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Morphology and coupling of environmental boundaries in an iron and steel industrial system for modelling metabolic behaviours of mass and energy

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ABSTRACT

Iron and steel processing is a complicated system in which various processing units and environmental boundaries exist. Mass and energy metabolize on those environmental boundaries. The morphology of an environmental boundary can shape how mass and energy interact in an iron and steel industrial system. Environmental boundaries in these situations couple all subsystems together to constitute an integrating system in the form of a hierarchical model. The metabolic behaviours are simulated and optimized by using the genetic algorithm of NSGA-II based on the energy intensity indicator under the conservation law of mass and energy. The hierarchical morphology and coupling styles of environmental boundaries in an iron and steel industrial system are fully demonstrated through the characterization of the metabolic behaviours of mass and energy. This study is based on a comparison of the computed values of metabolic behaviours with actual data from an iron and steel company located in the East of China. This investigation shows that the morphological and coupling model of environmental boundary is valid for a complex iron and steel industrial system. This will lead to better resource allocation and more environmental benefits.

1. Introduction

The over-consumption of natural resources in the iron and steel industry often results in a severe environmental contamination. The systemic conservation for mass and energy running in the industrial system, instead of the end-of-pipe treatment for local processes or devices, is vital for the reduction of resource consumptions and environmental emissions. Many systemic approaches have been applied to analyze the energy and mass activities in the iron and steel industry (Katarina Lundkvist et al., 2013). The Input–Output Process Model (IOPM) and the inventory analysis is often used to analyze the life cycle of a product especially on environmental impacts and energy flow analysis. A cokemaking process-flow model based on an improved IOPM was built by Polenske et al. to study resource efficiency and emission impacts of the cokemaking sector. The investigation analysed mass and energy flow and pollution generation through a micro-level examination of three alternative cokemaking technologies in China (Karen R. Polenske and Michael, 2002). Dong evaluated and compared the amount, scale, the related environmental and economic benefits of the industrial symbiosis activities in the steelmaking industrial areas in China and Japan. A quantified Life Cycle Assessment (LCA) method by segmenting the systemic boundaries of the symbiotic industry was applied (Liang Dong et al., 2013). Burchart-Korol defined the major sources of environmental impacts and performed a LCA for steel productions, relevant fuel consumptions and the Green House Gas (GHG) emissions in Poland (Dorota Burchart-Korol, 2013). Yellishetty et al. examined a case of the steel industry using LCA and provided useful insights on potential future threat of shortages due to depletion of abiotic mineral resources (Mohan Yellishetty et al., 2011). It is quite clear that LCA and the inventory analysis with a quantified approach are generally applied to gain an in-depth understanding on the environmental impacts of industrial systems.

The concept of the system boundary is applied in the field of LCA and environmental sustainability analysis for various industrial

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systems. Wang et al. indicated that expanded system boundary under various considerations which resulted in various environmental estimations for various industrial productions (Lei Wang et al., 2012). Roer also found the validity of comparisons of GWP (Global Warming Potential) impacts with other studies was lower due to differences in allocation and system boundaries of the agricultural productions (Anne-Grete Roer et al., 2013). As for the iron and steel industries, Tanaka illustrated the critical role of proper boundary definitions for a meaningful assessment of energy efficiency in Japanese iron and steel industry (Kanako Tanaka, 2008). Hasanbeigi built a Conservation Supply Curve (CSC) model with a bottom–up sensitivity analysis and predicted the potential capacity of energy conservation and the volume of CO_2 emission for the Chinese steel industry from 2010 to 2030 (Ali Hasanbeigi et al., 2013). Moya et al. conducted an analogical research on the financial aspects of environmental impacts (José Antonio Moya and Nicolás Pardo, 2013). Berkeley National Laboratory, jointly with China Iron and Steel Research Institute, proposed a method for the boundary definition and compared the energy intensity and efficiency of the iron and steel industry in China with the US. It aimed at constructing a universal and accurate framework to obtain boundary definition of iron and steel industrial system, energy conversion coefficient design and resource efficiency indicators (Ali Hasanbeigi et al., 2014). Parallel studies on energy efficiency improvements and emission reduction potentials were also conducted for Indian iron and steel industry (William R. Morrow III et al., 2014).

Yin et al., studied the interface technologies for the blast furnace-convertor. They investigated time analysis for various processing interfaces and the computation model for sector energy consumption and environmental loads as well as the quantitative analytic approaches for energy flows in a large scaled metallurgical system (Xiuping Li, 2005; Xiuping Li et al., 2006; Jian Qiu et al., 2005; Jian Qiu and Naiyuan Tian, 2005). Essentially, a generic engineering approach was adopted to link, match, balance and stabilize all elementary parameters of mass energy behaviours and flows, including the temperature and duration of the metallurgical processes (Ruiyu Yin, 2009). Analogous studies were made by Lu, with specific attention on the relations between the internal mechanics and the surrounding environmental loads. Processing technologies, optimization of mass and energy flows, LCA and the systemic ideas on the industrial ecology were all considered in energy conservation and emission reduction (Zhongwu Lu and Jiuju Cai, 2010). A tracing observation method based on the common features of fluid flow and mass flow was adopted to derive a set of equations with the indexes of mass flows under different steady or transient state conditions (Zhongwu Lu, 2006). Such advanced in the iron and steel industry research are significant although mesoscopic simulation for the industrial system remain outstanding.

Generally, most of the flow analysis approach and models mentioned earlier are more suitable for analyzing or simulating an industrial system in a macroscopic rather than a mesoscopic perspective. With reference to previous research, especially the concept of systemic energy conservation and interface technology, a new mathematical modelling approach is proposed for the morphology and coupling style of environmental boundaries for complex steel industrial systems. The metabolic behaviours of mass and energy in the industrial system are optimized with the application of the morphology and coupling model of environmental boundaries. The new model offers applicable and quantitative means to distinguish the metabolic behaviour vectors of each subsystem and is capable of coupling all of them into a macro-system in a bottom-up progression. The mass and energy states in the hierarchical system are computed and analysed in order to identify the fundamental metabolic behaviours occurring on environmental boundaries. This investigation offers a quantified approach to building up a bridge across the macro and micro systems as well as the steel industry and the natural environment. This approach is also beneficial for optimizing resource allocation and production parameters within the context of energy conservation and environmental impact.

2. Generic morphology of environmental boundary in an industrial system

2.1. Definition of environmental boundary

System boundary is an abstract concept and it is different for different scientific disciplines. Dixit gave a generic definition of system boundary for the calculation of embodied energy over the life cycle of buildings. The system boundaries was regarded the same as the stages of the life cycle (Manish K. Dixit et al., 2013). Many literature (Miller AJ., 2001; Edwards and Bennett, 2003; Khasreen MM et al., 2009) applied the term of system boundary in LCA, however, very few of them discussed the detailed quantitative or mathematical concept of system boundary.

Generally, system boundary refers to the limits of coverage as defined by some physical and chemical laws of mass and energy. It also distinguishes the objective system from the surrounding systems. The physical field could change drastically or discontinuously across the system boundary. The surrounding systems could be either the natural ecological environment or the artificial environment relevant to the objective system. The system boundary between the industrial system and the surrounding systems as indicated by the metabolic behaviours of mass and energy is defined as the environmental boundary. Actually it is a special system boundary whose morphology is only indicated by massive metabolic behaviours of mass and energy. Different from the system boundary, the environmental boundary is a concept in a relative narrow sense, it is neither an entity concept, nor a physical boundary to divide the systems. It is usually concerned with the scope definition for an industrial system and involves interaction with the surrounding system through mass and energy metabolization.

To characterize the metabolic behaviours of mass and energy quantitatively, it is necessary to analyze and discretize the steel industrial system into separate and hierarchical subsystems with the consideration of environmental boundary. These subsystems consist of processes, equipments, materials and energy. They distinguish themselves from other subsystems and natural environment with the environmental boundaries. Environmental boundaries are used to clarify the scopes and scales of the systems and facilitate the identification of the operational laws of mass and energy in an industrial system. Environmental boundaries organized in a systematic morphology will maximize the utilization of resources as well as minimize the environmental impacts to a wider extent. Environmental boundary can be represented by a set of mass and energy variables which can be tested, monitored and controlled when mass and energy metabolize between the industrial system and the surrounding systems. The morphological characterization of the environmental boundary and the associated mathematical model can be used to discover the primary laws of metabolic behaviours of the input and output of the industrial system. A generic morphology of the environmental boundary in an industrial system is shown in Fig. 1.

The environmental boundary consists of the physical channels and surfaces between the executive system and the surrounding system. Physical channel allows the executive system import or export the mass, energy and information. The physical surface isolates mass and energy by some physical devices and operates them in the executive system to complete their transforming processes. The environmental boundary distinguishes the executive system