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Development of a Dynamic Material Flow Analysis Model for French Copper Cycle

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Abstract

Resource depletion leads government and industrials to a crucial question: will one resource still be available at a reasonable price in ten, twenty or even in a hundred years? This work is included in a more general project that addresses this issue by developing a new methodology for optimizing resources management. This study presents its first step, which is applied to the example of copper cycle management in France with the so-called Material Flow Analysis method. This paper shows that copper production and utilization are slowly decreasing while waste production is increasing. Moreover, the recycling rate is lower in France than in the rest of Europe, since there is neither copper extraction nor first transformation industry in France.

Keywords: Material Flow Analysis, Resources Management, Copper, Stocks and Flows.

1. Introduction

More than twenty years after the release of the Brundtland report, many questions still focus on the evaluation of systems unsustainability, and the way to reach a sustainable state. Indeed, in the current situation, the industrial metabolism is still depleting its resources and overloading the environment with wastes and emissions in many respects. This work is thus integrated in a comprehensive approach that aims at contributing to the development of a model representing the relationships between economic system, resource consumption, product manufacturing and generation of wastes and pollution, thus broadening the traditional scope of process systems engineering.

The objective is to develop a methodology based on classical approaches of process systems engineering, especially through mass balance concept, that take into account both environmental and economic aspects of substance utilization through the level of an economic region. This study illustrated by the example of the French copper cycle is carried out within the framework of the ANR program [ESPEER].

2. Methodology

The first step of this methodology is the mapping of the targeted substance by using a dynamic Material Flow Analysis (MFA), which is an analytical method of quantifying flows and stocks of materials or substances in a system. It is an important tool to assess the physical consequences of human activities and needs, and is used to develop strategies for improving the material flow system in form of material flow management.

Figure 1 shows a traditional flowchart for tracking substances across countries or continents. It was widely used for the characterization of the European [Graedel et al., 2002], but also for the Japanese copper cycle [Daigo et al., 2009]. In that context, a dynamic MFA is particularly useful to take into account the evolution of the system in time, in order to define scenarios for potential future development. The copper cycle can be divided into four steps appearing in figure 1: production, fabrication/manufacturing, use and finally waste management, each one involving more or less detailed sub-stages. This presentation is attractive since it covers copper life cycle in its main forms, that are mined and refined copper, semi-product, product and waste for elimination or recycling.

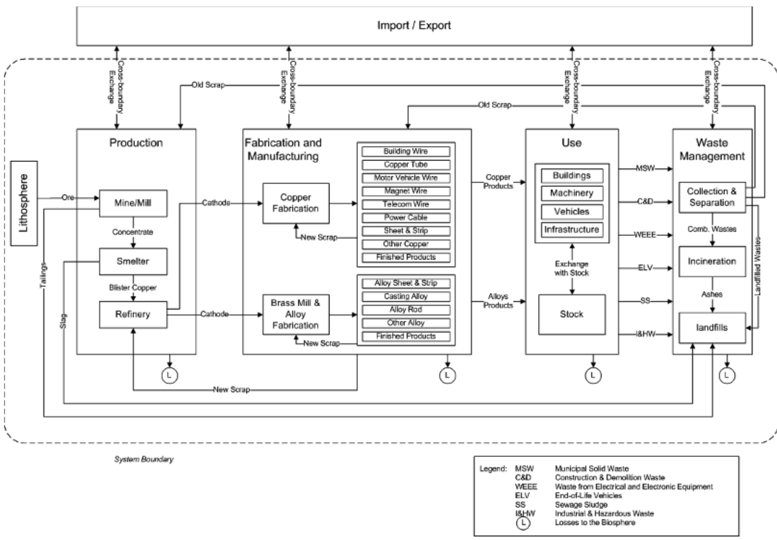

Figure 1: French Copper Cycle System Boundary

This study can be divided into three major steps that are detailed in section 3: first, data have to be collected to complete the diagram presented in figure 1, then they must be validated and reconciled; finally, they are computed and analyzed.

3. Data collection and reconciliation

3.1. Data collection

As the project objective is to use the MFA of copper to study resource management scenarios in the medium and long terms, an exhaustive data collection was performed, involving various sources, in particular the International Copper Study Group [ICSG] for every flow of production, fabrication and manufacturing steps, the French agency of environment and energy management [ADEME] for use and waste flows, the import/export customs and the Interprofessional Technical Center for Atmospheric Emission Study [Citepa] for emissions into environment. However, some of these data are available from different sources and slightly different according to the source. For this reason, data uncertainty has to be evaluated. Moreover, depending on the sources, data have to be aggregated or disaggregated to obtain similar precision levels, thus leading to validation and reconciliation issues, as it is discussed in section 3.2. With the obtained data, it was possible to carry out a dynamic copper cycle from year 2003 to 2009. However, it was quite difficult to find data of copper storage in the technosphere: this explains why only stock variation has been considered in this work; the evaluation of the total French in-use stocks will be the core of another study.

3.2. Data reconciliation

When performing data reconciliation, two cases have to be taken into account, i.e., either the system is redundant, which means that there are less unknown values than equations, or the system is not redundant.

If the system is redundant, the objective of the reconciliation is to satisfy mass conservation: *Input +Generation = Accumulation + Output + Consumption*. In this case, as there is no chemical reaction, the equation can be simplified: *Input = Accumulation + Output* with *Output = Emission + Waste + Useful Output*. In this study, since data come from different sources, the mass conservation equation rarely holds and reconciliation is necessary to respect mass conservation.

If the system is not redundant, it is either observable or not. The system is observable when unmeasured (or missing) values can be estimated from known values and process constraints (e.g. mass conservation). For an observable system, reconciliation aims at calculating unknown average values and standard deviation. For a non-observable system, data reconciliation cannot be carried out.

3.3. Calculations

The computation and reconciliation are implemented by using the STAN software [STAN]: it allows to draw a map of the copper cycle and to give flow data and uncertainties for successive periods (in this case, the period is one year). Then, redundant and missing flows are calculated with an integrated data reconciliation method: uncertainty is considered as normally distributed and STAN performs data reconciliation using a method of error propagation, based on the classical least square method.

3.3.1. Least square general method

Generally, least square method is used to fit experimental data to a mathematical model that describes these data. A reconciled value ($y^*+\sigma^*$) respecting the mathematical model is determined from measured values ($y_i+\sigma_i$) (i being the number of measures) by minimizing X^2 in equation (1): the difference between the measured values and the reconciled value, weighted by the standard deviation (to take into account uncertainty differences), has to be as low as possible.

$$X^2 = \sum_{i=1}^{N} \left(\frac{y_i - y_i^*}{\sigma_i}\right)^2 \tag{1}$$

Then, the reconciled standard deviation, σ^*, is determined with equation (2):

$$\sigma^* = \left[\sum_{i=1}^{N} \frac{1}{\sigma_i^2}\right]^{-1/2} \tag{2}$$

3.3.2. Least square adapted to material flow analysis problem

In the case of MFA, the mathematical model is the mass balance conservation and there are two "measured" values of one flow j: the collected data called y_j, and the value calculated with the mass balance and the other flows i: $\sum_{i=1}^{n}(\lambda \cdot y_i)$ with $i \neq j$ and $\lambda = 1$ if the flow is an input and $\lambda = -1$ if the flow is an output (in these equations, stocks are considered as output flows) [Narasimhan and Jordache, 2000]. Thus, to determine the reconciled values of flow j, STAN uses the formulae presented in equations (3) and (4):

$$X_j^2 = \frac{\lambda \cdot y_j - \lambda \cdot y_j^*}{\sigma_j} + \frac{\left(\sum_{i=1}^{n}(\lambda \cdot y_i) - \lambda \cdot y_j^*\right)^2}{\sum_{i=1}^{N} \sigma_i^2} \tag{3}$$

$$\sigma_j^* = \left[\frac{1}{\sigma_j^2} + \frac{1}{\sum_{i=1}^{N} \sigma_i^2}\right]^{-1/2} \tag{4}$$

If one flow value is missing, it is calculated by using the mass balance equation and the standard deviation σ_j^* is calculated according to equation (4) assuming an infinite σ_j.
It must be noted that the classical assumption of a normal distribution of uncertainty is necessary because there is no other general method to perform reconciliation without the distribution normality assumption. However in many real world problems data uncertainty distribution is more probably trapezoidal and a specific reconciliation model should be implemented: this is an important issue that will be discussed in future study.

4. Results and discussion

French dynamic MFA has been carried out from 2003 to 2009 with STAN software. Figure 2 shows a typical snapshot result (year 2007). It can first be observed that there is nearly no stream in the production stage for French copper cycle: there is no copper primal transformation industry in France and product fabrication and manufacture are achieved through imported refined copper or semi-finished products.

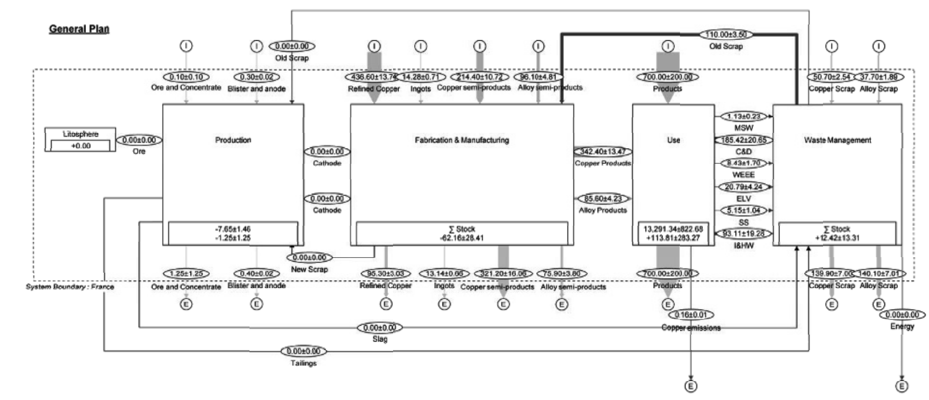

Figure 2: French MFA - year 2007

A second observation is that most of French scrap is exported while secondary copper is not widely used in France: from 2003 to 2009 the utilization rate of secondary copper in raw material is 25% in average [Gie et al., 2010a] which is a low value compared to the average in Europe countries, around 40% [Gie et al., 2010b]. This may be explained by the lack of first transformation industry: there is neither equipment infrastructure to refine copper, nor an industry to transform copper scrap into new refined copper.
Figure 3 shows the evolution of total copper importations, exportations, emissions and waste production of France from 2003 to 2009 expressed in kilo tons. It can be observed that productions, importations, exportations and copper added to stock have decreased while waste production has increased. This behavior can be explained by the fact that copper consumption in France has reached a steady state while copper has been accumulated in technosphere as stocks in the use compartment for the past fifty years. Thus, copper used during this period is now reaching the waste phase of itself and stocks should become nearly constant in a few years.
Finally, copper emissions are negligible compared to the other flows: they cannot be seen as a source of material recovery. It is yet important to quantify their environmental burdens, by using for instance Life Cycle Assessment.

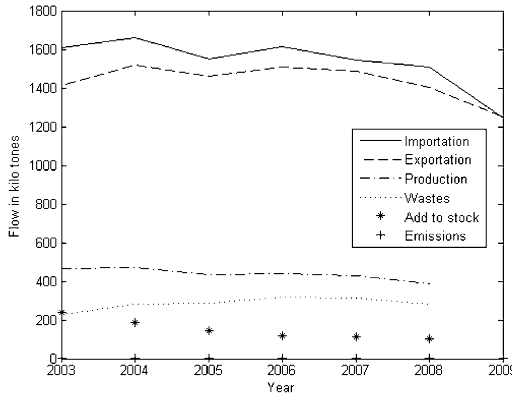

Figure 3: Evolution of Copper Flows in kilo tons

5. Conclusion and perspectives

This example illustrated how material flow analysis can give relevant information of a specific resource situation in a large area. The MFA can then be used to analyze different scenarios, for instance, the utilization and waste management, and to predict if there will be enough resource or not in the upcoming future. In this study the mass balance is performed at a national scale, but it would be possible to generalize for an entire continent. This study can be viewed as the first step of a global resource management methodology, which also has to include environmental and economic consideration: the different processes involving copper will be identified and life cycle assessment will be performed to evaluate their environmental impact. Particular attention will be focused on waste elimination and recycling processes to determine the best waste management options. Scenarios to decrease the global environmental burdens of French copper cycle will be studied together their economic feasibility.

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STAN - Software for Substance or Material Fow Analysis. Institute for Water Quality, Resource and Waste Management.