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Substance flow analysis of production process: a case study of a lead smelting process

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A R T I C L E I N F O

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A B S T R A C T

The metabolism of a production process can be researched by identifying all the material or substances that flow into or out of the production system. Effective methods for tracing the material and substance destinations and quantities in a system could determine the metabolism efficiency and the pathways through which pollutants are generated and emitted—very useful information for the resource and environmental management of a factory, particularly for pollution prevention and control. In this study, substance flow analysis (SFA), an analytical tool, was applied in a lead production system. To apply SFA in the lead smelting process, the framework for applying SFA in a typical lead smelting system was outlined, and a substance flow chart model of a single process and the entire system were developed. Lead was selected as the objective substance, and all lead-containing material flows were sampled and tested. The lead substance balance account of each process and the entire system were established based on producing one ton of final product: lead ingot. The unsuspected losses of the system were viewed as a kind of virtual substance flow. Several indicators—such as process rejection rate, process waste circulation rate, resource efficiency—were set up to evaluate the metabolism efficiency of the system. The result shows that the lead resource efficiency of the investigated production process was 81.28% and the total resource efficiency was 85.02%. Furthermore, to produce one ton of lead ingot, 0.0466 t of the solid waste generated was reused in other systems instead of being discharged into the environment. While 0.0062 −0.0641 t lead was discharged or emitted into the environment, taking into consideration of unsuspected losses. Pollutant prevention and control could benefit both resource utilization and environmental protection for the lead smelting production. Some recommendations for improving emission control and pollution prevention for a lead smelting factory are put forward in the conclusions of this study.

1. Introduction

Substance flow analysis (SFA), as an analytical method, can systematically assess the flows and stocks of a material or substance through a given system that be clearly defined in space and time (e.g. production, economic or social system). SFA also can be used to efficiently track substances released to different environmental compartments (Loiseau et al., 2012), and is especially useful for assessing flows and impacts of chemical substances (Finnveden and Moberg, 2005). Moreover, SFA can also provide relevant information on the relative magnitude of pollution and reveal unsuspected losses (Antikainen, 2007). Therefore SFA has become a widely used policy decision support tool in many fields, including process control, resource management, waste treatment, environmental management, product design, and life cycle assessment (Udo de Haes et al., 1997).

As far as we know, SFA has been used mostly to analyze flows of substances, particularly metals (lead, copper, zinc, etc.), over very large areas, at the local (PALMQUIST et al., 2004; Lindqvist et al., 2004), regional (Igarashi et al., 2007; Tabayashi et al., 2009; Lifset et al., 2012; Cha et al., 2013), or global scale (Mao et al., 2009; Elshkaki et al., 2013). Recently, SFA has also been used to investigate hazardous materials for environmental risk assessment and management (Chèvre et al., 2013; Eriksson et al., 2008; Earnshaw et al., 2013; Herva et al., 2012; Long et al., 2013; Oguchi et al., 2012; Huang et al., 2014). SFA has also been applied, meanwhile,

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to small systems such as a production process. You et al. studied the mass balance of wastewater to evaluate the appropriateness and effectiveness of reusing it to cool a semiconductor plant (You et al., 2001). Williams et al. studied the material and energy inputs into microchip manufacturing (Williams et al., 2002). Yu et al. used SFA to research the material and energy flows in iron and steel manufacturing (Yu et al., 2007; Zhang et al., 2013). Leo et al. applied SFA to the waste from a small electrical and electronic equipment recycling plant to study transfer coefficients for selected metals (Cu, Sb, Hg etc.) and non-metals (Cl, Br, P) and PCBs (Leo et al., 2007). Chancerel et al. conducted SFA to evaluate precious metal flows during the preprocessing of waste electronic equipment (Chancerel et al., 2009). Oguchi et al. studied the toxic metals in the electrical equipment in waste treatment processes using SFA (Oguchi et al., 2012).

The quantity function of SFA and improving resource efficiency of a particular substance in a system were the first concerns of almost all these studies. Moreover, the quantity information of the substance flows' flux and distribution could also indicate and provide the pollution prevention strategies for hazardous materials management. In fact, SFA is one of the most useful tools for pollution prevention and control in production processes, especially for a system that contains hazardous or noxious substances such as heavy metals. These metals are key concerns in environmental policy and management because they pose risks and have negative impacts on human health and ecosystems. Because of their poor decomposition capabilities, heavy metals, especially lead, tend to accumulate in the natural environment, and will eventually affect human beings exposed to the contaminated air, water, soil and even food. Given the accumulating scientific evidence of adverse health effects at lower blood lead levels and the absence of a known toxicity threshold, lead exposure needs to be taken more seriously as a public health concern (Anne et al., 2014; Canfield et al., 2003; Jusko et al., 2008; Lanphear et al., 2000).

SFA was used in this study as an analytical tool for emission control and pollution prevention in a lead production system. Lead was selected as the objective substance, and the lead mass balance account was established and evaluated by indicators put forward here. Unsuspected losses from the system were determined and evaluated using the quantity function of SFA.

2. Methodology: applying SFA in a production process

2.1. A step-wise framework of SFA

No standard methodology of SFA, comparable to the ISO14040 of Life Cycle Assessment (LCA), has yet been formed. However several proposals for applying SFA have been put forward. Udo de Haes et al. suggested that SFA should be implemented in three steps (Udo de Haes et al., 1997). The first step consists in defining the objectives (identification of pollution sources, stocks and missing flows, loops etc.) and the system (substance choices, system boundaries, economic and environmental subsystems, etc.). Then the inventory is determined, either by computing all the relevant flows with the aid of a flow chart, or by using a stationary or dynamic model. The last step involves interpreting the results, which are presented as a set of flows and stocks.

Brunner et al. suggested that the M/SFA process include the following six basic steps (Brunner et al., 2004; Huang et al., 2012):

(1) Definition of research objective and selection of monitoring indicators;
(2) System definition including scope, boundaries, and time frame;
(3) Identification of relevant flows, processes, and stocks;
(4) Design of material or substance flow chart;
(5) Mass balancing; and
(6) Illustration and interpretation of results, and conclusions.

The steps of definition, identification, mass balancing, and interpretation are indispensable in SFA. In addition, evaluation of the substance using specific indicators or methods is usually necessary. A step-wise framework for SFA is shown in Fig. 1.

2.2. Identification of SFA

Compared to applying SFA on a global, regional or local scale, applying SFA to a production process of an enterprise is more microcosmic and more specific. The entire production process of any industry, particularly a manufacturing industry, is composed of a series of processes, and industries like iron and steel manufacturing and non-ferrous metal metallurgy are typical in this regard. Correspondingly, the SFA model of a production process is composed of two parts: a substance flow chart of a single process and a substance flow chart of the entire process (Du, 2005).

2.2.1. Substance flow chart model of a single process

If we trace all the materials input to and output from a single process within the system boundary defining the workshop of process j, it can be concluded that six kinds of substance flows constitute the substance flow model of process j. The six kinds of substance flows are explained below and shown in Fig. 2.

① Input upstream products substance flow, p_{j-1}, refers to the product needs of process j from process $j-1$.
② Input material flow, α_j, refers to the raw materials fed into process j.
③ Circular substance flow, β_j, refers to the all the circular substance flows related to process j. There are three kinds of circular substance flows. The first one is called inner circular flow, $\beta_{j,j}$, meaning that the substance flow is only recycled within process j, from the end of process j back to the beginning; the second one is called upstream circular flow, $\beta_{j,k}$, meaning that the substance flow is reused by the upstream processes; the third one is called downstream circular flow, $\beta_{m,j}$, meaning that the substance flow is reused from downstream back to process j.
④ Emission substance flow, γ_j, refers to the waste substances leaving the system without including in the products to the up or down streams. It is usually composed of three parts: by-products, pollutants discharged into the environment, and unsuspected losses in process j. In some production systems, especially in the metallurgy industry, most of the wastes produced by process j can be reused in other systems; hence these reused wastes are viewed as by-products.
⑤ Stock substance flow, θ_j, refers to the qualified products that are not converted to the final product in the production process. These products are simply stocked in the warehouse of the factory, waiting to put back into the production line when they are needed.
⑥ Output substance, p_j, refers to the qualified product produced in process j that is transferred on to process j+l.

According to the principle of conservation of mass, for a single process j, there is:

$$p_{j-1} + \alpha_j + \beta_{j,j} + \beta_{m,j} = p_j + \gamma_j + \beta_{j,j} + \beta_{j,k} + \theta_j \quad (1)$$