Chapter II
Industrial Metabolism:
Materials and Energy Flow Studies

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ABSTRACT

This chapter introduces the concept of quantitative physical flow analysis, known as industrial metabolism, which is a basis for modeling the environmental impact of products in the course of their life-cycles. This also includes a discussion of the reverse product-process chain, which includes reuse and recycling. Apart from transformation of materials, also transformation of energy is discussed. This is followed by the introduction of gross energy requirement. After this, the life-cycle assessment method is explained. After this, a section on available types of software is presented, followed by some examples from practice that illustrate the value of quantitative modeling. Finally, some future trends are discussed and a conclusion is given.

INTRODUCTION

Design and management of environmentally conscious products and production processes has various aspects that require a multidisciplinary approach. As the complete life-cycle of products has to be considered for a thorough analysis, which is a prerequisite in assessing the environmental performance of a product, the problem grows still more complicated. Because dealing with all those aspects in a satisfactory way is hardly possible, we are obliged to restrict our approach to those aspects of the reality that are particularly relevant to our purposes, thus simplifying the reality by means of modeling. Such models thus do not provide us with the complete truth, but modeling opens the way toward investigating some relationships that cannot be made available by other ways.

The aspects that are highlighted in this chapter refer to the physical basis that is inherent to the production of commodities and the impact that this has on the environment. This manifests itself by the fact that the relation of the product's life-cycle with its environment is understood in terms of materials and energy flows. In frequently used environmental analysis techniques, such as life-cycle assessment, the analysis of materials and energy flows is at the basis of these methods.

Such an approach is incorporated in *industrial metabolism*, which is a subdomain of *industrial ecology*, although some confusion on the precise use of these concepts can be detected in the literature.

INDUSTRIAL ECOLOGY AND INDUSTRIAL METABOLISM

The Origin of Industrial Ecology

Industrial ecology is an approach to minimize the environmental impact of human economic activities by means of mimicking the nature, which implies that no finite resources are consumed and no waste is produced.

The history of industrial ecology has its roots in growing consciousness about the finiteness of the natural resources that provide us with a supply of raw materials. Confronted with a growing population and with the globally rapidly increasing pro capita consumption, science has long attempted to quantify the impact of these phenomena. An early attempt has been made by Thomas R. Malthus, who published in 1798 a rather pessimistic vision in his principal work: *"An essay on the principle of population*." He argued that the linear growth in possible (agricultural) resources was never able to cope with the requirements of an exponentially growing population. Later on, other scientists have developed various alternative theories, some of them optimistic and other rather pessimistic. In the sixties of the 20th century, for instance, some extremely optimistic opinions were published, from which Herman Kahn was a notorious exponent (see, e.g., Kahn & Wiener, 1967).

In the same years, more worried authors, who observed overuse of natural resources, started to publish. Since the Apollo project brought men in space, who saw the Earth as a tiny and vulnerable sphere, called *"spaceship Earth*," people such as Buckminster Fuller (1963) and Kenneth Boulding (1966) were inspired to formulate criticism on those optimistic and careless attitudes: *"Anyone who believes exponential growth can go on forever is either a madman or an economist*." Boulding's plea was to reconsider the physical roots of economy. These can be found in the first and second law of thermodynamics, which refer to energy conservation and to growing disorder, respectively. The way of thinking with regard to this postulate is called *neo-Malthusianism*.

The Report of the Club of Rome (Meadows, Meadows, & Randers, 1972) soon confronted a more extended public with the results of such studies. In this report, a dynamic modeling approach has been utilized aimed at forecasting the future according to a variety of scenarios. About in the same time, the term *"industrial ecology"* had been coined by Evan (1974), who advocated a broad, multi-disciplinary approach with an emphasis on social sciences.

Later on, possibly unaware of Evan's work, a more dedicated interpretation of this term had been proposed, particularly by Frosch and Gallopoulos (1989), who referred to a globally organized closed-cycle economy. The drastic restructuring of industrial processes was considered a crucial condition for attaining this objective. The term *"industrial ecology'* was assigned to the attempt for mimicking the natural processes in the industrial system, particularly the use of renewable energy resources and the closing of materials cycles. The authors stressed that no waste was produced in the natural environment, but instead, everything was recycled. The authors stated this as follows: *"Wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment*."

In the same couple of years, the related concept of *sustainability* was introduced by Brundtland (1987). Awareness of this originally came from development economics: It is intended to meet the needs of the present generation in such a way that

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