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Development and validation of a dynamic material flow analysis model for French copper cycle

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ABSTRACT

This study performs a quantitative description of the copper life cycle at the scale of France from 2000 to 2009 with special focus on waste streams. The approach is based on substance flow analysis and includes data reconciliation. The model takes into account the relationships between economic system, resource consumption, product manufacturing, waste generation and pollution, thus broadening the traditional scope of process systems engineering. The more important results concern waste management since France exports most of its collected copper wastes because there is no industry for recycling low-grade scrap. The paper shows the interest of using substance flow analysis methodology coupled with data reconciliation to obtain a precise cartography of a substance flow inside a large area. Indeed, statistic data from institutional organisms and industries may vary from one source to the other, and the utilization of the redundancy of information is an efficient tool for obtaining more precise data. Moreover, the dynamic analysis allows modelling the stock evolution with more accuracy than in previous studies. Finally, the results are compared with existing values for other countries or continents, and some perspectives concerning the use of copper in France are given.

Keywords: Substance flow analysis; Resources management; Copper; Data reconciliation; Stocks and flows

1. Introduction

More than twenty years after the release of the Brundtland report and the first definition of sustainable development, many questions still focus on the evaluation of systems unsustainability, and the way to reach a sustainable state. The paradigmatic vision of a sustainable industrial system is characterized by minimal physical exchanges with the environment, with internal material loops being driven by renewable energy flows. However, in the current situation, the industrial metabolism is still depleting its resources and overloading the environment with wastes and emissions in many respects.

This is especially true in the metal industry, in particular in the case of copper. Indeed, copper is the third metal used in the world after iron and aluminium (Muchova et al., 2011), it is used in a wide range of applications (electricity, electronic equipment, building, chemistry, etc.), it is expensive and pure copper is infinitely recyclable at 100% without any property losses. Moreover, according to Ayres et al. (2002), copper production peak is likely to occur before the end of the 2020s, while demand should continue to grow for several more decades. Thus, according to Graedel et al. (2004) depletion should arrive no later than the 2050s and according to Jamet et al. (2009), world copper reserves will be exhausted by 2030.

Abbreviations: C&D, construction and demolition waste; DM, dry material; EEE, electrical and electronic equipment; ELV, end of life vehicles; I&HW, industrial and hazardous waste; LCA, life cycle assessment; MFA, material flow analysis; MSW, municipal solid waste; RSMW, residual municipal solid waste; SFA, substance flow analysis; SS, sewage sludge; STAF, stocks and flows; WEEE, waste from electrical and electronic equipment.

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In countries with no copper ores, as it the case for France, this situation will lead very quickly to problems in new refined copper supply. Thus, there is an urgent need to know where copper is used, stocked and lost along its life cycle, to guide decision makers in taking good management decision to face this situation.

Material flow analysis (MFA) is the analysis of flows in every stream of a process, including extraction or harvesting, chemical processing, product manufacturing, material consumption, recycling or material elimination. This flow analysis is based on flow account in physical units (tons) that quantify inputs and outputs of a process. Involved data can be chemicals (C, CO_2, etc.), natural compounds or techniques as well as bulk materials (coal, wood, etc.). Accounting of any substance has a clear link with economic accounting: MFA covers mass flow analysis in an economic system. Substance flow analysis (SFA) is a kind of MFA that is used when only one specific chemical is studied (Ayres and Ayres, 2002), which is the case in this study. This tool is thus commonly used in the industry at process scale, sometimes combined with a life cycle assessment to obtain very accurate data on environmental impacts of a process (Jeswani et al., 2010). However, it is also a powerful tool to study the industrial metabolism of a substance (for instance a metal) at a regional scale. The interest of SFA and MFA to draw substances cycle, as described by Brunner and Rechberger (2004), has already been highlighted by many studies.

In fact, different works have already been conducted on the implementation of SFA to help facing problematic of copper management, especially in the framework of the stocks and flows (STAF) project initiated by the Center for Industrial Ecology at Yale University: a macro-level study has been conducted on the characterization of the European copper cycle and on its waste management subsystem (Bertram et al., 2002), as well as a study on the copper stocks and flows in Asia by Kapur et al. (2003) and North America by Spatari et al. (2005); moreover, substance flow analysis of copper (and other metals) have been carried out in many other area, most of them based on the "STAF model", for instance by Guo and Song (2008) in China, by Daigo et al. (2009) in Japan and by Tanimoto et al. (2010) in Brazil. In these different works, methodologies and tools were proposed to conduct and analyse material flow analysis. Finally a study conducted by Graedel et al. (2004) presents many copper cycles performed on an annual basis at different governmental unit levels: country, region and planet. This work was also conducted within the framework of the STAF project and aimed at giving global information on the anthropogenic copper cycle. Therefore French copper cycle was performed among others and is available in the supporting information linked to this paper; results are discussed in Section 4.

This work aims at developing a more comprehensive methodology, based on the application and validation of the STAF model on the French copper cycle from year 2000 until 2009, with a special emphasis on data reconciliation and on the dynamic behaviour of the system. The methodology is described in Section 2, along with the definition of the system. Then, Section 3.1 presents how data collection with a significant level of accuracy was conducted, and Section 3.2 deals with data reconciliation. Moreover, attention is focused on the waste streams, which can be considered as a secondary material source rather an environmental burden as described in Section 3.1.5.

2. Methodology

2.1. System boundaries

According to Brunner and Rechberger (2004) definition, "MFA is systematic assessment of materials within a system defined in space and time". In other words, MFA gives information of a material mass flow into defined boundaries. As this study consists in evaluating French copper cycle, the space boundary is obviously France. In fact, given that the decisions are taken at a country level, SFA is applied at this level. The time boundary is based on ten years, to obtain not only a picture at a specific time but also an overview of the evolution in the recent past. Thus it is possible to take into account the evolution of the addition of copper into the technosphere, and this can be useful to anticipate consumption scenarios in the near future. Indeed the evolution of copper production, fabrication, use and waste production has been very important along the twentieth century all around the world. Yet, with the increasing use in electric and electronic equipment, this evolution has changed radically since the end of the last century, which justifies a study on a 10-year period.

Moreover, a study has already been conducted to carry out the dynamic copper cycle in North America, which gives a good understanding of copper cycle evolution along the twentieth century. However, the lack of data, especially concerning product end-uses and product residence times, leads to many modelling assumptions thus providing, according to the authors, quite high uncertainty in results (Spatari et al., 2005). Furthermore, this study shows that for most of the flows (trade, use and stock), the evolution has varied a lot from 1900 to about 1995 and then has started to increase very quickly, as society is more and more a material-intensive industrial one. That is why this paper only focuses on the recent past: fairly accurate data have been available for most of the flows since the end of the twentieth century and flows change has known a break at the end of the twentieth century that does not allow using past trends for prediction purpose.

The choice of such a large area for the space boundary leads to a major issue insofar as every flow of materials containing copper has to be identified and estimated. This means that the entire life cycle of copper in France has to be considered.

Along its life cycle, usually a metal passes through four major steps: first it is extracted and transformed into a refined metal, then, semi-finished and finished products are manufactured, then the products are used, and finally, they become wastes that have to be managed. Fig. 1 presents the system boundaries of the French copper cycle. As mentioned earlier, a similar representation has been used in the STAF model.

Fig. 1 shows every copper flow and stock that has to be determined, including importations and exportations, losses into the environment as wastes and emissions, recycling, etc. The objective is to collect as much data as possible even if a redundant system is obtained, as explained in Section 3.2.

2.2. Flows and stocks estimation

The system under study concerns only material flows, and the calculation of both stocks and flows, which is then based only on the principle of mass conservation (Eq. (1), with I the importations, P the production, C the consumption, S the stock and E the exportation flows), is performed.

$$I + P = C + \Delta S + E \quad (1)$$