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# Changing Industrial Metabolism: Methods for Analysis

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Research in the field of "industrial metabolism" traditionally has been focused on measuring and describing physical flows of economic systems. The "metabolism" of economic systems, however, changes over time, and measuring material flows is insufficient to understand this process. Understanding the relation between economic activities and material flows can help to unravel the socio-economic causes of these physical flows. Three issues are addressed: The importance of spatial scales and trade flows, empirical analysis of relations between economic development and material flows, and treatment of behaviour of and interactions between stakeholders. For each of these issues, methods for analysis are suggested.

**KEY WORDS:** industrial metabolism; material flows; structural decomposition.

## 1. INTRODUCTION

On a physical level economic systems import material and energy resources, process them into usable forms, and reprocess and export wastes. The total of such physical processes has been referred to as *industrial metabolism* (Ayres & Simonis, 1994). Metabolism in the biological context refers to the internal processes of a living organism. The organism needs

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energy-rich, low entropy materials (food) to provide for its own maintenance and functions, as well as to permit growth of high-entropy materials. In analogy with biological metabolism we can consider the metabolism of industrial activities as the total of physical processes that convert raw materials and energy into finished products and wastes. In this paper we will focus on materials and not include energy explicitly.

The concept of industrial metabolism is interesting for ecological economics since it analyses material flows from an integrated perspective, allowing the study of system-wide effects and problem shifting due to environmental policies. Case studies are done at various scales ranging from the country level (Ayres & Simones, 1994), to the household level (Noorman & Schoot Uiterkamp, 1998).

An important difference between the metabolism of economic systems and that of organisms is the fact that the metabolism mechanism of economic systems changes over time. In fact, this has happened during the whole history of mankind, from the 'stone' age to the 'information' age. Nowadays, mankind produces new materials, transports material all over the globe, and, as a consequence, disturbs biogeochemical cycles.

Research on industrial metabolism has focused on *the description of material flows* in economic systems (see, for example, the case studies in Ayres and Simonis, 1994). Studies along these lines provide interesting and useful insights on the size of material flows and the identification of stocks in which certain materials accumulate. This leads to concepts like "chemical time-bombs" (accumulation of chemicals in the mud of rivers) and "waste mining" (materials accumulating in cities can become an important resource for the future) (Stigliani et al., 1991; Rohatgi et al., 1998). However, several issues cannot be addressed properly with such a descriptive approach. An analytical approach requires that attention should be given to: the material flows between regions; the empirical relation between economic activities and material flows; and the role of behavior of and interactions between stakeholders on material flows.

Considering the first issue, analysis of material flows in a region often leads to detection of net imports or exports of certain materials. This relates to the recent discussion of the ecological footprint (Wackernagel & Rees, 1996; and for a critical review of the method see van den Bergh & Verbruggen, 1999). This discussion focuses on the relation of trade and the environment. The ecological footprint suggests that imports of goods relate to depletion of resources elsewhere. However, there are many reasons to believe that trade improves environmental quality. An interesting example is the import of waste paper by India, which improves the quality of paper and saves local forests (Van Beukering & Duraiappah, 1998). For an indepth discussion of the relation between material flows and trade we refer to Van Beukering et al. (2000).

The second issue is the relation between economic activities and material flows. During the last ten years much empirical research has tested for Environmental Kuznets Curves (EKC). These are inverted U-curve relationships between environmental pressure and income, which have been found in various case studies. De Bruyn (1999), however, shows that the evidence for EKC is very weak. Actually, a N-shape relationship seems more realistic, as it reflects a relinking of economic growth and environmental pressure once technological savings have been exhausted. The explanation is that delinking during the seventies and eighties was caused by the oil crises that stimulated technological improvement, whereas during the nineties relinking was caused by low energy prices reducing incentives for technological development. For an excellent review of empirical analysis of economic growth and the environment we refer to de Bruyn (1999).

The third issue is the behavioral dimension of stakeholders that influence material flows. Stakeholders are associated with activities like resource extraction, production of capital and consumer goods, consumption, and waste collection and treatment. Although the invisible hand of Adam Smith has an important influence on the regulation of interactions between stakeholders, not all their decisions can be explained by economic rationalities. Limited knowledge, habits, institutional structures, social interactions and culture all influence the behavior of and interactions between stakeholders.

The three issues together illustrate a number of fundamental problems understanding the logic underlying material flows. This requires, besides a description of the material flows, comprehension of the *processes behind the material flows*. Deeper understanding the processes leading to changes in material flows can also provide insights about how to develop policies that lead to a reduction in harmful material flows, and which impacts the current rapid changes in information and communication technology can have on material flows.

This paper discusses a number of concepts and methods that can be used to study the behavioral, technological, market and spatial processes behind the material flows. A conceptual framework that explicitly addresses the spatial dimension of industrial metabolism explicitly is the international material-product chain (MPC) (Beukering et al., 2000). This framework combines the traditional material cycle of Ayres (1998), material-product chains (Kandelaars, 1999), and trade flows.

A method suitable for empirical analysis of structural change of material flows as a consequence of economic activities is structural decomposition analysis. This has already been applied to energy use and related emissions, and in this paper we will examine how it can be applied on material flows. Finally, a modeling approach is discussed that enables to describe behavior of stakeholders from the bottom up. Modeling approaches from complex adaptive systems research can be used to describe behavioral rules of individual stakeholders, and simulate the resulting interactions and material flows. Since these behavioral rules are based on local knowledge, macro-behavior of the system is not predictable. Nevertheless, such models can be used to study under which assumptions (rules) macro-phenomena such as decoupling, emerge.

The paper is organized as follows. In Section 2 material flow models, and economic models with material flows are discussed. Features of the international MPC are examined in Section 3. Section 4 is devoted to a discussion of structural decomposition analysis. Section 5 introduces a complex adaptive systems approach to study industrial metabolism. Section 6 concludes.

## 2. MATERIAL FLOWS OF ECONOMIES AND THE ECONOMICS OF MATERIAL FLOWS

Two different branches of research can be distinguished, both able to study the material flows of economic systems. The first one is rooted in natural science and is focused on measuring material flows. The second branch is rooted in economics and is focused on allocating material flows. We briefly discuss the most important characteristics of these approaches. Different types of approaches have been developed to analyze material flows (Kandelaars, 1999; Bouman et al., 2000). These approaches include material flow analysis, physical input-output tables and lifecycle assessment. These approaches are mainly descriptive and static, although recently dynamic aspects have been introduced in the approaches. They all focus on the description of flows in an economic system. Material flow analysis focuses on material flows in a specific geographic area, in terms of both the economic as well as the environmental system. Input-output analysis focuses on material flows in and between the sectors of an economy. Lifecycle assessment studies all physical aspects of a product. The most crucial elements of the material flows approaches are accuracy and completeness of effects considered. Solutions to tackle the data requirements are static analysis and a high aggregation level.

Most of the current studies in the field of industrial metabolism are related to material flows models. They capture a broad spectrum of temporal and spatial scales (see various chapters in Ayres and Simonis, 1994). An alternative perspective of metabolism focuses on households. Noorman and Schoot Uiterkamp (1998) describe household metabolism in the Netherlands. The material flow studies, which are representative for industrial metabolism research, concentrate on describing flows of specific materials for a certain period of time.

Although economics often addresses allocation of scarce resources, it pays relatively little attention to the physical dimension of allocation decisions. Only a few economists, mainly with a natural scientific background, have devoted attention to the physical dimensions of economics (Ayres & Kneese, 1969; Kneese et al., 1970, Georgescu-Roegen, 1971, 1976; Ayres, 1978). They have introduced concepts like mass-balance, entropy and the second law of thermodynamics into economic analysis.

Nowadays, a number of approaches exists that try to describe the physical economy such as input-output modeling, cost minimization models, equilibrium models, dynamic optimization and system dynamics (Kandelaars, 1999; Janssen & van den Bergh, 1999). Nevertheless, most economic models include the physical dimension only implicitly, for example, through external costs. Explicit inclusion of material flows within economic models remains rare. This may lead to the question whether appropriate tools are used in economics to analyze the behavioral dimensions of material flows. Industrial metabolism is a concept that can ultimately cover both the features of natural science, as well as the economic approaches to studying material flows in economic systems.

## 3. ECONOMICS OF INDUSTRIAL METABOLISM

The concept of industrial metabolism provides an interesting starting point to develop an integrated approach to study material flows. As Ayres (1994) noted, the economic system is a metabolic regulatory mechanism that balance supply and demand for both products and labor through price mechanisms. The economic system as a whole is essentially a collection of firms, together with institutions and worker-consumers. A manufacturing firm converts material inputs into marketable products and waste materials. Like biological systems, firms specialize in certain types of activity. From a material flow perspective, the following products can be distinguished:

Primary commodities or virgin materials: raw materials that have been extracted from natural resources.

Secondary commodities or recyclable waste materials: raw materials that have been recovered after production or consumption.

Final commodities: intermediary products suitable to be converted directly into consumer goods.

Consumer products or final goods: generated in the final production (manufacturing) stage before consumption.

Waste materials: residue materials that no longer can be converted in useful materials or products in an economically feasible manner. The materials can come from various stages in the industrial material cycle.

Products of one firm can be used as an input to another. Firms are part of some sort of material cycles. This is related to the general scheme of industrial metabolism as defined by Ayres (1994). We have adapted the terminology in this scheme, and added an additional stock, waste, to include explicitly the waste treatment sector (Figure 1). Materials are extracted from the environment and used to produce final commodities, which are used to produce consumer products. In every step of the material cycle waste is generated. This waste disappears to the environment, or is collected for reuse or recycling.

Although the material cycle of Figure 1 takes into account a variety of stakeholders, we want to include the spatial dimension of material flows explicitly. Therefore, we will propose to analyze material flows by an international material product chain (IMPC) as introduced by van Beukering et al. (2000). This approach combines material flows models with descriptions

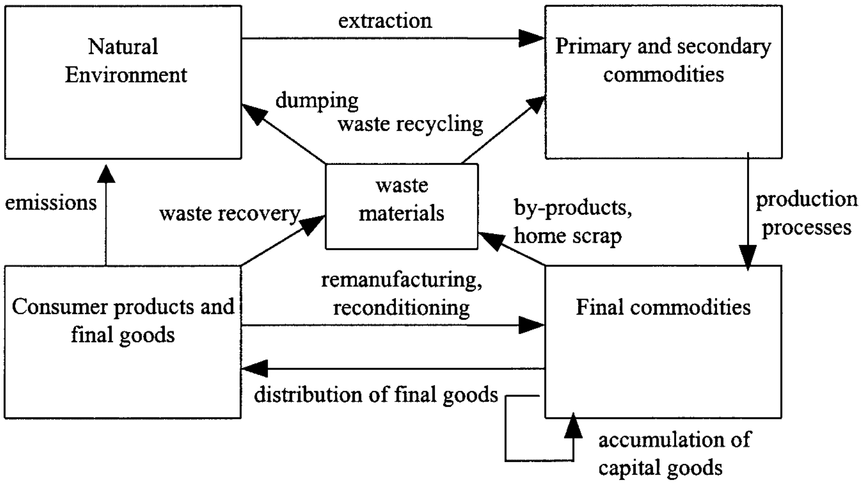

**FIGURE 1.** 5-Box scheme for industrial material cycles (adapted from Ayres, 1998).

of interactions between various economic agents of activities or countries. A MPC is defined as a set of linked flows of materials and products and covers the complete lifecycle of a material. The international MPC tries to describe the physical dimension of economic systems in a setting of international interactions. Material flows in the international MPC originate from one of the economic activities in the MPC.

The international MPC is a multi-region variant of Figure 1 as depicted in Figure 2. Country A, representing the standard developed country, is well endowed with high-tech capital, skilled labor and recyclable waste materials. Country B, symbolizing a typical developing country, maintains a reverse endowment pattern. It is poorly endowed with capital, recyclable waste and know-how and well endowed with unskilled labor and primary raw materials. The arrows between country A and B represent international trade flows of raw materials and products. The traditional MPC is represented by the autarchic material flows within each country. In this case

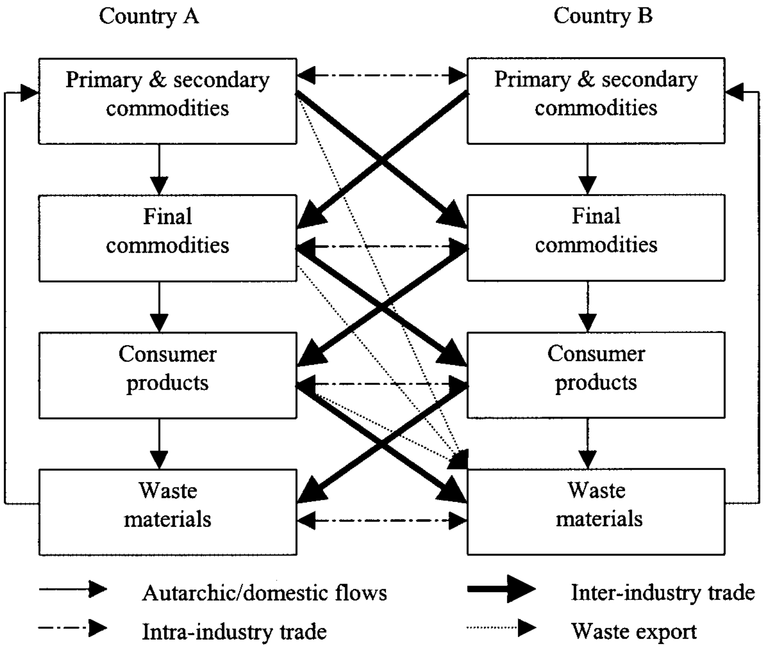

**FIGURE 2.** International trade theories and the product chain (from Beukering et al., 2000).

borders are closed and countries are fully dependent on their own resources.

Traditionally, immobility of labor and capital has caused natural resource endowment to be the main driving factors in inter-industry trade. Materials and products flow vertically from one segment to another within the international MPC. With the mobilization of capital, production centers have become less dependent on the local availability of material resources. Technological knowledge, scale effects and vicinity to consumer markets have become decisive factors, causing intra-industry trade. Materials and products have been traded horizontally between segments in the international MPC. Differences in strictness of environmental policies have caused polluted materials and products to flows to developing countries.

Empirical studies confirm changes in the international MPC (van Beukering & Bouman, 2000). A specific pattern within the international MPC, linking developed and developing countries, has emerged. Developing countries have become more important as importers of primary and secondary commodities, and as exporters of commodities to the own region.

## 4. EMPIRICAL ANALYSIS OF STRUCTURAL CHANGES

Changes in material flows in an economy are affected by the changes in economic structure. The input-output framework is suited to this type of analysis because it gives detailed information about economic transactions. As we will argue in this section an added advantage of input-output analysis is that it is capable of integrating monetary and physical information. We will focus, however, on Structural Decomposition Analysis (SDA), which is an application of input-output analysis that analyzes the changes in economic structure which contribute to policy variables changes such as labor demand, value added, output and environmental emissions (see Rose & Casler [1996] for an overview of the literature). Recently publications include Albala-Bertrand (1999), Casler (2000), Oosterhaven and van der Linden (1997), Oosterhaven and Hoen (1998). Since the introduction of this decomposition technique by Leontief and Ford (1972) the method has been used in about 15 publications to decompose environmental variables. Most of the papers dealt with energy use (Rose & Chen, 1991; Lin & Polenske, 1995), or related emissions such as $CO_2$ or other air pollutants (Casler & Rose, 1998). Only one article dealt with physical flows that are not related to energy use: nitrogen loading (Wier & Hasler, 1999).

SDA is a method that applies comparative static analysis to the input-output data framework and model. It is capable of assessing the importance of technological and demand "effects" on energy use or other environmental indicators. An advantage of SDA is that it is based on the input-output model and therefore includes indirect effects. In other words, if output grows in a material extensive sector, then it will require increasing inputs from its suppliers and they in turn will increase their inputs, and so on. If supplying sectors are material intensive then growth in material extensive sectors could still lead to an important increase of material throughput. SDA of a physical flow generally takes the following form:

$$\Delta M = \Delta I \cdot L \cdot Y + I \cdot \Delta L \cdot Y + I \cdot L \cdot \Delta Y$$

in words:

> *change in physical indicator = Intensity effect + Leontief technological effect + Final Demand effect*

where:

$M$ = *Material use*
$I$ = *Material use per unit output per sector*
$L$ = *Leontief inverse*
$Y$ = *Final demand per sector*

The first two effects of the equation reflect technological changes in the use of materials. The last effect reflects the effect of final demand changes on the material use. The articles that have appeared in this field have decomposed these 3 general effects into sub-effects to gain even more insight into the determinants of change. The changes in the Leontief inverse have for example been decomposed into substitution and efficiency effects (Rose & Chen, 1991; Casler & Rose, 1998). The final demand effects have been decomposed further into the effects of exports and consumption changes. It is also possible to find the effects of changes in the level and product mix effects of consumption changes. It is expected that over the last decades the absolute level of consumption has grown, which has resulted in a greater throughput of material. The types of consumer products have also changed. These shifts are rather less abstract than the overall "consumption effects" and one could imagine creating scenario's of consumer behavior in these terms. On a critical note that the effects that SDA is capable of finding are still economy-wide aggregate effects. The insights gained from these applications should be supplemented with knowledge of institutional, regulatory and technological changes.

The advantage of SDA is the knowledge obtained about the importance of each of these driving forces on the material flow. Since the entire economy is taken into account, the resulting decomposition gives a complete overview of the effects and the magnitudes thereof on the variable under investigation.

Although the SDA method has been applied for environmental issues there is room for methodological improvement. The articles so far have restricted themselves to energy or related emissions. These are however physical flows that are easily attributable to a sector because they are depletable resources. Metals, plastics and other materials are however passed on from sectors to sectors and in some cases recycled. Tracking these flows is more challenging and has lead to the development of physical input-output tables. The table is based on the monetary input-output tables but is based on the material balance principle. This means that all the material inputs for each sector and the destinations of material flows are traced. Because these types of studies have only been empirically applied fairly recently (Konijn et al., 1995 and Stahmer et al., 1997), the accounting rules that apply still differ significantly. So far no country has produced no country has produced physical input-output tables for two separate years, which is why they have not been used in SDA studies. A simple physical input-output table would look like Table 1. SDA could use the information from the physical input-output tables for decomposition purposes. The physical data could for example be combined with monetary input-output data to form "hybrid unit" tables (see Miller & Blair, 1985). The table contains a wide variety of information. Decomposition of several indicators of materials use is feasible. For example, a decomposition could be done of the

## TABLE 1

**A Simple Physical Input-Output Table**

| | Sector 1 | Sector 2 | Consumer | Export | Waste | Total |
|---|---|---|---|---|---|---|
| Sector 1 | | | | | | |
| Sector 2 | | | | | | |
| Recycled Waste | | | | | | |
| Import | | | | | | |
| Natural Resources | | | | | | |

change in the quantity of recycled materials, natural resources use, waste production or total material use.

SDA is a suitable method for empirical analysis of the economic causes of material flows. If all the necessary monetary and physical information is available the changes in flows indicated in the (international) MPC can be unraveled. Nevertheless, application of SDA is constrained by the limited availability of reliable information. This is mainly caused by the fact that national statistics of many countries provide no consistent and detailed information on material flows. Furthermore, a problematic issue is the fact that sectors in the IMPC do not exist in their "pure" forms. In the input-output data available there are very few sectors that deliver exclusively to other sectors or act only as suppliers for consumers, particularly at the aggregation levels those prevail in the data. The data would need to be modified by separating these heterogeneous sectors to suit the classification used in the IMPC.

Another challenge in SDA is using the method to do policy projections. So far SDA has been exclusively used as a tool for historical analysis of policy variables. In a related field Ang and Lee (1996) have introduced these type of projections.

## 5. INDUSTRIAL METABOLISM AND COMPLEX ADAPTIVE SYSTEMS

Complex adaptive systems contain many components that interact, and the behavioral rules of these components can change in reaction to changes in the social and physical environment (Holland, 1992; Waldrop, 1992; Janssen, 1998). Examples of complex adaptive systems are economies, ecosystems, immune systems and nervous systems. Characteristic of the research on complex adaptive systems is a bottom-up approach. A population of agents is equipped with simple behavioral rules, leading to emergent properties on a higher level. The agents have only local knowledge, and no central control exists. Researchers in the field of complex adaptive systems are interested under which local behavioral rules, which type of structures emerge on the macro-level. The general approach of studying these multi-agent systems is the use of computer simulation models. This enables the inclusion of heterogeneity of agents and bounded rationality.

The physical economic system can be viewed as a complex adaptive system. Many different agents are involved in generating and changing material flows. Changes in material flows are caused by changes in technological development, preferences of consumption, and governmental policies.

In this section we will explore how the tools developed in complex adaptive system research can be applied on understanding industrial metabolism. Materials flows are the result of interactions between different kind of agents or stakeholders. We can view industrial metabolism as a web of agents in which each agent tries to survive by transforming materials and yielding value added products (Figure 3). The success of survival depends on agents' strategies, institutions affecting the social and legal environment, technological development, and changes in agents' preferences. Because of the continuous change of the system, agents that were successful in the past may not survive in the future. For example, agriculture changed enormously during the last century due to technological and organizational developments, leading to less agricultural "agents" in Europe.

A number of current developments are foreseen that will change industrial metabolism. An example is the increasing globalization of economic

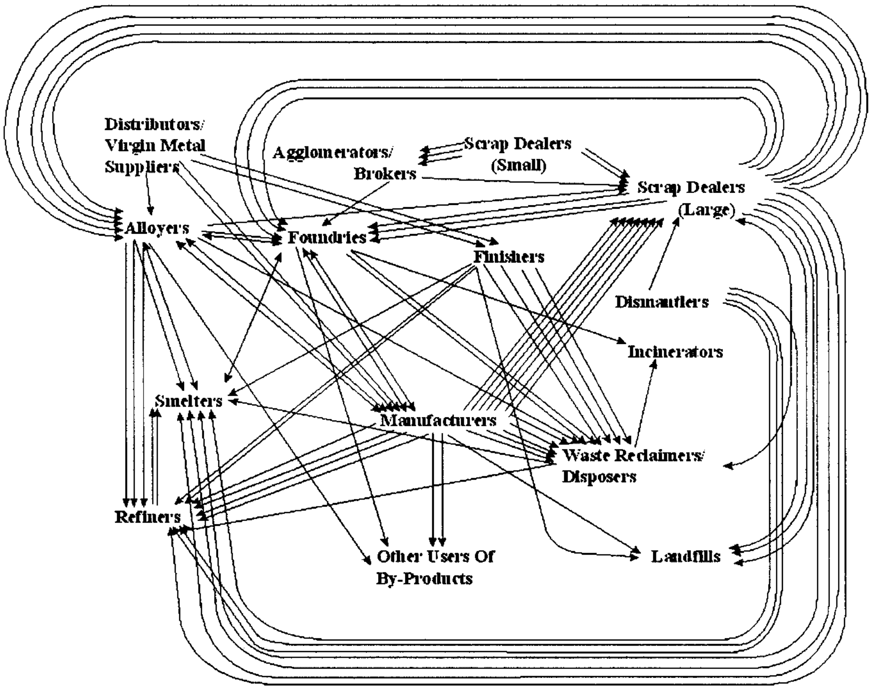

**FIGURE 3.** Flows of metals among a sample of metals processors in New England (after Frosch et al., 1996).

activities due to increased mobility of capital and labor, domination of multinationals, and continuous expansion and innovation of computer and telematica network technology. An intriguing question is then how globalization will change national and international material flows.

Another example is the increasing environmental regulation, on different levels of scale. Policies on environment and trade are more and more based on international agreements. The current negotiations on a climate change policy show the complex process of international policy. An important danger for the international environmental policy is the emergence of coalitions of stakeholders that are specialized in a certain chain of the product chain which can delay and soften environmental policy. For example, countries that export large amounts of fossil fuels are trying to influence the negotiations on climate change policy. This is a threat for a successful international policy but also an opportunity for some countries that have environmental or technological suitable conditions for non-fossil fuels such as solar energy, wind energy and commercial biomass. International policy can stimulate the global competition on non-fossil fuels to reduce the influence of fossil fuel exporting countries, and to stimulate a global energy transition. Similar coalitions can also be found with regard to negotiations in the Basel Convention (Kellow, 1999).

Concepts and tools from complex adaptive systems research can help us to explore how industrial metabolism change due to globalization, or understand when coalitions of stakeholders are formed to delay environmental policy (Axelrod, 1997; Epstein and Axtell, 1996). Furthermore, it can provide insights about how new consumption patterns and technology diffuse through economic systems and social networks. Janssen (2000) argues that these tools can be especially useful for understanding observed stylized facts. For example, some empirical studies have assessed environmental Kuznets curves, but it is still unclear under which plausible assumptions (characteristics of firms, consumers, institutions, and their interactions) such Kuznets curves emerge.

Using the IMPC as a starting point we will now sketch a complex adaptive systems approach for industrial metabolism (Figure 4). Four different types of agents are distinguished on various spatial scales: primary and secondary commodity firms, produce final commodity firms, consumers, and waste treatment agents. On each scale there are four types of agents. Each type of agent consists of a heterogeneous population of agents who differ in location, skills, size, strategies, innovators versus imitators, etc. On each level, agents are assumed to interact with agents of different sectors, inter-industry, and between agents of the same sector, intra-industry. When the scale is beyond the country level, these interactions involve trade. At a

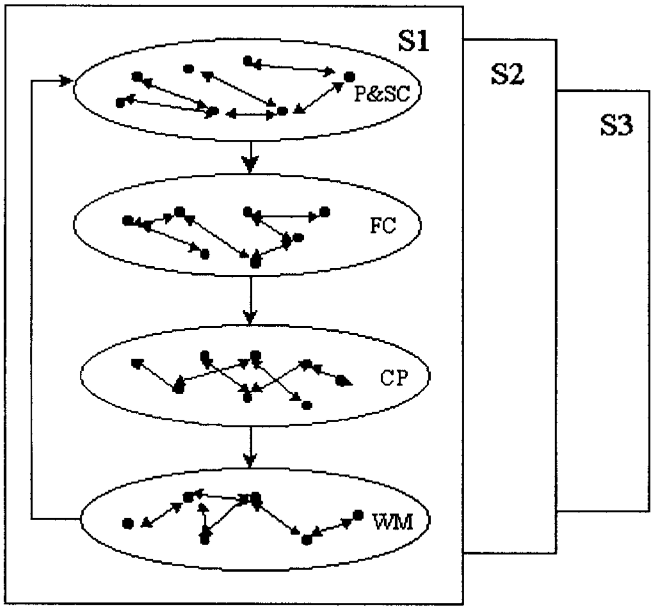

**FIGURE 4.** The international MPC as a complex adaptive system.
*Notes:* Si are spatial scales; P&SC stands for Primary & Secondary Commodities; FC stands for Final Commodities; CP stands for Consumer products; WM stands for Waste materials; The dots represent agents (nations, firms, households); The arrows represent the (social) interactions of the agents.

lower scale, still large spatial movements may occur, but from an accounting point of view no trade occurs. On each scale, specific rules, laws, constitutions and norms shape interactions between the agents. Examples of such institutions are the (de)regulation of trade (GATT), national policies (environmental regulation) and norms on consumption (environmentalists versus materialists).

One of the interesting questions is whether structures emerge on different levels of scale. What type of networks between firms will appear? How will policy on different scales influence these networks? And what will be the influence of globalization on material flows between countries and material use in absolute terms on a global level?

To translate the conceptual model into a computational model, methods can be used from evolutionary economics to simulate innovation, strategies of firms and diffusion of technology (Kirman, 1997; Basu, 1998), social simulation to simulate emergence of institutions, social networks, consumer behavior (Gilbert & Troitzsch, 1999; Jager, 2000) and non-linear economics (Anderson et al., 1988; Arthur et al., 1997).

The resulting model can be used to study, among others, the following research questions:

Which assumptions are needed to produce an EKC?
What type of firms survives the world of increasing globalization?
How can environmental regulation change industrial metabolism into a sustainable fashion?

## 6. CONCLUSIONS

Research activities in the field of industrial metabolism are focused on describing physical flows in economic systems. Since industrial metabolism change over time, understanding of the behavioral processes behind changes of material change is required. For each of the three issues addressed in this paper a promising approach is suggested.

To include spatial scales more explicitly into the study of material flows, the international MPC is introduced. It can serve as a concept to explain the increase of material flows between regions. SDA is introduced as a method suitable to unravel empirical relations between economic activities and material flows. Up till now, practical problems of data collections limit the wide potential of SDA. Finally, to study industrial metabolism from the perspective of interacting stakeholders, the use of complex adaptive systems tools is suggested. These can contribute to a better understanding of the stylized facts found by empirical research.

Research on changing of industrial metabolism is needed to improve our understanding of the physical dimension of economic system. Industrial metabolism can become a powerful concept only if social science develops tools to operationalize it.

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## REFERENCES

Albala-Betrand, J.M. (1999). Structural change in Chile, 1960–1990. *Economic Systems Research*, 11, 301–319.

Anderson, P.W., Arrow, K., & Pines, D. (1988). *The Economy as an Evolving Complex System*. Redwood City, CA: Addison Wesley.

Ang, B.W., & Lee, P. W. (1996). Decomposition of industrial energy consumption, the energy coefficient approach. *Energy Economics* 18, 129–143.

Arthur, W.B., S. N. Durlauf, & D. Lane (1997). *The Economy as an Evolving Complex Systems II*. Redwood City, CA: Addison Wesley.

Axelrod, R. (1997). *The Complexity of Cooperation, Agent-Based Models of Competition and Collaboration*. Princeton, NJ: Princeton University Press.

Ayres, R.U. (1978). *Resources, environment, and economics, application of the materials/energy balance principle*. New York: John Wiley and Sons.

Ayres, R.U. (1994). Industrial metabolism. In R.U. Ayres & U.E. Simonis (Eds.), *Industrial metabolism—restructuring for sustainable development*. Tokyo: United Nations University Press.

Ayres, R.U. (1998). Industrial metabolism, work in progress. In J.C.J.M van den Bergh & M.W. Hofkes (Eds.), *Theory and Implementation of Economic Models for Sustainable Developments*, 195–228. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Ayres, R.U. & Kneese, A. V. (1969). Production, consumption and externalities. *American Economic Review*, 59, 282–297.

Ayres, R.U., & Simonis, U. E. (Eds.). (1994). *Industrial metabolism—Restructuring for sustainable development*. Tokyo: United Nations University Press.

Basu, N., Pryor, R., & Quint, T. (1998). ASPEN, A Microsimulation Model of the Economy. *Computational Economics*, 12, 223–241.

Beukering, P.J.H. van, van den Bergh, J.C.J.M., Janssen, M. A., & Verbruggen, H. (2001). International material-product chains, an alternative perspective on international trade and trade theories.

Beukering, P.J.H., & Bouman, M. (2000). *Empirical Evidence in International Trade and Recycling of Secondary Materials*. Washington, DC: World Bank Working Paper, Environment Department, The World Bank.

Beukering, P.J.H. van, & Duraiappah, A. (1998). The Economic and Environmental Impact of Wastepaper Trade and Recycling in India, A Material Balance Approach. *Journal of Industrial Ecology*, 2(2), 23–42.

Bergh, J.C.J.M. van den, & Verbruggen, H. (1999). Spatial sustainability, trade and indicators: A critique on the ecological footprint indicator. *Ecological Economics*, 29, 61–72.

Bouman, M., Heijungs, R., van der Voet, E., Bergh, J.C.J.M. van den, & Huppes, G. (2000). Material flows and economics models, an analytical comparison of SFA, LCA and partial equilibrium models. *Ecological Economics*, 32, 195–216.

Bruyn, S.M. de (1999). *Economic growth and the environment, An empirical analysis*. Amsterdam: Tinbergen Institute Research Series, no. 216, Thesis Publishers.

Casler, S. (2001). Interaction terms and structural decomposition: an application to the defense cost of oil. In: E. Dietzenbacher & M. Lahr (Eds.), *Input-output Analysis, Frontiers and Extensions*. London: Macmillan.

Casler, S., & Rose, A. (1998). Carbon dioxide emissions in the US economy. *Environmental and Resource Economics,* 11(3–4), 349–363.

Epstein, J., & Axtell, R. (1996). *Growing Artificial Societies: Social Science from the Bottom up*. Cambridge, MA: MIT Press.

Frosch, R.A., Clark, W.C., Crawford, J., Tschang, T.T., & Weber, A. (1996). *The Industrial Ecology of Metals: A reconnaissance*. From a talk delivered at the Royal Society/Royal Academy of Engineering meeting, May 29–30, London, U.K.

Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process*. Cambridge, MA: Harvard University Press.

Georgescu-Roegen, N. (1976). *Energy and Economic Myths: Institutional and Economic Essays*. New York: Pergamon Press.

Gilbert, N., & Troitzsch, K. G. (1999). *Simulation for the Social Scientists*. London: Open University Press.

Grübler, A. (1998). *Technology and Global Change*. Cambridge, UK: Cambridge University Press.

Holland, J.H. (1992). Complex Adaptive Systems. *Daedalus,* 121(1), 17–30.

Jager, W. (2000). *Modelling consumer behaviour*. PhD thesis, University of Groningen.

Janssen, M.A. (1998). Use of Complex Adaptive Systems for Modeling Global Change. *Ecosystems*, 1, 457–463.

Janssen, M.A. (2001). Modeling human dimensions of global environmental change. In R. E. Munn (Ed.), *Encyclopedia of Global Environmental Change*. Chichester, UK: John Wiley and Sons.

Janssen, M.A., & Bergh, J.M.J.M. van den (1999). SIMBIOSES, Modelling Industrial Metabolism in a Multi-Regional Economic System. Discussion paper TI-99-060/3. Amsterdam/Rotterdam: Tinbergen Institute.

Kandelaars, P.P.A.A.H. (1999). *Economic Models of Material-Product Chains for Environmental Policy Analysis*. Dordrecht, the Netherlands: Kluwer Academic Publishers.

Kellow, A. (1999). Baptists and bootleggers? The Basel Convention and metals recycling trade. *Agenda*, 6(1), 29–38.

Kirman, A. (1997). The economy as an evolving network. *Journal of Evolutionary Economics*, 7, 339–353.

Kneese, A.V., Ayres, R. U., & d'Arge, R. C. (1970). *Economics and the Environment: A Materials Balance Approach*. Baltimore: John Hopkins Press.

Konijn, P.J.A., de Boer, S., & van Dalen, J. (1995). *Material flows and input-output analysis, methodological description and empirical results*. Statistics Netherlands. Notanr. 006-95-EIN-PNR/int and BPA-nr, 698-95-EIN.PNR/int.

Leontief, W., & Ford, D. (1972). *Air Pollution and Economic Structure: Empirical Results of Input-Output Computations*. Geneva: Input-output Techniques.

Lin, X., & Polenske, K. R. (1995). Input-output anatomy of China's energy use changes in the 1980's. *Economic Systems Research*, 7, 67–83.

Miller, R.E., & Blair, P. D. (1985). *Input-Output Analysis: Foundations and Extensions*. Englewood-Cliffs, NJ: Prentice-Hall.

Noorman, K.J., & Schoot Uiterkamp, A.J.M. (Eds.) (1998). *Green Households? Domestic Consumers, Environment and Sustainability*. London: Earthscan Publications Ltd.

Oosterhaven, J., & Hoen, A. R. (1998). Preferences, technology, trade and real income changes in the European Union, an intercountry decomposition analysis for 1975–1985. *Annals of Regional Science*, 32, 505–524.

Oosterhaven, J., & Linden, J. van der (1997). European technology, trade and income changes for 1975–1985: an intercountry input-output decomposition. *Economic Systems Research*, 9, 393–411.

Rohatgi, P., Rohatgi, K., & Ayres, R. U. (1998). Materials futures, Pollution prevention, recycling, and improved functionality. In R.U. Ayres (Ed.), *Eco-restructuring, Implications for sustainable development*, 109–148. Tokyo: United Nations University Press.

Rose, A., & Casler, S. (1996). Input-output structural decomposition analysis, A critical appraisal. *Economic Systems Research*, 8(1).

Rose, A., & Chen, C. Y. (1991). Sources of change in energy use in the US economy, 1972–1982: A structural decomposition analysis. *Resources and Energy,* 13, 1–21.

Stahmer, C., Kuhn, M., & Braun, N. (1997). *Physical input-output tables for Germany, 1990*. Prepared for DG XI and Eurostat by the Geramd Federal Statistics Office. Working paper No 2/1998/B/1, 19 January.

Stigliani, W.M., Doelman, P. Salomons, W., Schulin, R., Smidt, G.R.B., & Zee, S.W.A.T.M. van der (1991). Chemical time bomb: Predicting the unpredictable. *Environment,* 33, 26–30.

Wackernagel, M., & Rees. E. E. (1996). *Our Ecological Footprint: Reducing Human Impact on the Earth*. Gabriola Island: New Society Publishers.

Waldrop, M. (1992). *Complexity: The Emerging Science at the Edge of Order and Chaos*. New York: Simon and Schuster.

Wier, M., & Hasler, B. (1999). Accounting for nitrogen in Denmark: A structural decomposition analysis. *Ecological Economics,* 30, 317–331.