THE EMERGY ANALYSIS OF MULTI-PRODUCT SYSTEMS

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Abstract: Emergy analysis can analyse the resource utilization and environmental performance of a system. The majority of the process industry systems belong to multi-product systems, but mistakes often occur when emergy analysis is carried out to a multi-product system due to misunderstanding of the emergy concept and lack of understanding of the system structure. To avoid the mistakes, multi-product systems are classified into two categories: inseparable multi-product systems and semi-independent multi-product systems, both of which are theoretically distinguished, and a systematic procedure of emergy analysis is proposed to avoid mistakes. Finally, a case study of biodiesel production is adopted to demonstrate the methods.

Keywords: emergy; multi-product system; sustainable development; process industry.

INTRODUCTION

Sustainability has apparently become a vital issue for long-term industrial development and effective environmental protection, because of wider awareness of the following two factors: (1) there is limited availability of non-renewable resources and (2) there are limits to the biosphere's ability to adsorb wastes. Clearly, criteria of sustainability must include net energy, material, environmental loading, and so on. Because the inputs to a system are composed of energy, material, equipment and services, these different inputs cannot be compared on or summed by only energy quantity. To overcome this problem, Odum (1971), proposed the concept of solar emergy as a measure of the total environmental support to processes in the biosphere. The solar emergy is defined as the sum of all inputs of solar exergy either directly or indirectly required in a process. The units of solar emergy are solar emjoules derived from solar embodied energy joules and have the abbreviation sej. Input flows that are not from a solar source (like geothermal and gravitational flows) are expressed as solar equivalent exergy by means of suitable transformation coefficients, i.e., transformity (Tr). The emergy value is a 'memory' of resources invested over all processes leading to a product. Emergy analysis provides a common platform to quantitatively express economic values, as well as environmental factors. It facilitates the comparison of the economic and environmental status of different entities on a common ground.

Many researchers have applied the emergy theory to eco-economic systems in recent years. Ulgiati and Brown (2002) proposed an emergy-based method to quantitatively study the function of the environment in absorbing and diluting byproducts generated by a process. Bakshi (2000) introduced an emergy analysis method for industrial systems, where waste treatment was considered. The wastes are handled not only by an end-of-pipe treatment approach and ecosystem dilution, but also by waste reuse techniques, and therefore waste reuse in different ways should be considered in industrial systems. A new emergy analysis method, which considered waste treatment and reuse, was proposed by Yang *et al.* (2003). Brown and Buranakarn (2003) evaluated the emergy used in the life cycles of major building materials as well as the emergy inputs to waste disposal and recycle systems. A new sustainable development index (SDI), proposed by Lu *et al.* (2003), considered not only the ratio of the sum of inputs from the economy (F) and non-renewable resources (N) to renewable resources (R), but also the pollutants grade. Wang *et al.* (2006) applied emergy analysis to the systematic evaluation of a CHP plant EIP (combined heat and power plant eco-industrial park). Modified emergy indices for a CHP plant EIP, considering both material circulation and energy cascade utilization and clean energy technology, were presented. Lou *et al.* (2004) introduced a set of new sustainability indices to assess the environmental and economic performances as well as the sustainability of

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DOI: 10.1205/psep07007

0957–5820/07/
$30.00 + 0.00

Process Safety and Environmental Protection

Trans IChemE,
Part B, September 2007

industrial systems in a uniform structure. As compared to the existing emergy-based sustainability indices that originated from the study on agricultural or nature ecological systems, the newly defined indices improved the applicability and the effectiveness of the existing indices by addressing the unique features of industrial systems systematically. Feng *et al.* (2005) proposed joint indices and weighted average indices to compare co-generation systems and individual systems which produce one product.

In addition, there were some researchers combining emergy with traditional sustainability assessment methods. Brown and Buranakarn (2003) combined emergy with LCA (life cycle assessment), which has been mentioned above. Zhao *et al.* (2005) combined emergy with ecological footprint to form a modified ecological footprint and applied it to analyse an eco-economic system of the Gansu province in China. Singh and Lou (2006) defined the improvement of economic and environmental sustainability of IEs (industrial ecosystems) as a multi-objective optimization problem and introduced a novel Hierarchical Pareto Optimization Methodology to achieve the most sustainable solution.

Clearly, the majority of the current emergy research belongs to the macro aspects, i.e., applying existing or newly defined emergy indices to assess the sustainability of an industrial system or to compare some different systems by giving a holistic evaluation. However, due to the complexity of the process industry and interactions between different energy and material flows, some mistakes, which lead to unreasonable conclusion and weaken the capability of emergy analysis to guide practical production, often occur in the emergy analysis, especially for the emergy analysis of a multi-product system. For example, Yang *et al.* (2003) studied a coal gasification process, whose byproducts are brick and methanol. It is not reasonable that the emergy for brick production and methanol production was included in the emergy for coal gas gasification. This is because brick production and methanol production are the subsequent processes of coal gasification, and thus the emergy for brick production and methanol production does not influence the emergy for coal gas gasification. Although the rules of emergy analysis were discussed by Brown and Herendeen (1996) in their emergy accounting procedures (emergy algebra), they were too general and ambiguous to be of general use and there is no practical production example to support them. Furthermore, some of the rules are not complete, e.g., the rules of the emergy analysis of a multi-product system. To overcome these problems and apply the emergy theory more efficiently, in this paper, the structure that is most likely to lead to mistakes in emergy analysis—multi-product system—is discussed in detail. In other words, the mistakes themselves, the reason for the mistakes and how to avoid them are theoretically analysed and demonstrated.

THE DEFINITION OF THE TWO CATEGORIES OF MULTI-PRODUCT SYSTEM

For accurate analysis, multi-product systems shown in Figure 1 are classified into two categories: inseparable multi-product systems and semi-independent multi-product systems. In Figure 1, N, R and F represent non-renewable emergy inputs, renewable emergy inputs and purchased inputs from outside the system, respectively. P_i represents product i. An inseparable multi-product system can be defined as a production system whose different products cannot be produced individually, i.e., it is impossible to produce one product without producing other products. The biodiesel production through transesterification of soybean oil triacylglycerols with methanol, cogenerating glycerol, is an example of an inseparable multi-product system because biodiesel and glycerol are the products of one and the same chemical reaction. Oppositely, a semi-independent multi-product system can be defined as a production system whose different products can be produced individually, i.e., some products can be produced without producing others. For example, if a chlor-alkali enterprise is taken as a production system, the products of the electrolysis of brine—chlorine gas, hydrogen gas and sodium hydroxide—and PVC (polyvinyl chloride) will be the yields of this system. In this production system, PVC polymerization must use hydrochloric, which is the product of chemical combination reaction of chlorine gas and hydrogen gas. Whether to produce PVC or not is not determined by the production technology, because PVC polymerization and the electrolysis of brine are two different chemical reactions. That is to say, the chlor-alkali enterprise can produce only the products of the electrolysis of brine without producing PVC. Therefore, this enterprise is an example of a semi-independent multi-product system in terms of the products from the electrolytic cell and PVC.

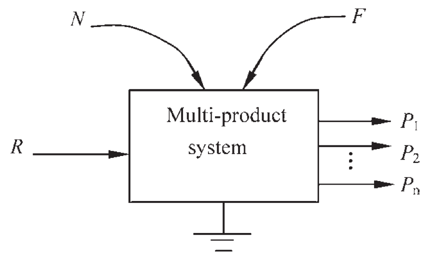

Figure 1. Chart of a multi-product system.

INSEPARABLE MULTI-PRODUCT SYSTEMS

Easily Made Mistakes

Influenced by the law of energy conservation, people often think that the entire input energy of a multi-product system could be apportioned to each product based on a certain relationship. For instance, the energy consumption can be apportioned on a mass basis over the outputs of a system (Boustead and Hancock, 1979). However, only when all the products are similar (e.g., the hydrocarbons produced from crude oil), can this kind of method, apportioning energy consumption based on a certain relationship, be adopted. Szargut and Morris (1987) also pointed out only when the production method in a complex process is the same for all products, can the partition of exergy consumption be based upon the exergy values of useful products. As far as a inseparable multi-product system is concerned, the production method is the same for all products. Therefore, some people think that, according to Boustead and Hancock (1979) and Szargut and Morris (1987), the entire input emergy of an inseparable multi-product system seems to be apportioned on a exergy or mass basis over the outputs.