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Statistical entropy analysis of substance flows in a lead smelting process

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ABSTRACT

Substance flow analysis (SFA) is of the most useful decision-support tools in environmental management, and has been applied in many studies. This research used SFA at the production-process level to realize the purposes of pollution prevention and control. One of the lead smelting processes – SKS lead smelting – was chosen as our study object, and onsite monitoring data was collected from a large state-owned lead smelting enterprise in central China. All of the lead-containing material flows in the process were sampled and tested. Lead accounts of each production process and the entire system were established. Statistical entropy analysis, a method tailor-made for SFA, was applied to evaluate the SFA result of the investigated lead smelting process. Two scenarios were put forward to address the problem of mass balance failure. Scenario I represents the situation where all the lead loss is considered and is assumed to be caused by either measurement errors or uncontrolled emissions. Scenario II represents the situation of no lead loss (the ideal conditions). The results showed that lead ingot (the final product) accounted for 81.08% of the output lead, lead bullion stock accounted for 9.96%, emissions (including lead loss) accounted for 8.96%. The results also showed that the production process of Scenario II concentrated more lead than did Scenario I. Four lead-loss flows, which accounted for only 4.69% of the output substance flows, were found to determine whether the smelting process of Scenario I diluted or concentrated the lead. The uncontrolled lead-containing dust and gas emissions from the processes of casting, reverberatory furnace, and primary smelting are cause for concern. This lead loss from uncontrolled emissions and measurement errors has been long ignored, but should be given top priority for pollution prevention and the control of heavy metals in the lead smelting industry. Some recommendations for improving heavy-metal controls in production enterprises are put forward at the end of this article.

1. Introduction

Material flow analysis (MFA) and substance flow analysis (SFA) are analytical methods used to systematically assess the flow and stock of a material or substance through a given system (productive, economic or social) that can be clearly defined in space and time. Since the mid-1990s, analyses of material flows through regional economies, from the highest level – economic regions such as the European Union – down to the lowest level – individual enterprises, have been addressed using MFA (Stefan Bringezu, 2003). MFA, then, has become a fast-growing field of research with increasing policy relevance. There have been several parallel developments in MFA since its introduction as a decision-support tool in resource management, waste management, and environmental management, resulting in diverse usages and meanings of both MFA and SFA.

Because the term “material” can refer to both substance and goods, SFA can be seen as a specific type of MFA. Here the term “substance” means any (chemical) element or compound composed of uniform units (Brunner and Rechberger, 2004). Material flow analysis encompasses product flow accounting, material balance, and total material flow accounting, while substance flow analysis includes element and chemical flow analysis (Chancerel et al., 2009).

Both MFA and SFA studies claim to contribute to sustaining industrial metabolism and resource utilization. However, the two methods used to pursue that aim are quite different. MFA usually starts with the question of whether the volume and structure of the throughput of selected sectors or regions is sustainable. For instance, total or main throughputs, or the mass flow balance of a city, region or national economy, are studied to determine

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structural properties of the regional metabolism. SFA, on the other hand, usually starts with specific problems related to selected substances. For example, the flows of eco-toxic heavy metals are studied because these substances are associated with environmental problems (e.g. through accumulation) (Stefan Bringezu, 2003).

SFA provides indicators of pressure and can be used to efficiently track the substances released to different environmental compartments (Loiseau et al., 2012). SFA also has a clear role as a tool for assessing flows and impacts of chemical substances (Finnveden and Moberg, 2005). The flows are composed of inflows, outflows and stocks (quantities of substances accumulated in the products in the study area) (Jonsson et al., 2008).

Previous studies using SFA were conducted mainly to analyze flows of metals (lead, copper, zinc, etc.) on a very large system boundary, such as at the local (Palmquist, 2004; Lindqvist and von Malmborg, 2004), regional (Igarashi et al., 2007; Tabayashi et al., 2008; Lifset et al., 2012; Cha et al., 2013), or global scale (Mao and Graedel, 2009; Elshkaki and Graedel, 2013). SFA has also been applied to some production processes, such as material and energy inputs into microchip manufacturing processes (You et al., 2001), the mass balance of waste water volume in a semiconductor factory (Williams et al., 2003), or material and energy flows in iron and steel manufacturing (Yu et al., 2007; Zhang et al., 2013). In recent years, SFA has been conducted on a process level, such as for the assessment of precious metal flows during the preprocessing of waste electronic (Chancerel et al., 2009), and electrical equipment (Oguchi et al., 2012).

Almost all these studies outlined above took advantage of the quantity function of SFA to focus on the efficiency of substances or resources. Emission control and pollution prevention were neglected, or at least not the first concern in these studies. SFA, however, is one of the most useful tools for realizing the goal of pollution prevention and control on production processes, especially for those raw materials or products containing hazardous or noxious substances. Although SFA does not provide a sufficiently detailed base for decision-making, it does give relevant information on the relative magnitude of pollution, and can reveal unsuspected losses (Antikainen, 2007).

It should also be mentioned that SFA is an indispensable first step and a necessary base for many tasks, but alone it is not a sufficient tool for assessing or supporting engineering or management measures. It should be followed by an evaluation or design step. Statistical entropy analysis (SEA) is such a method, tailor-made for SFA. It considers all the information from an SFA and requires little additional computing (Brunner and Rechberger, 2004). This method provides a tool for quantitative analysis of variations in the congregating extent of a substance during a process in a system. The idea of applying statistical entropy to SFA results was developed at the Vienna University of Technology (Rechberger, 1999). The concept of entropy can be seen as an indicator of how efficient a process is utilizing the natural resources. Entropy analysis therefore is introduced as an analytical method for many resource consumption studies. Up till now, there are two perspectives of entropy analysis in a system. One is carried out from the material or substance point of view. In these studies, entropy analysis is usually based on the MFA or SFA results of the system. For instance, it has been applied to researches of copper cycles in Europe and China to discuss the resource management problem of copper (Rechberger and Graedel, 2002; Yue et al., 2009). It also has been applied to process such as waste treatment process to improve the waste management (Brunner and Rechberger, 2004). The other is carried out from the thermodynamic point of view. For example, the entropy analysis has been tested in case studies of copper production process and integrated biomass utilization system to discuss the entropy generation of the investigated system. (Gößling-Reisemann, 2008a,b; Samieia and Fröling, 2014). Since the SEA is used as a tailor-made for SFA in this paper, the former perspective of applying entropy analysis shares the same approach with this study.

Lead smelting is a process for reducing and refining lead compounds to elemental lead in a series of high-temperature furnaces, where the lead is mixed with other heavy metals such as Zn, Hg, As, Cd, Au, Cu, etc. There were several lead-pollution incidents in China during the years 2008–2010. Lead blood levels in human populations, especially children in certain communities (mostly villages) sharply increased. In some of these incidents it was found that a nearby lead smelting factory bore most of the responsibility. Lead-containing substances generated in the production process of the lead smelting factory were emitted to air and water without timely or correct treatment. Since these incidents, increasing attention has been drawn to lead contamination prevention and quality control in lead smelting factories. As smelting technology continues to be upgraded, pollution controls in the production process have been steadily improving. Still, many problems remain unresolved: for example, the internal environment of the smelting factory, which endangers workers' health. Hence, a detailed SFA of a lead smelting process could improve our understanding of the activity and effects of heavy metals (especially lead) throughout the factory.

The paper is organized as follows. In Section 2, the steps of applying SEA were carefully introduced. In Sections 3 and 4, a typical lead smelting process was worked out by SFA and SEA. A Pb substance flow chart of the typical lead smelting process was sketched out, the mass balance and uncertainty was also discussed. SEA was applied according to the mass balance results of each process. Particular substance flows were discussed in the paper to check out the SEA results. Some recommendations to improve the lead smelting process were put forward in the last part.

2. Methodology

2.1. A step-wise framework of SFA

Although SFA methodology has not been standardized like the ISO14040 of Life Cycle Assessment (LCA), several proposals have been put forward, on how to implement an SFA. Udo de Haes et al. suggests that SFA should be implemented in three steps (Udo de Haes et al., 1997). First, define the objectives (identification of pollution sources, stocks and missing flows, loops etc.) and the system (substance choices, system boundaries, economic and environmental subsystems, etc.). Secondly, perform an inventory, either by computing all the relevant flows with the aid of a flow chart, or by using stationary or dynamic modeling. The third and last step involves interpreting the results, which are presented as a set of flows and stocks. Brunner et al. suggests that the MFA and SFA process should include six basic steps. The first is definition of research objective and selection of monitoring indicators. The second is system definition – including scope, boundaries, and time frame. The third is identification of relevant flows, processes, and stocks. The fourth is design of material or substance flow chart. The last two steps are mass balancing and interpretation of results (Brunner and Rechberger, 2004; Huang et al., 2012).

Generally, the five basic steps – definition, identification, mass balancing, evaluation and interpretation – are indispensable in SFA, as shown in the step-wise framework of SFA in Fig. 1.

2.2. Statistical entropy analysis

An SFA of a system consists of analyzing one or more processes and substance flows. A process denotes the transformation, transport, or storage of substances. Thus a substance flow system can be viewed as a unit (or a series of units) that concentrates, dilutes, or leaves unchanged its throughput of substance, meaning that the