptions in kWh (for electricity, fuel, and also oxygen, silica, etc.) and the total flowrate needing physical transformation. The model can also provide a list of the unprocessable products and the flowsheet from which they were obtained. Note that, in this construction process, there is no obligation to follow the conventional copper scrap recycling process presented in Fig. 1. The only condition is to reach a purity of 99.9% of copper in the copper cathode. If this can be done using, for instance, only a chain of many smelting processes, it is accepted; there is no restriction.

This model was encoded with Matlab© in a function (shown schematically in Fig. 3) for which the required inputs were the initial scrap composition (percentage of copper, iron, zinc, lead, tin and remainder) and flowrate (M) $Sc_0 = [\%\text{Cu}; \%\text{Fe}; \%\text{Zn}; \%\text{Pb}; \%\text{Sn}; \%\text{B}; M]$, and its physical properties $Sp_0 = [\text{size}; \text{moisture}]$. Its output is five matrices: final products (P_f), unprocessable products (U_f), solid and liquid wastes (W_{1f}), gaseous wastes (W_{2f}) and total energy (NRJ_T). P_f, W_{1f}, W_{2f} and NRJ_T all have the same number of columns, which is equal to the number of flowsheets that gave copper cathode, while U_f shows the flowsheets leading to unprocessable products, together with the compositions and flowrates of these products. Unprocessable products are not considered in the rest of this study but it is interesting to have this information because most unprocessable products have a copper content between 0.99 and 0.999 and a comparison between the flowsheets leading to final products with the flowsheets leading to unprocessable products can show the impact of manufacturing cathodes with such high copper content. This could form the core of another study.

2.2. Optimization strategy

As previously mentioned, the objective of this study was to find the best flowsheet for a given waste. Thus, once all the possible flowsheets had been identified, it was necessary to formulate the problem, and then use an optimization algorithm to select the best option. Moreover, to compare the different flowsheets “impartially”, one, or a set of, impartial comparison criteria had to be chosen.

2.2.1. Problem formulation

The objective is to find the best copper waste management model, i.e. the best strategy for treating a fixed amount of a specific waste.

To reach this objective, it is necessary to construct the structure of the problem, encompassing all management options. This structure must include the decision variables. Then, the mathematical formulation of the problem has to be written.

Fig. 4 presents the structure of the problem treated here. Three major steps can be identified:

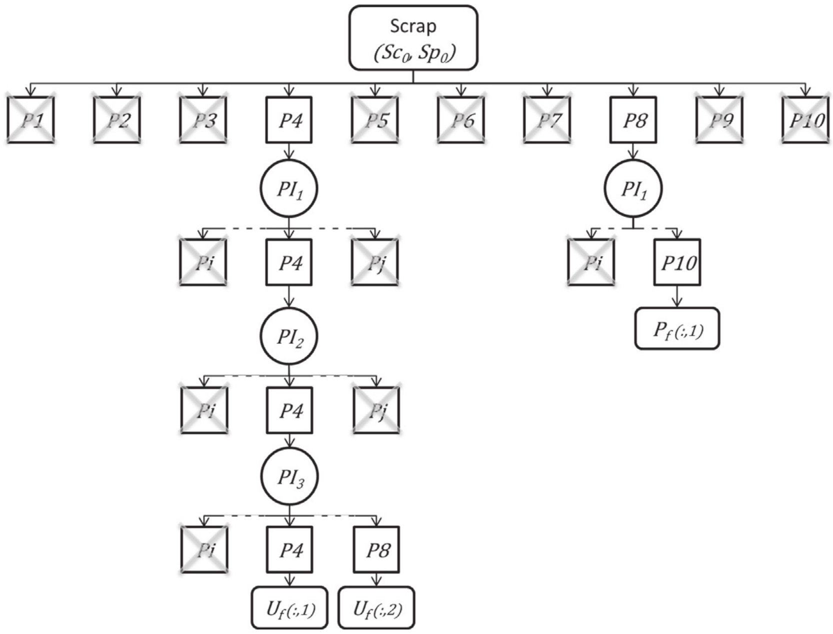


Fig. 2. Illustration of the flowsheet construction process (for readability purpose, the waste streams are not represented). In this illustration, the scrap is neither a high grade scrap nor a alloy; it can be processed by processes 4 and 8. The intermediate product obtained with process 8 has directly a sufficient purity to be considered as refined copper, while the one obtained with process 4 has to be processed again. Finally, after 3 other steps, only unprocessable products are obtained with this intermediate product, thus, in this illustration, only 1 flowsheet (with 1 process) can be used.

(1) The copper-containing waste flow (W) can either be discarded (W_d), sorted (W_s) or directly processed (W_p) (Eq. (1)): if it is sorted, it is divided among the five scrap categories (No.1, No.2, LGS, Alloy, Remainder – Eq. (2)) depending on the copper content (the quantity of each kind of scrap in the wastes has been determined in a previous study, Bonnin et al., 2013)

$$\begin{array}{ll} \text{if} & d1 = 1 \\ & W_p = W \\ \text{else if} & d1 = 2 \\ & W_s = W \\ \text{else if} & d1 = 3 \\ & W_d = W \end{array} \tag{1}$$

$$W_s = S_{\text{No.1}} + S_{\text{No.2}} + S_{\text{LGS}} + S_{\text{Alloy}} + S_{\text{Remainder}} \tag{2}$$

(2) The discarded waste flow is eliminated by either incineration (W_i) or landfill (W_l) (Eq. (3)) and each of the five scrap flows is either processed (e.g. $S_{No.1_p}$) or discarded (e.g. $S_{No.1_d}$) (the mathematical formulation is only given for No.1 scrap – Eq. (4), but is similar for the other scraps)

$$\begin{array}{ll} \text{if} & d2 = 0 \\ & W_i = W_d \\ \text{else if} & d2 = 1 \\ & W_l = W_d \end{array} \tag{3}$$

$$\begin{array}{ll} \text{if} & d7 = 0 \\ & S_{No.1_p} = S_{No.1} \\ \text{else if} & d7 = 1 \\ & S_{No.1_d} = S_{No.1} \end{array} \tag{4}$$

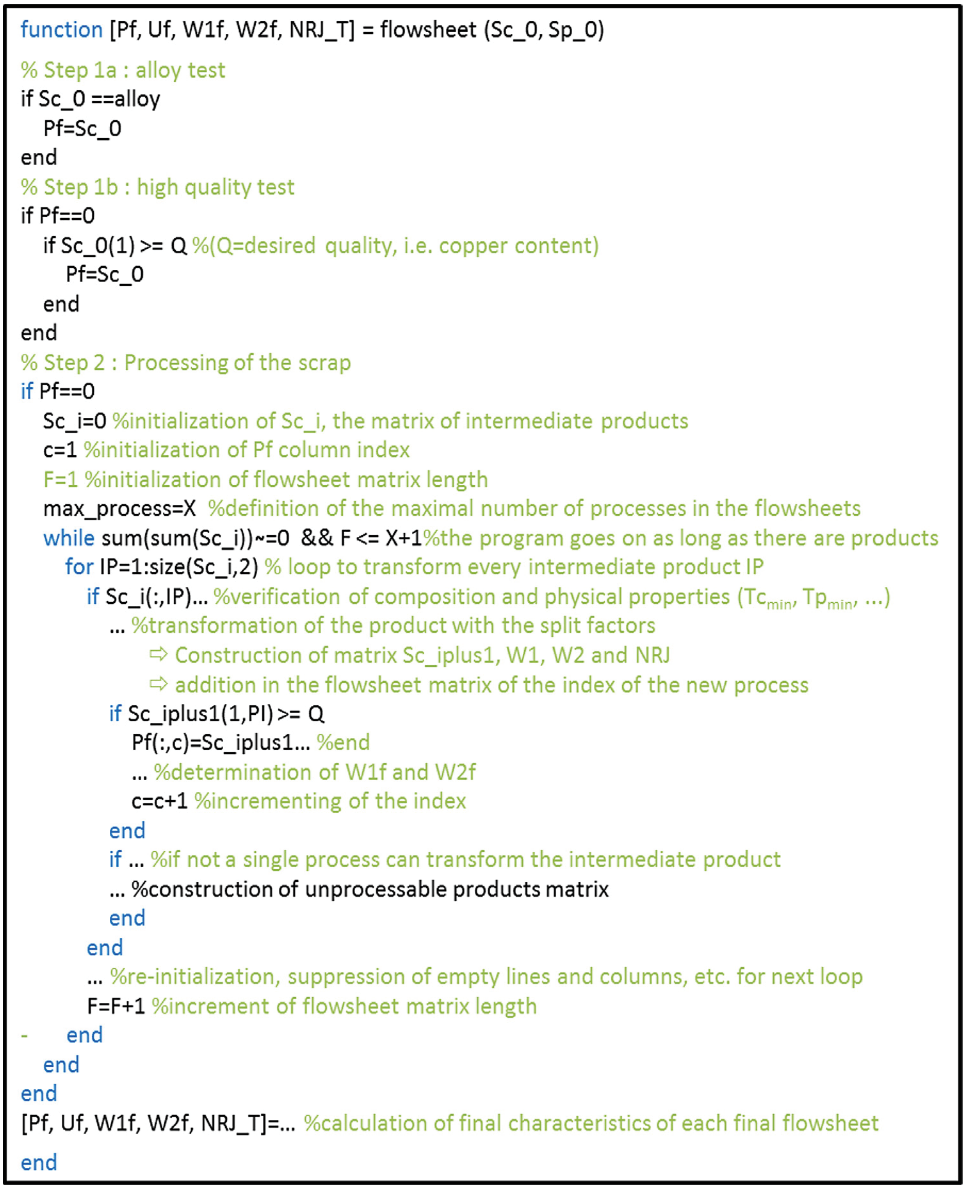
(3) The directly recycled waste flow and the recycled scrap flows are sent to the flowsheet construction step. If the waste is sorted, different configurations can be considered, for instance:

- the different types of scrap are treated with the same flowsheet but are injected at different steps depending on their copper content (solution presented in Fig. 4 and associated with the decision variables presented in Table 2)
  – the *flowsheet* function is integrated in the general code with some modifications: Sc_0 and Sp_0 are defined as the mixture of sorted ($S_{\text{Remainder}}$) and imported ($d11$) remaining scraps, then at each iteration the intermediate product is mixed with the first higher grade scraps (sorted and imported) before looking for the next possible processes;

Table 2
Decision variables.

di	Variables	Type	Lower bound	Upper bound
d1	Choice between P, S and D	1	1	3
d2	Choice between incineration and landfill	1	0	1
d3	Choice between P and D for remaining scrap	1	0	1
d4	Choice between P and D for low grade scrap	1	0	1
d5	Choice between P and D for No.2 scrap	1	0	1
d6	Choice between P and D for alloy scrap	1	0	1
d7	Choice between P and D for No.1 scrap	1	0	1
d8	Pre-treatment process choice	1	1	10
d9	Smelting and converting processes choice	1^2	1^2	10^2
d10	Fire-refining process choice	1	1	10
d11	Remaining scrap I–E (kt/year)	0	$-\infty$	$+\infty$
d12	LG scrap I–E (kt/year)	0	$-\infty$	$+\infty$
d13	Copper concentrate I–E (kt/year)	0	$-\infty$	$+\infty$
d14	Copper matte I–E (kt/year)	0	$-\infty$	$+\infty$
d15	No.2 copper scrap (kt/year)	0	$-\infty$	$+\infty$
d16	Copper blister I–E (kt/year)	0	$-\infty$	$+\infty$
d17	No.1 copper scrap I–E (kt/year)	0	$-\infty$	$+\infty$

Legend: P: processing, S: sorting, D: discarding, I–E: importation minus exportation.
Variable type: 0: continuous variable, 1: integer variable.
Import. and export. flows are continuous on $\mathbb{R}$: boundaries are fixed depending on the case considered.



```
function [Pf, Uf, W1f, W2f, NRJ_T] = flowsheet (Sc_0, Sp_0)
% Step 1a : alloy test
if Sc_0 ==alloy
   Pf=Sc_0
end
% Step 1b : high quality test
if Pf==0
   if Sc_0(1) >= Q %(Q=desired quality, i.e. copper content)
      Pf=Sc_0
   end
end
% Step 2 : Processing of the scrap
if Pf==0
   Sc_i=0 %initialization of Sc_i, the matrix of intermediate products
   c=1 %initialization of Pf column index
   F=1 %initialization of flowsheet matrix length
   max_process=X  %definition of the maximal number of processes in the flowsheets
   while sum(sum(Sc_i))~=0  && F <= X+1%the program goes on as long as there are products
      for IP=1:size(Sc_i,2) % loop to transform every intermediate product IP
         if Sc_i(:,IP)... %verification of composition and physical properties (Tcmin, Tpmin, ...)
            ... %transformation of the product with the split factors
                 ⇨ Construction of matrix Sc_iplus1, W1, W2 and NRJ
                 ⇨ addition in the flowsheet matrix of the index of the new process
            if Sc_iplus1(1,PI) >= Q
               Pf(:,c)=Sc_iplus1... %end
               ... %determination of W1f and W2f
               c=c+1 %incrementing of the index
            end
            if ... %if not a single process can transform the intermediate product
            ... %construction of unprocessable products matrix
            end
         end
         ... %re-initialization, suppression of empty lines and columns, etc. for next loop
         F=F+1 %increment of flowsheet matrix length
-     end
   end
end
[Pf, Uf, W1f, W2f, NRJ_T]=... %calculation of final characteristics of each final flowsheet
end
```

Fig. 3. Simplified structure of the Matlab© code.

- or each type of scrap is treated with an independent flowsheet, but the waste from higher-copper-content scrap processing can be mixed with lower-copper-content scrap (in this case, a matrix of all possible flowsheets is constructed and the decision variables $d8$, $d9$ and $d10$ are replaced by five other integer variables that indicate the index of the retained flowsheet for each scrap – No.1, No.2, LGS, Alloy and Remainder):
  - the *flowsheet* function is used to construct a matrix containing all the possible flowsheets for each scrap category by browsing all the possible component contents of this specific category;
  - a flowsheet is selected for the highest copper grade scrap retained for processing;
  - the scrap obtained with this first flowsheet ($W1_f$) are mixed with the next highest copper grade scrap retained for processing and a second flowsheet is retained for this scrap mixture;
  - the same method is applied until all the remaining scraps are treated.

The decision variables (di) that appear in the Equations and Fig. 4 are listed and detailed in Table 2.

It can be observed that there are both continuous and discrete decision variables. The problem is thus a mixed one. It can also be observed that the problem is linear.

2.2.2. *Choice of criteria*

Once all management options have been highlighted, criteria have to be selected to evaluate and compare them. The choice of the criteria is an important step and has to be made carefully to obtain reliable results.

In today's economic context, viability considerations are very important. This is why the first criterion chosen is the running cost (C). It is calculated considering all the costs except the construction and dismantling of the recycling plant, minus the amount earned by selling recycled copper (Eq. (5)).

$$C_{\text{Total}} = C_{\text{recycling}} + C_{\text{disposal}} + C_{\text{sorting}} + C_{\text{I-E}} \tag{5}$$

with:

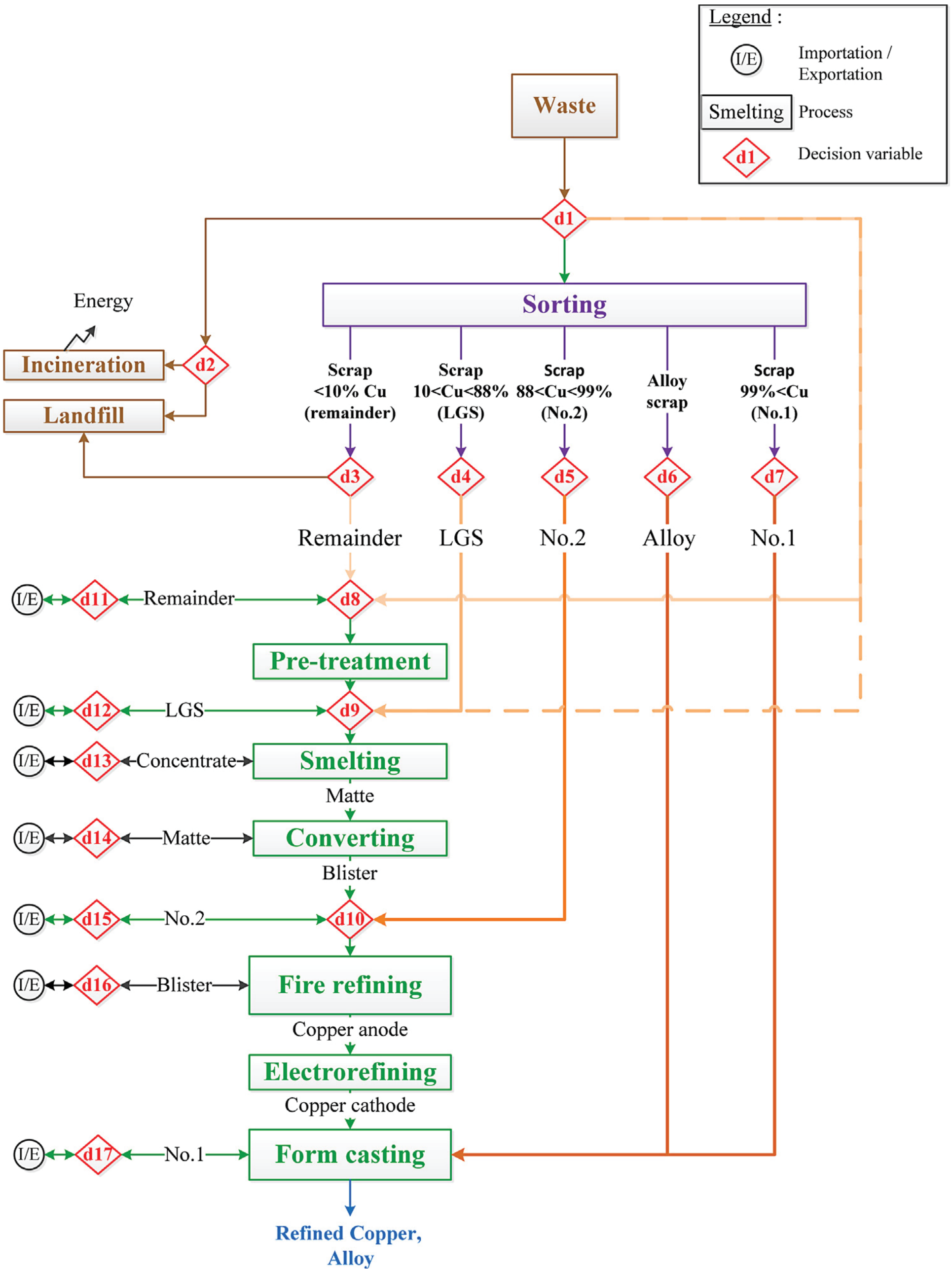


Fig. 4. Overall structure of the copper scrap treatment pathways.

- C_{Total}: total cost in monetary units;
- $C_{\text{recycling}}$: cost related to recycling processes, calculated from energy and material consumption (does not take into account the investment costs, like infrastructures, etc.);
- C_{disposal}: cost of waste disposal (landfill or incineration) (Andrup et al., 2011);
- C_{sorting}: cost of sorting waste (to extract scraps);
- $C_{\text{I-E}}$: cost of imports and exports.

To ensure the durability of the planet, the environmental impacts of every human activity have to be evaluated. In this perspective, it was decided to evaluate the global warming potential (GWP) by using the flowsheets with a life cycle assessment approach (Eq. (6)). As this information does not cover all environmental impacts, it was completed by an evaluation of the energy consumption corresponding to each flowsheet (Eq. (7)). Energy production is always a source of impacts but they differ depending on the energy. The combined minimization of these two criteria (GWP and energy consumption) can lead to a good compromise. However, if a complete life cycle assessment was conducted, all the environmental impacts could be kept as criteria and energy minimization would be unnecessary.

$$EI_{\text{Total}} = EI_{\text{recycling}} + EI_{\text{disposal}} + EI_{\text{sorting}} + EI_{\text{I-E}} \tag{6}$$

$$NRJ_{\text{Total}} = NRJ_{\text{recycling}} + NRJ_{\text{disposal}} + NRJ_{\text{sorting}} + NRJ_{\text{I-E}} \tag{7}$$

with:

- EI_{Total}: total environmental impacts, expressed in equivalent CO_2;
- $EI_{\text{recycling}}$: impacts related exclusively to recycling processes, calculated from the energy consumption and material processes and using impact factors of the database EcoInvent (Classen et al., 2007) (extracted from SimaPro software);

- EI_{disposal}: impacts associated with waste disposal (landfill or incineration);
- EI_{sorting}: impacts associated with waste separation (to extract scraps);
- $EI_{\text{I-E}}$: impacts attributed to imports and exports (copper, waste, etc.);
- NRJ_{Total}: total energy consumption;
- $NRJ_{\text{recycling}}$: processes energy (and materials) consumption;
- NRJ_{disposal}: energy consumption linked to waste disposal;
- NRJ_{sorting}: energy consumption related to waste sorting (to extract scraps);
- $NRJ_{\text{I-E}}$: energy consumption attributable to imports and exports.

Finally, a fourth and last criterion was chosen: copper losses (Eq. (8)). As mentioned above, copper resources could be exhausted within 30 years. It is thus important not to discard too much. It is difficult to assess the impact of exporting copper scrap, as importing countries do not necessarily have to say how they will use it (recycling, with which process, etc.). Thus the consideration of losses can be used to associate an impact with copper scrap exportation.

$$L_{\text{Total}} = L_{\text{disposal}} + L_{\text{recycling}} + L_E \qquad (8)$$

with L_{Total}: total losses of copper; L_{disposal}: copper contained in the categories of waste neither sorted or sent directly to recycling, or in disposed scraps; $L_{\text{recycling}}$: copper contained in scraps from recycling processes (W_1 and W_2); L_E: copper contained in exported waste or scrap.

2.2.3. Choice of optimization algorithm

Many optimization algorithms exist, some using deterministic formulations, others using heuristic methods. The choice of the algorithm and formulation depends on the characteristics of the problem and on the decision variables: Is the problem linear or not? Are the decision variables continuous or mixed? Is the problem mono- or multi-objective?

It has already been pointed out that the problem treated here is mixed and linear. To determine whether it is multi-objective or not, mono-objective optimizations have to be conducted for each of the selected criteria to identify whether they are antagonistic or not.

If the criteria are not antagonistic, a mono-objective optimization is sufficient. As the problem treated here is linear, a mixed-integer linear programming (MILP) formulation is the most suitable.

If the criteria are antagonistic, a multi-objective optimization has to be conducted: the idea is then to find the best compromise solution. For this, the classical method is to construct the Pareto front, i.e. the set of non-dominated solutions. Then, the best solution is chosen thanks to a decision support tool, for instance TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). An MILP formulation can also be used, but is has to be coupled with a strategy such as ε-constraint to construct a Pareto front (Haimes et al., 1971). Another possibility is to use a method specifically adapted to multi-objective optimization, such as the genetic algorithm (GA), which builds a Pareto front directly (Gomez et al., 2010). The advantage of the MILP formulation is that linear programming finds the true best solution, while metaheuristic algorithms, like GA, do not find it systematically. However, linear programming needs many calculations to construct the Pareto front.

For the problem treated here, with four objectives, the number of optimization runs needed to build a Pareto front with the ε-constraint method would be too large. A genetic algorithm seems here more appropriate as a multi-objective optimization method, because it is particularly well suited for the solution of problems with a set of several criteria, which exhibit a marked combinatorial aspect and where the mathematical properties (continuity, convexity, derivability) are difficult to verify. For all these reasons, a genetic algorithm was selected here. A modified version of the algorithm NSGA II (Non-Dominated Sorting Genetic Algorithm II) developed by Gomez et al. (2010), taking into account both continuous and integer variable has been used. The crossover and mutation operation are based on the Simulated Binary Crossover and on the parametric mutation described by Deb and Agrawal (1995).

2.3. Conclusion on the methodology

A complete strategy has been proposed for choosing the best treatment option for a specific waste. This strategy is divided into three steps:

- formulation of the problem, with identification of the decision variables and mathematical formulation;
- choice and calculation of the criteria that have to be optimized: cost, environmental impacts, energy consumption and losses;
- mono- or multi-objective optimization to find the best (compromise) solution.

3. Application to printed wiring board management

To prove its interest, the methodology was applied to a simplified example: the case of printed wiring board (PWB) recycling in France. This example was inspired by the work presented by Suljada (2001) to apply its recycling flowsheet construction methodology. The idea here is to validate and illustrate the application of the proposed waste management optimization method by determining if it is more interesting to treat all PWB in one plant or if it is better to use different small plants, which may or may not use the same recycling technology (i.e. flowsheet), to reach a good compromise solution.

3.1. Data collection

To demonstrate the principle of the most sensitive steps of the method (flowsheet construction and multi-objective optimization), some simplifying assumptions were made in the model. It was considered that the scrap had been sorted and that PWB had been isolated for specific processing. It was also decided that all the scrap was treated, without any import or export. The scrap characteristics are given in Table 3.

Under these assumptions, the first step of flowsheet design was to find all the possible combinations of the ten unit processes mentioned above that could transform PWB scrap into refined copper.

3.2. Flowsheet construction

By applying the flowsheet construction method described above to PWB scrap, seven flowsheets were obtained (see Table 4), giving seven products, with the associated liquid, solid and gaseous waste streams, and also thirteen flowsheets that gave “unprocessable” products with a copper concentration ranging between 99.73% and 99.89%.

Then, energy consumption, operating cost and environmental impacts were determined for each of the seven products. Energy consumption was calculated by considering, as is generally assumed, that a part of the consumption was fixed (arbitrarily set at 20%), while the remaining consumption depended on the amount processed. The operating cost was calculated according to French market prices for electricity, fuel, etc. taking the contract power and subscription cost into account. The environmental impacts were determined with SimaPro© software (mid-point

Table 3
PWB scrap characteristics (Suljada, 2001).

	Cu	Fe	Zn	Pb	Sn	Balance	Flowrate	Size	Moisture
PWB	0.22	0.036	0	0.0155	0.026	0.7025	5 t/day	0.1 mm	0

Table 4
Flowsheets (F) obtained with the technologies used, the flowrates of refined copper and the impacts if the flowsheet was used alone.

F	Technology	Flowrate (t/month)	Energy consumption (MW/month)	Environmental impacts ($t_{eqCO_2}/month$)	Total cost (k€/month)
1	LSXEW	210	970	89	51
2	Elec + PS + A	300	3100	600	200
3	TEN + PS + A + ER	270	1400	340	83
4	NOR + DTB + Elec + A	210	2800	490	150
5	Elec*5 + A	280	9700	1400	570
6	TEN + Elec*4 + A	250	7800	1200	450
7	NOR + Elec*3 + A + ER	280	6900	1100	400

method CML) considering only the energy and material consumptions, the emissions to the environment (gaseous waste stream) and the solid and liquid waste treatment (landfilled). Only global warming potential impacts were considered for this example. The results are presented in Table 4.

It has to be highlighted that, considering the chosen hypothesis, if several flowsheets are used to recycle the scrap, the total flowrate is directly proportional to the flow treated with each flowsheet whereas, for energy consumption, the fixed part implies the absence of a proportional relationship.

Once all the flowsheets were constructed and characterized, the objective was to find the flowsheet, or the flowsheet combination, that led to optimized criteria: maximization of product flowrate with minimization of cost, environmental impact and energy consumption.

3.3. *Multi-objective optimization*

At first glance, the optimization to be conducted here involves seven decision variables (the rate τ_i of use of each of the seven flowsheets) and four objective functions. However, before starting the optimization algorithm, it is interesting to check whether it is possible to simplify the problem. Thus, looking more specifically at the results of Table 4, it appears that flowsheets 5, 6 and 7 are dominated by flowsheet 2 for all criteria, and flowsheet 4 by flowsheet 3. These four flowsheets may be discarded for optimization, which now aims to choose between flowsheets 1, 2 and 3. Moreover, the sum of the utilization rates has to be equal to one. The problem can be written with two continuous variables ranging from 0 to 1 (τ_1 and τ_2) and a constraint $\tau_3 = 1 - \tau_1 - \tau_2 \geq 0$. Then, before starting the algorithm with the four objectives, in order to ensure that the problem has been correctly formulated and to take a critical look at the results, it is advisable to start by solving mono- and bi-objective problems. This ensures that the solutions found by the algorithm correspond to what might be expected.

A mono-objective optimization was therefore performed for each of the four criteria. Since the cost and energy consumption optimization results were similar, a bi-objective optimization was conducted. This showed that the relationship between the cost and energy consumption was linear, so that they could be assimilated to a single criterion. This eventually transformed the problem into a tri-criteria optimization problem.

A tri-objective optimization with two variables and one constraint was therefore achieved, with the parameters presented in Table 5 (recommended by Gomez (2008)). The optimization resulted in the production of a Pareto front (that is to say a set of non-dominated solutions) in three dimensions, presented in Fig. 5.

Table 5
Parameters used for the genetic algorithm.

Parameter	Value
Population size	200 individuals
Number of generations (= 2× population size)	400
Crossover probability	0.9
Mutation probability	0.5

Fig. 5 shows a piecewise linear curve, the linear portions being combinations of two identical processes with different usage rates. It is important to note that up to two flowsheets were used in combination.

3.4. *Results*

The multi-objective optimization gave a set of non-dominated solutions. To choose the most suitable option, the use of an ordering technique was necessary to classify the points of the Pareto front. One of the most widely used ordering techniques is the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, which builds the best theoretical point (taking the best solution on the Pareto front for each criterion: Utopia) and the worst theoretical point (taking the worst solution on the Pareto front for each criterion: Nadir), then searches through all points of the front to find the one that is both closest to Utopia and farthest from Nadir (Ren et al., 2007). Another method could be to find the barycenter of the Pareto front.

In this example, a Pareto front of 161 distinct points was obtained, so the items were ranked from 1 to 161. The best theoretical point would be a process costing 51 k€/month (best: flowsheet 1 alone), with environmental impacts of 88.80 t_{eqCO_2}/month (best: flowsheet 1 alone) and a product output flowrate of 304.50 t/month (best: flowsheet 2 alone), while the worst point would have a cost of 200.87 k€/month (worst: 5% flowsheet 1 and 95% flowsheet 2), environmental impacts of 622.68 t_{eqCO_2}/month (worst: flowsheet 2 alone) and an output flowrate of 214.50 t/month (worst: 80% flowsheet 2 and 20% flowsheet 3) (Table 6).

In Fig. 6, it appears that the best ranked point according to TOPSIS is the one obtained when using only flowsheet 1. This makes sense because it is the best for two of the three criteria. Then, points

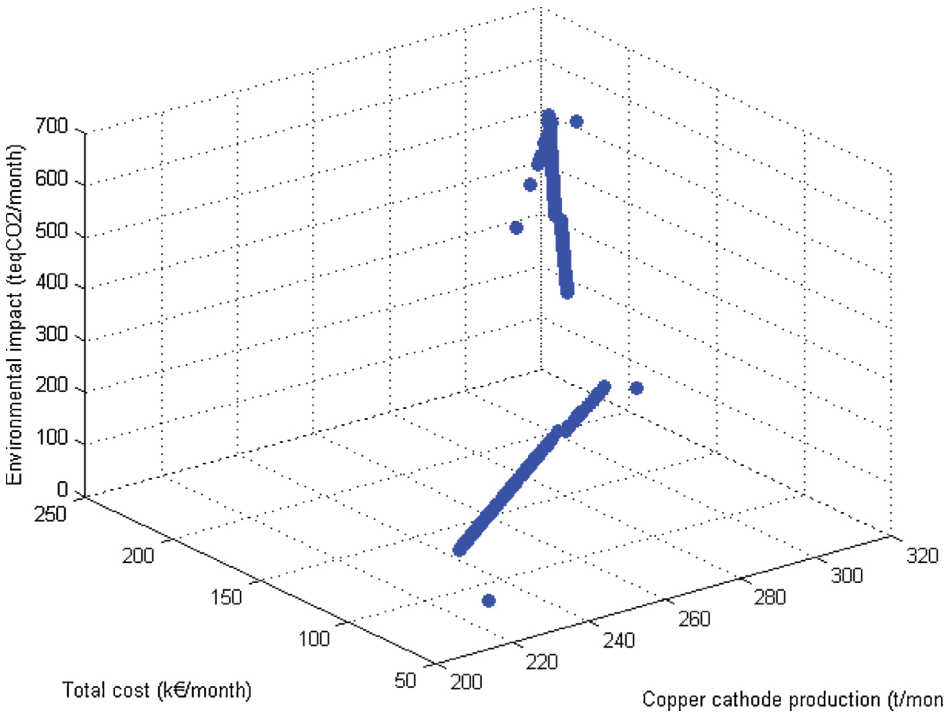


Fig. 5. Results of the tri-objective optimization: Pareto front.

Table 6
TOPSIS results.

Criterion	TOPSIS 1	TOPSIS 69	TOPSIS 129	Difference 1 vs 69	Difference 1 vs 129
Cost	51	83.04	196.49	−62.80%	−285.30%
GWP	88.8	337.64	596.59	−280.20%	−571.80%
Flowrate	214.5	267.96	304.5	−24.90%	−42.00%

2–77 are combinations of flowsheets 1 and 3, with a rate of use of flowsheet 1 decreasing from 99% to 9%, with the exception of point 69, which corresponds to the use of flowsheet 3 only. The items classified 78–130 are almost all obtained by combinations of the 2nd and 3rd flowsheets with a utilization rate of flowsheet 3 decreasing from 99% to 46%, with the exception of points 111 and 125, which are combinations of flowsheets 1 and 2, and point 129, which corresponds to the use of flowsheet 2 alone. Points classified from 131 to 147 are combinations of either flowsheets 1 and 2 or flowsheets 2 and 3, and points classified from 148 to 161 are combinations of flowsheets 2 and 3, with a utilization rate of the flowsheet 2 increasing from 64% to 80%.

For this classification, the three criteria are assumed to have equivalent weights. However it is possible to introduce weighting to give more significance to one criterion than another: this would lead to a different classification.

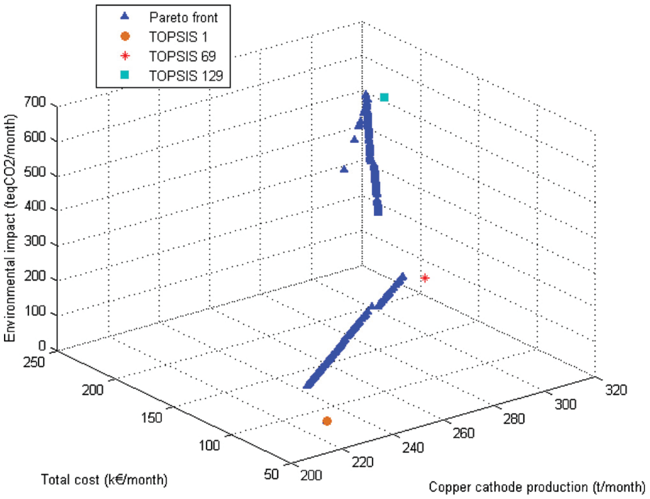


Fig. 6. Results of the tri-objective optimization: Pareto front with TOPSIS ranking.

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 of considering waste management at a large area scale. The main perspective is now to apply the model to a more realistic and also more complex issue related to the choice of technologies that could be used to optimize waste management in France, taking multiple streams into account.

A further investigation would be to challenge the systematic production of such high grade refined copper, since such a high level of purity is required for many applications. The consideration of processes leading to degraded properties would extend the search space for optimization.

An interesting continuation of this work would be to also evaluate installation and dismantling costs, and to perform a life cycle assessment of the copper management loop, or at least of the processing flowsheets, to evaluate all the environmental impacts.

Finally, it has to be highlighted that the methodology presented here can be extend and adapted to any other metal, as well as for many other kind of resources.

Acknowledgments

We would like to thank the French National Research Agency for its financial support. We also would like to thank Marie Stewart who sent us Timothy Suljada's thesis, as well as Damien Giurco and Jim Petrie who sent us some of their interesting articles on the subject.

Appendix A. Process characteristics

Tables A1–A10

Table A1
Pierce Smith Converter characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	**Pierce Smith Converter**				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	$SF_{product}$	SF_{waste1}	SF_{waste2}
Copper	0.35	0.97	0.96	0.04	0.0
Iron	0.03	0.4	0.00	1.0	0.0
Zinc	0	1	0.04	0.84	0.12
Lead	0	1	0.03	0.47	0.51
Tin	0	1	0.03	0.47	0.51
Balance	0	1	0.01	0.89	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	0	0	0		
Moisture (%)	0	0	0		
Energy and material consumption (kWh/t_{Cu})					
Electricity	110–860				
Fuel	0–1050				
Water	0				
Oxygen	0				
Silica	0				
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition				
$SF_{product}$, 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)				
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

Table A2
Anode furnace characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	Anode furnace				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	$SF_{product}$	SF_{waste1}	SF_{waste2}
Copper	0.97	0.997	0.99	0.01	0.0
Iron	0	0.005	0.40	0.60	0.0
Zinc	0	0.005	0.40	0.60	0.0
Lead	0	0.005	0.54	0.46	0.0
Tin	0	1	0.54	0.46	0.0
Balance	0	1	0.01	0.89	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	0	0	1		
Moisture (%)	0	0	0		
Energy and material consumption (kWh/t_{Cu})					
Electricity	0				
Fuel	1500–1700				
Water	0				
Oxygen	0				
Silica	0				
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition				
$SF_{product}$, 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)				
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

Table A3
Outukumpu flash smelter characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	Outukumpu flash smelter				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	$SF_{product}$	SF_{waste1}	SF_{waste2}
Copper	0.2	0.55	0.99	0.01	0.0
Iron	0.127	0.26	0.40	0.60	0.0
Zinc	0	1	0.40	0.60	0.0
Lead	0	1	0.54	0.46	0.0

Table A3 (*Continued*)

Process	Outukumpu flash smelter				
Tin	0	1	0.54	0.46	0.0
Balance	0	1	0.01	0.89	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	0	0	0		
Moisture (%)	0	0.005	0		
Energy and material consumption (kWh/$\mathrm{t_{Cu}}$)					
Electricity	0				
Fuel	790				
Water	23				
Oxygen	890				
Silica	12				
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition				
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)				
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

Table A4

Direct to Blister flash smelter characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	Direct to Blister flash smelter				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	SF_{product}	SF_{waste1}	SF_{waste2}
Copper	0.274	0.6	0.72	0.27	0.0
Iron	0	0.125	0.08	0.92	0.0
Zinc	0	0.04	0.04	0.84	0.12
Lead	0	0.04	0.03	0.97	0.0
Tin	0	0.04	0.03	0.97	0.0
Balance	0	1	0.01	0.89	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	0	0	0		
Moisture (%)	0	0.005	0		
Energy and material consumption (kWh/$\mathrm{t_{Cu}}$)					
Electricity	0				
Fuel	790				
Water	23				
Oxygen	890				
Silica	12				
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition				
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)				
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

Table A5

Electric furnace characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	Electric furnace				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	SF_{product}	SF_{waste1}	SF_{waste2}
Copper	0.1	0.997	0.97	0.03	0.0
Iron	0	0.45	0.40	0.60	0.0
Zinc	0	1	0.15	0.45	0.4
Lead	0	1	0.25	0.75	0.0
Tin	0	1	0.25	0.75	0.0
Balance	0	1	0.20	0.70	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	0	0.1	0		
Moisture (%)	0	0	0		
Energy and material consumption (kWh/$\mathrm{t_{Cu}}$)					
Electricity	5600				
Fuel	1100				
Water	0				
Oxygen	0				
Silica	0				
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition				
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)				
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

Table A6
SKS bath furnace characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	SKS bath furnace				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	SF_{product}	SF_{waste1}	SF_{waste2}
Copper	0.18	0.3	0.89	0.11	0.0
Iron	0.2	0.35	0.26	0.74	0.0
Zinc	0	1	0.29	0.71	0.0
Lead	0	1	0.525	0.15	0.325
Tin	0	1	0.525	0.15	0.325
Balance	0	1	0.20	0.70	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	0	0.1	0		
Moisture (%)	0	0.14	0		
Energy and material consumption (kWh/t_{Cu})					
Electricity	–				
Fuel	–				
Water	–				
Oxygen	–				
Silica	–				
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition				
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)				
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

Table A7
Teniente furnace characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	Teniente furnace				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	SF_{product}	SF_{waste1}	SF_{waste2}
Copper	0.2	0.35	0.863	0.138	0.0
Iron	0	0.45	0.371	0.629	0.0
Zinc	0	1	0.11	0.66	0.23
Lead	0	1	0.31	0.27	0.42
Tin	0	1	0.31	0.27	0.42
Balance	0	1	0.20	0.70	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	0	0.1	0		
Moisture (%)	0	0.14	0		
Energy and material consumption (kWh/t_{Cu})					
Electricity	370				
Fuel	1600				
Water	0				
Oxygen	930				
Silica	190				
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition				
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)				
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

Table A8
Noranda furnace characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	Noranda furnace				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	SF_{product}	SF_{waste1}	SF_{waste2}
Copper	0.2	0.35	0.94	0.06	0
Iron	0	0.45	0.19	0.81	0
Zinc	0	1	0.125	0.75	0.125
Lead	0	1	0.2	0.3	0.5
Tin	0	1	0.2	0.3	0.5
Balance	0	1	0.2	0.7	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	0	0.05	0		
Moisture (%)	0	0.14	0		
Energy and material consumption (kWh/t_{Cu})					
Electricity	369				
Fuel	1562				
Water	0				

Table A8 (*Continued*)

Process	Noranda furnace
Oxygen	929
Silica	190
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition
$SF_{product}$, 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)
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input
Tp_{out}	Output physical characteristics

Table A9
Leach-solvent extraction electrowin process characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	Leach-solvent extraction electrowin process				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	$SF_{product}$	SF_{waste1}	SF_{waste2}
Copper	0.005	0.35	0.863	0.138	0.0
Iron	0	0.5	0.371	0.629	0.0
Zinc	0	1	0.11	0.66	0.23
Lead	0	1	0.31	0.27	0.42
Tin	0	1	0.31	0.27	0.42
Balance	0	1	0.20	0.70	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	0	0.1	1		
Moisture (%)	0	1	0		
Energy and material consumption (kWh/t_{Cu})					
Electricity	4500				
Fuel	0				
Water	0				
Oxygen	0				
Silica	0				
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition				
$SF_{product}$, 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)				
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

Table A10
Electrolytic refinery characteristics (Suljada, 2001; U.S. Congress, 1988).

Process	Electrolytic refinery				
Compositional properties (%)					
Components	Tc_{min}	Tc_{max}	$SF_{product}$	SF_{waste1}	SF_{waste2}
Copper	0.985	1	0.863	0.138	0.0
Iron	0	0.001	0.371	0.629	0.0
Zinc	0	0.003	0.11	0.66	0.23
Lead	0	0.003	0.31	0.27	0.42
Tin	0	0.003	0.31	0.27	0.42
Balance	0	0.003	0.20	0.70	0.1
Physical properties					
Characteristics	Tp_{min}	Tp_{max}	Tp_{out}		
Size (m)	1	1	0		
Moisture (%)	0	0	0		
Energy and material consumption (kWh/t_{Cu})					
Electricity	400				
Fuel	0				
Water	10				
Oxygen	0				
Silica	0				
Tc_{min}, Tc_{max}	Minimum and maximum fractions acceptable in input stream composition				
$SF_{product}$, 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)				
Tp_{min}, Tp_{max}	Minimal and maximal physical properties acceptable for input				
Tp_{out}	Output physical characteristics				

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