Chapter 2

The Interface between Economics and Industrial Ecology: A Survey

J.C.J.M. van den Bergh and M.A. Janssen

2.1 Introduction

The Western consumer seems to be more and more enamoured by material things. This has resulted in a wide variety of products, in turn giving rise to increasing pressure on the environment. Nearly all important local and global environmental problems as well as environmentally-related human health risks can be reduced to the flows and the accumulation of substances and materials in the economy. This is illustrated by such different problems as climate change (fossil fuel use), acid rain (fertilizer use, animal fodder, meat consumption), toxicity (metal use), water pollution (paper use), desiccation (water use), and the depletion of fisheries (fish consumption).

In this chapter we will survey the field of research that is concerned with the physical dimension of economic activities and products. This will entail a discussion of the concepts, theories and methods that economists have used to study physical flows. Focusing on physical flows through the economy is valuable for the following reasons.

First, the “physical economy” approach enables research on the coherence of environmental problems. For example, by adding “end-of-pipe-technologies” to the production process, the emission of certain substances to air or water can be reduced. Without a reduction of material input, however, production will inevitably generate solid waste, which is also associated with negative environmental effects (Ayres, 1998). In the best case this will result in a saleable product, like gypsum with flue gas desulphurization.

A second reason for an explicit description of the physical dimension of the economy is that this creates a basis for dealing with notions like “sustainability” and “sustainable development”. Elaboration of these concepts usually involves referring to physical and biological stocks, and the feedback of changes therein to the physical economy (van den Bergh and Nijkamp, 1994). Sustainability can be considered as being strongly connected to physical constraints, determined by exhaustion of raw material supplies and the accumulation of substances in the environment.

The third and final reason for a “physical economy” approach is that it facilitates multidisciplinary use of economic models and insights, in particular linking these to physical, chemical and biological models of environmental processes and compartments. This is especially valuable in integrated modeling aimed at the study of long-term effects and risks of substance flows through the environment and economy (see, e.g., Rotmans and de Vries, 1997).

The interface between economics and industrial ecology has its roots in the late 1960s and early 1970s. Ayres and Kneese (1969) is generally regarded as the first article that presents a theoretical, formalized framework to combine economic modeling, based on the general equilibrium format, with physical flow accounting. This was regarded by the authors as a general approach to deal in a fundamental and correct way with externalities caused by the extraction, production, use, and waste of materials or commodities containing materials. An extended version of their work is contained in Kneese et al. (1970). Other early work combining economics and material flow analysis is Georgescu-Roegen (1971a), which is almost philosophical in nature, and Ayres (1978), which emphasizes the use of input-output techniques. Both Ayres and Georgescu-Roegen address the implications of thermodynamics for the specification of production functions in economic models (see also Georgescu-Roegen, 1971b, and for an evaluation of his work, Cleveland and Ruth, 1997). Contributions in Daly and Umaña (1981) and Faber et al. (1987) can also be considered as early contributors to the integration of economics with industrial ecology themes.

The structure of this chapter is as follows. Section 2.2 discusses in more detail the relationship between physical flows through the economy and environmental problems. This includes a typology of materials as well as a short review of the main implications of thermodynamics for the economic analysis of physical flows. In Section 2.3, the policy context is sketched. This involves discussing the traditional hierarchy in waste management, recycling and reuse, and dematerialization at various scales. Next, Section 2.4 surveys the wide range of concepts, theories and methods that are employed in environmental economic analysis of physical flows. These cover, among other things, materials and resource accounting, mass balance, material-product chains, mass-balance production functions, recycling models, input-output modeling, equilibrium theory and externalities, and economic growth theories. This is followed in Section 2.5 by a closely linked discussion of related perspectives on concepts and methods in industrial ecology, with particular attention to material cycles, international trade and qualitative network analyses. Section 2.6 presents conclusions.[1]

2.2 Materials, substances and the environment

2.2.1 A typology

This section discusses the relationship between materials (and substances) and environmental problems. Substances are amounts of atoms or molecules, for example, metals, sand and water. Materials are physically-bonded substances, such as paper, wood, plastic, metal alloys and fossil fuels. The impact of physical flows and the accumulation of substances and materials in the economy on the natural environment covers many categories of environmental problems. A first category concerns ‘resource problems’, connected to scarcity and exhaustion of natural resources and raw material supplies. A second category concerns ‘pollution problems’, connected to waste flows and the emission of substances to the environment. Those flows can be harmful to the health of humans or other living organisms due to their character (quality) or amount (quantity). Toxic and artificial substances are in the short term the most alarming, whereas solid waste and emissions of acidifying substances and greenhouse gases create long-term risks.

Several specific problems are associated with material flows in the economy. Substances accumulate in the economy and cause numerous indirect and delayed problems. Therefore, measuring and predicting their ultimate environmental effects, and determining the causes of these problems is not straightforward.

In addition, substance flows are connected in two essential ways to energy use and related environmental effects. First, there is a strong coherence between the use of materials and energy in production processes. The reason is that energy is needed to transform and modify materials. Second, energy supply is dominated by fossil fuels in most countries, and is linked to several substance flows, particularly carbon compounds and nitrogen and sulfur oxides. For instance, energy use based on fossil fuels in the United States leads to a share of almost 40% in the total input of substances and materials in the economy (Wernick and Ausubel, 1995). The enormous quantity of several substance flows additionally creates large amounts of movements of freight. This causes specific environmental problems, notably related to the use of space and energy.

Materials and substances can be classified on the basis of several characteristics, e.g. physical, biological and economic. The most important substances for biological processes on earth and for human beings are the nutrients carbon, nitrogen, sulfur, and phosphor. These elements take part in the nutrient-cycles of living and non-living systems. Such cycles are characterized by natural recycling. The four substances occur in the biosphere – the living earth – in larger concentrations than in the physical, a-biotic (non-living) natural systems. This is caused by biotic processes, and indirectly the result of a long and slow process of organic evolution. In this context the term “Gaia” is sometimes used, based on the theory of a living earth as a system of several complex chemical and biological feedbacks, which have tended towards natural balance by evolution (Lovelock, 1979). However, the nutrient-cycle is nowadays severely disturbed by human activities, in particular by the combustion of coal, oil and gas. This has caused an increase in the concentrations of carbon dioxide, nitrogen oxides and sulfur oxides in the atmosphere. This in turn creates the risk of a serious disturbance of the natural balance.

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[1] Other surveys are offered by Ruth (1993, 1999) and Kandelaars and van den Bergh (2001).

In addition to these nutrients, six other – partly overlapping – categories of substance and material flows can be distinguished, which mix physical and economic considerations. Some of these categories will receive detailed attention in later chapters.

(1) *Metals.* These are used in numerous products. Some of them are toxic, like cadmium, copper, lead and zinc. These are recycled only in small amounts by natural processes, so that they accumulate in the environment (Guineé et al., 1999; van der Voet et al., 1999). This creates long-term risks for the health of humans and ecosystems. Moreover, the extraction of metals produces huge amounts of waste flows, due to ores containing low concentrations of metals. This holds for copper, lead and nickel, and especially for gold, platinum and uranium (Ayres and Ayres, 1996). In addition, many metals are rather scarce anyway. Recycling by humans is possible, but is hampered by the fact that metals are regularly a part of alloys.

(2) *Plastics.* Our direct living and working environment is increasingly dominated by this category of materials. It covers a variety of synthetic substances, with polypropene, polystyrene, polyethylene and PVC as the most important ones. Production and waste treatment of some plastics is extremely environmentally damaging. Nowadays plastics are mainly manufactured from oil products. In a "post-oil" and "post-metal" world, plastics produced on the basis of plant material might contribute to a sustainable economy (Ackerman, 1997). Interestingly, the first plastics, cellulose, were already made of plant material. All knowledge about plastics that has accumulated in the last few decades – concerning material characteristics like stiffness, hardness, tolerance for different temperatures, and transparency – can be applied usefully to develop materials that satisfy the requirements set by modern life. Plastics are suitable for recycling, which often involves a process of moving through lower quality grades.

(3) *Chemical products*. These include products that can be toxic, carcinogenic or persistent, and some are completely artificial, i.e. not found in nature. Examples associated with considerable physical flows are chemical compounds of phosphate, sulfur, nitrogen and chlorine (Ayres and Ayres, 1996). The chemical industry and agriculture are the most directly involved sectors. To lower the environmental load in the chemistry sector, the following development directions have been identified (DTO, 1997): production of methanol based on photovoltaic solar energy; hydrocarbon-conversion where power stations produce raw material for the chemical industry in addition to energy; and integrated plant-conversion, which uses biomass as raw material for the chemical industry. The use of pesticides in the agriculture creates a specific problem, and, although the situation is improving, it is far from positive.

(4) *Minerals.* This covers stone, gravel, clay and sand. They are extracted in large amounts from the earth's crust. Although they are relatively harmless per unit of weight, they cause much transport, disturbance, water pollution and damage to landscapes, through erosion by opencast mining.

(5) *Packaging material.* This type of material makes up a considerable part of the total weight and volume of waste generated by human activities. The extremely short life duration is an important characteristic. The most essential types of materials encountered are glass, paper, cardboard, steel, aluminum and plastics. Some authors claim that the lightest packing is the best packing material in terms of minimal environmental load, with the exception of materials with toxic components (Ackerman, 1997).

(6) *Organic products.* These are connected to food production, the use of paper and wood, and other uses of biomass. Especially paper making and wood production generate toxic substances and cause eutrophication of surface water. Organic substances can be reused or biologically decomposed. Composting is possible, though this requires separation of organic and other

> waste, which is not so easily achieved. A specific problem is that metals accumulate in the soil via composting and eutrophication, resulting in increased metal concentrations in cultivated vegetables, which can after many feedback cycles exceed health-risk thresholds (see Molenaar, 1998). In addition, the biologist Vitousek and his colleagues (1997) have estimated that over 40% of the total biomass on earth is being used by humans or is severely threatened.

For a more detailed discussion see, for example, Ayres (1999a). Traditionally, environmental economics aims to make environmental effects comparable in measurement terms: namely, through monetary valuation and the notion of ‘external costs’.[2] This is an alternative to using weights, which is being done in life-cycle analysis. Table 2.1 shows a comparison of external costs for a number of packaging materials. It is based upon a large survey by the Tellus Institute in Boston, which has performed many studies of alternatives for waste management and recycling within the United States. The table shows that PVC, new aluminum and the plastic type PET are the most environmentally damaging substances per unit of weight. It has to be realized that for a complete picture, it is also necessary to take into account the weight of the packaging material needed per unit of packed product. From this point of view, especially glass packing is unattractive. This, however, is compensated by its relatively good performance in terms of external costs per unit of packaging material.

Table 2.1. External costs of packaging materials

Packaging material	***Estimation of external costs****
Plastics	
HDPE (high-density polyethylene)	$128,-
LDPE (low-density polyethylene)	$158,-
PET (polyethylene terephthalate)	$331,-
Polypropylene	$148,-
Polystyrene	$162,-
PVC (polyvinyl chloride)	$1714,-
Paper	
Bleached kraft paperboard	$121,-
Unbleached coated boxboard	$94,-
Linerboard	$95,-
Corrugating medium	$101,-
Unbleached kraft paper	$96,-
Boxboard from wastepaper	$76,-
Linerboard from wastepaper	$77,-
Corrugating medium from wastepaper	$109,-
Glass	
Virgin glass	$70,-
Recycled glass	$48,-
Metal	
Virgin aluminum	$928,-
Recycled aluminum	$76,-
Steel	$79,-

Note: * In 1993 US$ per ton packing material.
Source: Ackerman (1997, p. 102).

2.2.2 Fundamental physical backgrounds: thermodynamics

Next, we briefly describe the main insights from physics, as these define constraints on the physical and technological processes that occur in the economy. The main relevant discipline is thermodynamics, or the science of energy and mass (see for accessible treatments, among others,

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[2] The concept ‘external effect’ or ‘externality’ is part of microeconomic welfare theory. It is defined as an unplanned physical effect, outside the market, of a decision made by one individual on the welfare, health or production of someone else, without any compensation taking place. Environmental economics studies, in particular, negative external effects, or ‘external costs’. The welfare theory approach focuses attention on the optimal level of external costs, to be achieved through the implementation of adequate policy instruments (Baumol and Oates, 1988).

Ayres, 1978; and Ruth, 1993). The first and second laws of thermodynamics are of particular importance here. The first law, of energy conservation, states that physical processes always involve conservation of energy/mass.[3] In other words, energy can neither be created nor destroyed. The second law, of entropy, states that any physical process – biological or technological – leads to a loss of useful or concentrated energy (known as 'exergy'). Entropy is defined as the distance to a thermodynamic equilibrium. It is sometimes used in a loose manner to describe dimensions other than the energy dimensions of physical processes, using the analogy with energy entropy. It is then interpreted as a measure of structure, information or development. The term "material entropy" has been proposed to point to the diffusion of substances, the wastage of materials, and the erosion of material structures. This, however, has no formal background and cannot easily be transformed into a quantitative standard.

From the first law, conservation of energy/mass, the mass balance principle has been derived. It states that mass is preserved, so that inflow of substances in a system leads to accumulation or outflow of those substances. Although this principle is an approximation, the error margin is minimal under terrestrial conditions where materials and energy are almost perfectly separated categories. Creation or elimination of matter is very rare, unlike the transformation of materials and substances in a chemical sense.[4]

What do these laws and principles mean for environmental economics? First, they emphasize that economic activities do not take place in an independently operating system but in an open system that exchanges energy and matter with its environment, that is, the natural environment. Second, processes in the physical economy lead to a degradation of the environment and natural resources, which can only be compensated by a continuous inflow of solar energy. Third, even if many economists and technological optimists claim that substitution can solve most, if not all, environmental problems, there is no such thing as substitution of energy by other production factors. In other words, all physical, biological and technical processes require a continuous input of energy (or more precisely: exergy). Sources of potential energy are the basis of all processes, and their functions are unique and irreplaceable. However, substitution between different forms of energy is possible. Fourth, thermodynamics determines the absolute boundary conditions of technical efficiency of the most advanced machinery, even if it has not yet been invented. This sets limits to the substitution of materials; to the amount of exergy needed for waste separation; to the amount of exergy required for winning metals from ores, etc. Some limits are conditional, i.e. they can be determined on the basis of specific process characteristics, like required power, work per time-unit, or temperature of combustion (see Peet, 1992). Fifth, production and consumption are processes in which not mass but shape changes. This implies, for instance, that waste management, including incineration, will not reduce the total physical amount of waste (and emissions), but just its shape, form or medium. Waste can be gaseous, liquid or solid, which nevertheless highly influences spatial or temporal features of environmental damage. A particular case is the delay of environmental effects through the storage of toxic waste, which can cause the phenomenon known as 'chemical time-bomb'.

2.3 Principles for waste management, recycling and dematerialization

2.3.1 The hierarchy in waste management

The economic and environmental literature gives several suggestions for policy and strategies to influence substance and material flows. They can be categorized as pertaining directly to waste management, recycling and dematerialization. We now briefly review each of these, illustrated with some examples.

Many countries consider the dumping of waste as problematic because it shifts environmental risks to the future, or because dumping space is scarce. Instead, within the Dutch

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[3] The equivalence of mass and energy is demonstrated by the famous law $E= mc^2$, first formulated by Albert Einstein.

[4] Nuclear fission and fusion processes can both be neglected in terms of the mass of matter being transformed.

waste material policy, prevention has the highest priority, followed by reuse, recycling and then end processing such as incineration and dumping. The U.S. Environmental Protection Agency (EPA) uses a similar reduce-reuse-recycle hierarchy, but does not prefer incineration over land-filling. Since every option for waste management is associated with a variety of environmental effects, the most desirable choice from an environmental perspective is not immediately or generally clear. For example, if the contribution to an increased greenhouse effect by methane and carbon dioxide is considered, a comparison between dumping and incineration of waste results in a preference for dumping, as long as not more than 4.5% of the carbon in the dumped waste is released as methane. This preference is a consequence of the fact that one methane molecule is 24 times more effective than a carbon dioxide molecule in terms of warming-up potential (Ackerman, 1997).

There is a fairly large economic literature on waste management policy, by environmental and policy scientists (see Powell et al., 2001) as well as by economists. So far, no serious economic policy is implemented, which means that economic growth trends easily translate into trends of growing waste generation, both by industries and households. Economic theory emphasizes that markets for waste either do not exist or are distorted, which economist frame as market failures (Wertz, 1976; Choe and Fraser, 1999; Ferrara, 2003; Fullerton and Kinnaman, 1995, 1996; Morris, 1994; Palmer and Walls, 1997; Shinkuma, 2003). An important factor of distortion is flat-fee pricing, which means that the price paid to the (local) government for waste collection and treatment is unrelated to the amount of waste generated or supplied. But although theory and empirical work shows that user fees can reduce waste generation considerably, illicit dumping and burning may be unintended consequences (Hong et al., 1993; Linderhof et al., 2001; Mirada and Aldy, 1998; Sterner and Bartelings, 1999). See Chapter 9 for further discussion of this issue.

Waste management is best analyzed in an explicitly spatial dimension. For instance, the Netherlands are currently split into four waste regions, even if the primary responsibility for waste policy design and implementation is with the national government. The Dutch “Waste Management Association” organizes cooperation between the waste regions, on the one hand, and the provinces and municipalities on the other. The municipalities take care of the collection of waste and encourage prevention through licenses. The provinces are responsible for the removal of waste material and the granting of licenses for processing. The national government is attempting to promote the prevention and recycling of products, waste oil and legislation. This division of tasks is a historical legacy, which does not necessarily reflect a spatially optimal configuration. For this, only a carefully undertaken spatial analysis can provide information.

Although the waste problem is serious and regarded as such by policy makers, it should be pointed out that it is the environmental effects of using materials in production processes that are generally much more significant than the effects of waste processing after consumption (with the exception of nuclear and toxic wastes). This can be explained by the fact that extraction as well as chemical and physical processes in production generate a high level of emissions to air and water per ton of material, and use much more energy than end-processing of the same materials in a later waste phase. In addition, the environmental load of producing new materials is generally much higher than that of recycling materials.

2.3.2 Closing of cycles

Closing cycles of substances or materials is generally considered as an important strategy to reduce and prevent material waste, with the ultimate aim to achieve ‘zero emissions’. Recycling can apply to substances, materials and products. Products require repairing, whereas separation and physical and chemical processing are necessary for distilling substances and materials from waste. Certain materials are already reasonably well separately collected, particularly paper and glass (Ackerman, 1997; van Beukering, 2001). In addition, a distinction can be made between primary, secondary and tertiary recycling. Primary recycling concerns reuse within a production process. Secondary recycling points at the processing and reuse of materials and substances obtained from the waste flow after consumption. Tertiary recycling refers to the combustion of waste to release stored chemical energy (Kandelaars, 1999).

Reuse of a product is usually more attractive than separate reuse of the substances it contains, because the first option generally requires less physical and chemical processing, and therefore causes less energy use and environmental pressure. Nevertheless, old-generation products may consume more energy than new products, which can undo energy and material savings in production. In addition, the reuse of products requires maintenance and repairing. Repairing of products has become less attractive in recent decades for several reasons. In the first place, products have generally become more complex in terms of their three-dimensional structure and the number of different materials used. Increased purchasing power has resulted in the faster replacement of products by consumers, partly because of the availability of new designs, added functions and shifting fashions. However, supply factors have also shortened the economic life of products, due to an endless search for product innovations stimulated by ‘Schumpeterian competition’. This is clearly illustrated by the rapid changes characterizing current computer and telecommunications (mobile phone) markets. Even though this can be evaluated positively from an economic perspective, many disadvantages can be identified from an environmental perspective. Only a combined analysis can provide a definite answer with regard to how to define incentives for competition, innovation and management of materials and substances.

Cascading of materials is a useful and an underrated strategy of saving energy and virgin materials. It follows from the previous point, i.e. reuse of products being generally more attractive from an environmental perspective than separate reuse of the materials and substances of which they are made. Cascading means that recycling consists of different stages. Where possible, the aim is to try to achieve the same quality of use as in the preceding stage. Otherwise, recycling involves applications of waste materials and substances to lower, but still the highest possible, quality. In other words, high-quality applications of energy and materials have priority, but as soon as the quality of materials decreases, new applications of lower quality open up. From a cascading perspective, using natural gas to heat buildings represents an enormous waste of high quality (low entropy) energy (exergy). Similarly, using virgin wood to produce packing material and high-grade paper for magazines with a short life is an enormous waste of high quality material. To promote cascading of materials, physical flows from companies with very different, and preferably ‘complementary’ processes and material input-output characteristic, must be coordinated. This should already start in the planning phase of commercial areas, as it includes elements of spatial design and proximity. (This will be further discussed in Section 2.5 on industrial ecology). At a higher aggregation level, incentives can be given to potential suppliers and buyers of waste material to stimulate their cooperation. Although successful examples of cooperation between firms exist, the best-known perhaps being the Kalundborg site in Denmark (see Chapter 11 by Jacobsen and Anderberg in this volume), most policies aimed at stimulating eco-industrial parks do not go beyond investment projects with relatively short payback times (see Chapter 12 by Boons and Janssen in this volume).

2.3.3 Dematerialization

An additional, important aim in environmental policy focused on materials and substances is dematerialization. This refers to a reduction of material throughput of the economy. It can be interpreted in several ways: namely, a reduction of substance and material weight on the level of a product, a company or the whole economy. Dematerialization at a micro-level means that the same service can be given with less direct and indirect input of substances and materials, or a shift to other, lighter materials. At the product level, dematerialization simply means that products become lighter. At a firm level, it can also imply that production processes are more materials-efficient and thus use less resource input as well as generate less material waste. In addition, dematerialization at the firm level can involve a shift to other products, or a change in the mix of products supplied. Cleveland and Ruth (1999) offer a more detailed discussion of definitions, indicators and method of analyzing dematerialization.

Dematerialization will reduce the environmental load, just like recycling, at the beginning and end of activity chains, i.e. the extraction of raw materials and waste processing. A main difference with recycling is that dematerialization is generally associated with less energy use and transport. Other terms that reflect elements of dematerialization are “eco-efficiency” and “Factor Four” (see Section 2.5).

One can also consider dematerialization at the macro-level, i.e. of the whole national or even global economy. This creates a much more complex system of factors and impacts. Factors influencing dematerialization at this level are economic growth, changes in the structure of supply (sectors) and demand, changes in import and export, and technological innovations and substitution between materials in companies. The relation between, for example, the gross national product (GNP) per capita and material use has received some attention in the literature. Jänicke et al. (1988) performed an empirical cross-sectional analysis for 31 countries, and concluded that dematerialization has occurred at the macro-level during part of the 1970s and 1980s. A follow-up study by de Bruyn and Opschoor (1997), however, shows that this type of dematerialization came to a halt around 1990, and that recently GNP and material use at a macro level have started to move in the same direction again. These types of studies are obviously rather sensitive to the choice of macro-indicators for material use. In the aforementioned studies, attention was focused on steel, energy, cement production and freight transport.

The relationship between energy use and dematerialization in US metals sectors has received attention in the context of analysis of CO_2 emissions (Ruth, 1995a, 1998). This study focuses on copper, lead, zinc, aluminum and iron and steel sectors, and describes the dynamic interrelationships among resource extraction, materials processing, fuel use and technological change using time series data and engineering information. Subsequently, projections of material, energy and CO_2 emissions are made for the period 1990 to 2020.

From a commercial point of view, dematerialization can be considered as the result of a decision process that involves a number of considerations and trade-offs. Attention can be given to the size of a product (“miniaturization”), the use of light materials, the complexity of a product and its production, the physical and economic lifetime of a product, the available range of reuse options, and the safety of transporting and using a product (Herman et al., 1989). The expected costs and profits of alternative investments in new processes and products will, of course, be most influential on any decision. In addition to the supply perspective, a demand perspective can be adopted. This can create a longer time perspective. For example, a higher income can lead to a saturation of certain types of material consumption, closely linked to shifts towards services and leisure activities. It is not easy to make predictions in this area, due to the large number of factors involved. This in turn means that predicting patterns of dematerialization at a macro-scale will be extremely difficult. This is illustrated by the paradox that the electronic information technology revolution did not – as hoped and expected – result in less use of paper, but quite the opposite. Of course, one can argue that this revolution has only started and that in a future phase paper use per unit of output will finally decrease.

In sum, a reduction of waste through dematerialization of production and products is in principle preferred to the recycling of products, materials and substances, mainly because it involves less indirect activities and related energy use, transport, and space use, and associated environmental impacts. Recycling, however, is much easier than the control of dematerialization, because the latter has many more different dimensions and is influenced by numerous factors at micro- to macro-levels. Recycling prevents waste, but it does not reduce the size of material flows through the economy, i.e. if waste disposal and extraction phases are excluded. It is clear that a task is waiting for economists to systematically study the relations and considerations between the aforementioned strategies, as well as support choices among them with combined economic-environmental evaluation.

2.4 Themes and methods in environmental economic analysis of physical flows

2.4.1 Introduction

In this section, a brief overview is given of how economists include physical flows in their analyses. This will involve conceptual, theoretical and methodological points of view. Studying the relationship between physical changes in the economy and physical changes in the environment, and the influence of environmental policy on this relationship, is an important task of environmental economics. Changes in the economy can occur at different levels, which can be studied separately or in combination. Changes in inputs can be studied by formulating decision models with production functions; changes in intermediate products and indirect activities caused by, for instance, recycling can be examined with input-output models; changes in production and investment at a national scale can be studied by constructing growth models with material flows; and consumption and international trade can be linked to material flows in microeconomic market models.

2.4.2 Mass balance and economic analysis of material-product chains

Many studies of material flows use the earlier-mentioned mass balance principle. This allows us to make consistent statements about substances flowing in and out of a process, at any level: machine, factory, firm, industry, region, country, etc. With mass-balance conditions, the scarcity of resources can be coupled to problems of emissions and waste flows. For this purpose, models of substance and material flow have been developed (Moll, 1993; van der Voet, 1996).

For a thorough environmental or economic analysis, the concept of ‘material-product chain’ (M-P chain) can serve as a starting point (Opschoor, 1994). This indicates a system or network of coupled flows of at least one material and one product. These flows connect activities or phases in the chain, e.g. extraction, production, consumption, collection, reuse, dumping and combustion of waste. Chains are usually not isolated, even if this is often assumed in order to make analyses tractable or to restrict the amount of data required for an empirical analysis. This involves, among other things, focusing on a specific substance, material, sector, region or product.

An M-P chain can be used as a starting point for a specific analysis. It might be useful to make a distinction between an economic and an environmental M-P chain analysis. An example of the latter is life-cycle analysis (LCA), which gives an overview of the environmental effects of a product for the whole chain. This is mainly suitable for discrete decision problems (Guineé, 1995; and van den Berg et al., 1995). For example, the choice between milk packed in glass or cardboard can be based on the comparison of the most important environmental effects during the life cycle.[5]

By adding specific economic aspects to such a M-P chain, an economic M-P chain can be made. Such aspects include: the description of decision making agents in the chain; the allocation of scarce factors (work, capital); the substitution of inputs in production processes along the chain; changes in sector or firm structure that affect the structure of a chain; the dynamic aspects of investment and technological innovation; and the impact of various environmental policy instruments. Economic analysis can then be directed at questions of cost effectiveness of chain control, consequences of economic growth and development of substance flows, or the influence of environmental policy on physical flows (Ayres, 1978; Ruth, 1999). The implementation of economic M-P chain analysis requires that material balance or substance flow models are coupled to economic models. Kandelaars (1999) gives a good overview this type of work, and also presents her own studies of M-P chains.

It is possible to combine environmental and economic analyses of M-P chains. This means, for instance that a life-cycle analysis can be combined with an economic evaluation of environmental effects (van Beukering et al., 1998), or with an allocation mechanism and chain optimization (Weaver et al. 1997). The M-P chain approach makes it possible to illustrate problem shifts in environmental as well as economic dimensions, which is a central focus of industrial ecology. A choice can be made between an evaluation based on cost-effectiveness under given environmental and economic conditions (Starreveld and van Ierland, 1994; and Kandelaars and van den Bergh, 1996a and b), or on a multi-criteria analysis (Kandelaars and van den Bergh, 1997). The latter points to a difficult problem associated with environmental life-cycle analysis: namely, the

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[5] Heijungs (1997) presents a methodological comparison of the various formal methods of analysis commonly used within environmental science, notably MFA, LCA and I/O modeling.

comparison of different environmental effects. Ayres (1995) states that economic monetary evaluation is, despite its limitations, the only consistent approach for the comparison of different environmental effects. Beukering (2001) presents various models that operationalize this idea. In addition, he introduces the notion of an international material product chain (I-M-P chain), which combines material-flow models with descriptions of interactions between various economic agents of activities or countries. The I-M-P chain tries to describe the spatial dimensions of 'industrial metabolism', and will be discussed in more detail in Section 2.5 on industrial ecology.

What are the essential differences between the life-cycle analysis, economic M-P chain analysis and substance flow analysis (Bouman et al. 2000)? Unlike economic M-P chain analysis, life-cycle analysis and substance or material flow analysis do not address economic questions, since they lack a description of economic decision and market processes. Moreover, M-P chain analysis explicitly distinguishes the dimension 'products', while both substance and material flow analysis not. Contrary to life-cycle analysis, economic M-P chain analysis describes interactions between flows of different products. Finally, a major strength of economic M-P chain analysis is that it connects the essence of life-cycle analysis with the essence of substance flow analysis, albeit in manner that simplifies both approaches, so as to control the amount of complexity involved in description and analysis (Kandelaars and van den Bergh, 1997).

Unlike in traditional economics, M-P chain analysis does not consider consumption to be merely a process where consumption goods enter, and utility or welfare is the only output. Products have a life cycle, and can best be regarded as capital goods, in that they exist and are used during a considerable period of time to render services (Noorman and Schoot Uiterkamp, 1998). All this time, they retain materials and substances. From a capital perspective, the fact that many varieties of a certain product, produced at different times, are in use at the same time, suggests the use of a vintage model. This means that changes over time in the material composition of a product are taken into account. A vintage model for consumer goods in use can provide an accurate picture of accumulation of substances in the economy, as well as the time delay between the extraction of raw materials and waste processing (Kandelaars and van den Bergh, 1997). For illustrative case studies, see further Chapter 5 in this volume by Ruth et al., and Chapter 6 by Foran and Poldy.

2.4.3 Direct and indirect substitution of input and mass-balance production functions

In what way should production processes be described when material flows are studied? Georgescu-Roegen made an important contribution to environmental economics through publications on the relationship between economics and thermodynamics (Georgescu-Roegen, 1971a, 1976). Georgescu-Roegen emphasized the fact that we should distinguish between four aspects of production systems: "supplies"; "flows"; "stocks"; and "services". This division into qualitatively different inputs in the production process creates several views on substitution and complementarity. "Stocks" like machinery and work, generate services, which process "flows" (such as energy), substances and semi-manufactured products. The term "substitution" is cryptically used in many environmental-economic analyses, especially in the context of the growth debate. There is a distinction between direct and indirect substitution (van den Bergh, 1999). Direct substitution refers to changes within a category of relatively homogeneous production factors, which occupy the same function in a production process. An example within the input category "materials" is the replacement of steel by plastics and aluminum to lower the product weight. Indirect substitution refers to the relation between production factors that play a different role within a production process. This "different role" means they are to a certain degree complementary, but that some changes in the complementarity relation are possible, and these changes are identified as substitution. For example, through more input of work or machines in processing a material into a product, production waste (given a certain production level) can be avoided or primary recycling can be increased, all resulting in a reduction in material use. Direct substitution can be considered as the 'replacement' of one input by another, e.g. with different materials. Indirect substitution is closer to "saving" or "increase in efficiency and productivity".

Thermodynamics teaches us that indirect substitution of materials or energy and other inputs in production can only occur within limits. By using more work or machinery in the production, the amount of material input required can be reduced, but not to zero, at least if the production output is a physical good. What is the influence of technical change on these aforementioned relationships between production inputs? No fundamental changes occur, although a technological or thermodynamic optimum can be approached. This is, however, limited by certain characteristics of a production process (Berry et al., 1978).

The standard production functions used by economists, also named neoclassical production functions – for example, of the Cobb-Douglas type – at first sight, seem inconsistent with the lessons of thermodynamics, especially the derived material-balance principle. Cleveland and Ruth (1997) and Daly (1997) argue that production functions describe inputs usually in a symmetric or identical way, so that qualitative differences between the distinct categories of inputs do not become clear. Characteristics of flows, supplies and stocks are therefore not explicitly distinguished, which makes the models not very suitable for studying substitution problems. To achieve a minimal level of realism in material flow studies, a separate variable "material inputs" should be part of any production function, or be "essential".

According to the definition of "essential" by Dasgupta and Heal (1997), in order to have a positive output of production, a strictly positive amount of material input is required. The amount, however, does not need to have a positive lower limit, as long as the marginal productivity of production inputs is assumed to go to infinity when the production output approaches zero. Although this assumption seems unrealistic at first, this cannot be proved. This is caused by the fact that it involves a translation of physical units (substances, materials) into functional (product) units or monetary (value) units. It has turned out to be impossible to determine an absolute upper limit for the amount of value to be derived from a given amount of material inputs, even if it is thought that such a limit should exist (see Stern, 1997). This leaves room for different, subjective opinions, leading, for instance, to the coexistence of growth optimists and pessimists. A more explicit approach to studying substitution in production, as proposed above, could contribute to a better understanding of the differences between positions in the growth debate.[6]

2.4.4 Environmental economic analysis of recycling

The economic analysis of recycling is still underdeveloped within environmental economics. This might be caused by the fact that we do not consider recycling and processing of waste as standard categories of economic production.[7]

The economic study of recycling can start with an interaction between new and reused materials (or products), which can be considered as imperfect substitutes. The price of each good will depend on the prices of other goods and the cross-price elasticity of the demand, on the one hand, and the costs of new and reused materials (or products) on the other hand. The latter can include several categories of costs, such as of collection, cleaning, separation, and chemical processing. As long as these costs are relatively high compared with the costs of new materials, the recycling of some substances and materials will remain a small-scale activity. To equalize the two types of costs, scarcity of raw materials as well as environmental consequences of waste flows and emissions need to be translated into adequate levies on materials.

Generally, the prices of waste materials suitable for reuse are subject to much fluctuation as compared with product prices in general. In the United States, this is the case for old paper,

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[6] Production functions combined with the mass-balance principle have been formulated by Georgescu-Roegen (1971b), Gross and Veendorp (1990), van den Bergh and Nijkamp (1994), Ruth (1995b) and van den Bergh (1999).

[7] The following publications offer theoretical economic considerations of waste control and recycling. Turner (1995) uses a partial static equilibrium framework. Dynamic models of recycling are studied in Lusky (1975) and van den Bergh and Nijkamp (1994). Dinan (1993) and Fullerton and Kinnaman (1995) study recycling with theoretical general equilibrium models. Recent overviews of economic aspects and models of recycling can be found in McClain (1995), Kandelaars (1999), Kandelaars and van den Bergh (2001), and van Beukering (2001).

aluminum waste and iron. This is probably caused by a combination of economic business cycles and scarcity and price developments of new materials. In addition, an important factor may be that industrial activities often prefer new substances and materials instead of used ones (see Ackerman, 1997).

A striking feature of reuse and recycling is that the collection of some used products and materials seems to take place even when the cost savings are small and economic incentives are missing. Ackerman (1997) states that consumers seem to realize that their high level of material consumption has negative consequences for the environment. They try to compensate for this by regularly visiting the paper and glass containers. Probably this apparently altruistically behavior only occurs for their own peace of mind, since the material consumption does not become less. This view on recycling and reuse as the most logic practical contribution that individual consumers can make to a "better environment" corresponds to the recycling ideology as propagated by several environmental organizations. But perhaps a more credible explanation for "collection behavior" is that recycling has become a social norm, at least one which has spread through a part of society. Whatever the explanation, economists should ask themselves whether their models are correct in this respect, and which insights alternative behavioral theories suggest as to what can be expected from price instruments of material policy (van den Bergh et al. 2000).

A trend of the last decades is that recycling is increasingly linked to international trade, following the general pattern of globalization. In order to judge whether such a trend is desirable from economic, environmental and developmental perspectives, there is a need for careful analysis that takes into account the wide range of externalities in the material-product chain – from extraction through production to consumption and back through recycling to production. Van Beukering (2001) presents a number of statistical and optimization analyses to examine these issues (see also Section 2.5.3).

2.4.5 Input-output analysis of economic structure changes

Let us consider a higher level: namely, the structure of the economy. By relating changes in material flows to changes in economic structure, one can learn which changes are more or less desirable from a combined economic-environmental perspective. In particular, a structural decomposition analysis can be performed. This provides information about the relationship between changes in physical flows and changes in factors like volume, technology, sector structure, input structure of sectors, final consumption and export. Such an analysis uses, among other things, information contained in detailed input-output (I/O) tables of the economy. Such tables describe the economic structure through information about the mutual delivery of materials and semi-manufactured materials within economic sectors. By comparing two input-output tables for different years, the indirect effects of changes in one sector to other sectors can be taken into account. This technique is known as structural decomposition analysis (SDA). By linking this to environmental indicators, a detailed insight is obtained about which changes have gone along with, and possibly have caused, certain changes in environmental pressure and material flows (Rose and Casler, 1996). Rose (1999) and Hoekstra and van den Bergh (2002, 2003) present the state of the art of this technique as well as applications to material flow analysis. Rose et al. (1996) is the first application of SDA to material flow indicators. Wier and Hasler (1999) use SDA in a study of nitrogen in Denmark. Hoekstra (2003) presents a detailed analysis with SDA of material flows (iron and metals, and plastics) for the Netherlands. This study produced two hybrid-unit I/O tables, for 1990 and 1997, and analyses these using SDA. Subsequently, the results serve as an input to backcasting and forecasting scenario analyses (see Chapter 4 for more details).

When the relationship between economic structure and physical flows is studied, the purpose is usually to create long period views about economic development. Input-output modeling can be useful then, because not only does it focus on structure but it also avoids excessive assumptions regarding substitution, market characteristics and individual behavior. In addition, it allows integration with data on substance flows, which in turn can be linked to natural resources, waste and emissions in national accounts. Moreover, material balance conditions can easily be added, since they fit the linear I/O structure seamlessly. Second, an I/O model, however detailed it might be, can be extended with an optimization module without losing operationality. The Dutch WRR-study *Space for growth* (WRR, 1987), and the DEOS-study *Sustainable economic development structures* (Dellink et al., 1996) are examples of this. Finally, the coupling of I/O models to market models or applied (general-) equilibrium models is possible, although this requires much work. The most important advantage of a combined I/O-equilibrium model is that it allows more refined policy analysis in which the influence of specific policy instruments on the behavior of producers and consumers is taken into account.[8]

Duchin (1996) has argued in favor of using dynamic input-output analysis in environmental economics, and Duchin (1992) has done the same for industrial ecology. The implementation of this means that a great deal of attention needs to be given to the design of logical and detailed future scenarios. Those scenarios gather information about new technologies with respect to energy saving, reduction measures, dematerialization and recycling. Duchin and Lange, supported by Thonstad and Idenburg (1994), made an empirical input-output analysis to test a “hypothesis” given in the well-known report *Our Common Future* of the Brundtland Committee (WCED, 1987). This hypothesis states that economic growth and ecological sustainability at a world-scale can be united. The I/O model, through which this hypothesis was tested, is a sort of updated version of the Leontief I/O world model from the 1970s. The analysis relates to the period 1980 to 2020. The model describes 16 regions, 50 sectors and changes in the international trade of goods, capital flows and economic and development aid. Calculations with the model of the effects of detailed scenarios, mainly on energy and material use of metals, cement, paper and chemicals mainly, show rising trends for the world as a whole. Environmental pressure indicators are calculated as well: CO_2 emissions double worldwide in the studied period; emissions of SO_2 main nearly constant; and NO_x emissions more or less double. These and other results lead to a clear rejection of the hypothesis of the Brundtland Committee. Strictly speaking, this implies that we should think about how development instead of growth in GDP terms can be combined with sustainable environment quality at a world scale. For a similar study with a dynamic I/O model, but at a national level, see the DIMITRI-model study by Idenburg and Wilting in this volume (Chapter 8).[9]

Altogether, the scenarios and the I/O model can assemble an incredible amount of information in a clear and consistent way in a prospective dynamical analysis. “Natural resource accounting” and “social accounting matrices” offer a basis for this. Disaggregation is thus possible of households with respect to income, education, labor, family size or surroundings (for example city or countryside). This allows, for example, the study of changes in lifestyle and demographic developments. Evidently, both have wide ranging consequences for the use of products, and indirectly material and substance flows. In addition, the use of physical flow information at the level of economic sectors, leading to physical I/O tables, can provide much insight. The construction of these, however, is a very time-consuming task that has not often been performed (on this issue, see Chapter 4 by Hoekstra and van den Bergh in this volume). Conclusively, we can say that dynamic I/O models in combination with scenarios are able to translate a detailed description of reality into possible future patterns of physical flows and economic structure. Operationalizing them is, however, a very laborious task.

2.4.6 Other macro models

Endogenous substitution within sectors and price mechanisms does not play a role in input-output analysis. That would require market and price balance models, which can describe the total economy, or part of it. An example is the STREAM-model, which has been developed by the

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[8] Dellink and Kandelaars (2000) performed an analysis in which an applied general balance model is combined with a material flow model. A similar type of dynamic model has been developed by Ibenholt (2003) who applied it to Norway.

[9] Perrings (1986, 1987) presents a very abstract and general mass balance I/O approach that covers interactions not only among sectors within the economy but also between the economy and the environment.

Central Planning Bureau in cooperation with the RIVM, both of which are Dutch research institutes concerned, respectively, with economics and the environment (see Chapter 7 by Mannaerts, in this volume). STREAM is an empirical partial equilibrium model with sectors as units, developed to study the size and causes of environmental problems related to the flows of seven bulk goods through the Dutch and European economy: iron and steel, aluminum, artificial manure, chlorine, plastics, phosphor and paper. Each of these is characterized by specific options and costs coupled to dematerialization, reuse and waste management. Because of the aggregate character of the model, cost curves are constructed that classify the technically possible options within each of those strategies of marginal cost effectiveness. This allows, for example, the study of recycling at a macro-level.

STREAM employs a macro-level of aggregation. Other macro-level models have followed a resource accounting framework, which aims to include information on the use of flow and stock resources from the environment into an economic framework. Resource accounting explicitly links information on processes in the economy with that on processes in the environment. Energy is often used as the general resource factor. An interesting framework used to study the physical dimensions of economic systems is the ECCO approach: Enhancement of Capital Creation Options (Slesser, 1990). This has seen a number of applications (Noorman, 1995; Ryan 1995, Slesser et al. 1997; Battjes, 1999; and Chapter 6 by Foran and Poldy, in this volume). The ECCO modeling approach can be characterized as a dynamic energy-accounting approach that links the production of human-made capital to the natural capital that physically enables a given production level. The ECCO methodology determines the system-wide, long-term effects of implementing policy options at the national/regional level. It does this by determining the growth potential of the economy in the context of the existing economic structure and user-defined policies, technology options and environmental objectives. In turn, changes in growth potential alter a wide range of demand and supply terms, and so reflect many other aspects of the evolving economy.

The ECCO models emphasize the physical fixed capital requirement associated with a policy, and the ability of the economic system to deliver that capital, either by direct manufacture or trade. The wider impacts of policies are realized through their effect on the overall allocation of fixed capital between sectors, and therefore on the rate of growth of the system, which is endogenously computed.

2.4.7 Growth debate and material flows

The relation between economic growth and material flows in the longer run remains a difficult topic. The earlier discussed thermodynamical insights do not easily and directly lead to absolute physical limits at the macro-level. The reason is the aforementioned separation between value (welfare, use, monetary value) and physical amount (kg, joules). This is one of the reasons for the “growth debate”. This can be explained best by the following three main questions: Is economic growth desired? Is economic growth possible? And can we control or regulate economic growth? (van den Bergh and de Mooij, 1999). The growth optimistic view is disseminated by, among others, the economists Julian Simon (e.g. Simon and Kahn, 1984) and Wilfred Beckerman (1999). They state that growth is good and maybe even necessary for both a good environmental policy and the maintenance or recovery of environmental quality. The most recent support for this, according to some scholars, is “environmental or green Kuznets curves (ECK)”. These are empirical assessments of a “de-linking” of growth (income per capita) and certain environmental pressure indicators. A possible explanation is that a higher income is associated with a more advanced technology, allowing, for instance, to use resources in production more efficiently. Moreover, income growth leads to an increased interest in the quality of nature and the environment, which is known to economists as the “environment as a luxury good”. However, the hypothesis is valid for only a limited number of environmental indicators, which moreover have a weak relationship with global or even local sustainability issues (de Bruyn and Heintz, 1999). In addition, the EKC research reflects that environmental policy has emphasized urgent and local environmental problems threatening human health. Other problems, of a worldwide character, or waste problems, are postponed in space or time. However, due to the partial character of the EKC studies, these aspects are neglected.

What role do materials and thermodynamics play in the growth debate? Obviously, growth of all physical flows through economy inevitably leads to more environmental pressure, ceteris paribus. But what is the effect of GDP growth, which is not necessarily equivalent to an increase of the "physical economy". Maybe a substitution between inputs in production away from material resources, or from consumption of goods to services, can succeed in combining such a growth with dematerialization at the macro-level. For example, an increase of "clean" services in the GDP is noticeable for most countries over the recent decades. The question is, of course, whether such a trend can continue. The connection between activities suggests that it is likely that service sector growth implies growth of environmental pressure caused by intermediate sectors that are more material-intensive and pollutive. Such intermediate relations would imply a limit to dematerialization at the macro-level. D'Arge and Kogiku (1973), Gross and Veendorp (1990), van den Bergh (1993), and van den Bergh and Nijkamp (1994) have included mass balance in economic growth models to deal with this question at a theoretical level. Structural decomposition analysis, discussed in the Section 2.4.5, can get a grip on this issue from empirical and policy-relevant angle.

Next, an important question is whether recycling of substances, materials and products offers a solution for important environmental problems. This comes down to the question of whether 100% recycling is possible. Many individuals have studied this, but it is has turned out to be difficult, if not impossible, to come up with a resolute 'yes' or 'no'. The diffusion of substances is an argument for a 'no' – think of rubber particles lost from a tire being used on the road, or the peeling-off of metal-containing paint through weathering. Practically seen, it seems impossible to collect all substances. 100% recycling might be approximated when energy is available without limit and cost. But then problems related to energy will of course create a bottleneck. On the other hand, Ayres has stated that perhaps not all substances and materials are totally reusable at the same time, but that each time a considerable part can be reused. For this, he has proposed the terminology "waste mining" (see, e.g., Ayres and Ayres, 1996).

2.5 From extended material flow analysis to industrial ecology

2.5.1 Introduction

Since the late 1980s, an integrated perspective on physical flows industrial systems has been called "industrial ecology" (Allenby and Richards, 1994; Socolow et al., 1994; Greadel and Allenby, 2003; Ayres and Ayres, 2002). A central metaphor of this field is "industrial ecosystem", which reflects the fact that an objective in an industrial system can be that "the consumption of energy and materials is optimized and effluents of one process … serve as the raw materials for another process" (Frosch and Galopoulos, 1989: 94), much like nutrient flows in biological ecosystems. An ecosystem, is "the living community and the nonliving environment functioning together" (Odum, 1963: p. 4). The boundaries of ecosystems are not always clearly geographically-defined, except for islands or lakes, and are often linked to cycles of energy, water, nutrients and carbon. Analogously, industrial production units that are linked to one another through fluxes of materials and energy can be thought of as comprising an industrial ecosystem. An industrial ecosystem is seen as a network of mutually-dependent transformation processes, which form part of a larger whole, analogous to the function of a local community or ecosystem in relation with its global environment.

Below, we examine a number of themes in industrial ecology from an economic perspective.

2.5.2 Industrial metabolism

Related to the notion of industrial ecology is that of "industrial metabolism". This refers to flows of materials and energy within and between industrial and ecological systems, as well as their transformation in products, by-products and effluents (Ayres and Simonis, 1994; Ayres, 1999b). Both the metabolism of economic systems and that of organisms changes over time through natural or social-economic evolution as well as through coevolution of the environment-economy system (van den Bergh and Gowdy, 2000). Nevertheless, the change in the metabolism mechanism of economic systems is much more rapid: witness the history of mankind, from the Stone Age through to the Industrial Revolution on to the current Information Age. The diversity of products, materials and substances, as well as of production processes, human labor, and interactions among economic agents, has increased tremendously. Moreover, direct connections between agents now extend throughout the globe, which is the fundamental feature of the often misused concept of "globalization". Materials and substances that come in large volumes or are exotic to the natural environment have a disturbing influence on global biogeochemical cycles. The world economy can no longer be regarded as a minor influence on its environment.

One of the insights from industrial ecology and industrial metabolism is that partial policies focused on one part of a system may lead to problem shifting to another part of the system. To avoid this problem, an integrated, system-wide approach is required. It is fair to say, however, that all applied studies in the area of industrial ecology unavoidably have some element of incompleteness or partiality as well. The boundaries of the relevant system have then to be decided on the basis of interactions with a wider system that are considered negligible.

Research on industrial metabolism has focused on the description of material flows in economic systems (see, e.g., the case studies in Ayres and Simonis (1994)). Studies along these lines provide insights about the size of material flows and the identification of stocks in which certain materials accumulate. (For a study on heavy metals see, for instance, Guinée et al., 1999.) This leads to concepts like "chemical time-bombs" – think of the accumulation of chemicals in the river soils – and "waste mining" – materials accumulating that can become an important resource in the future (Stigliani et al., 1991; Rohatgi et al., 1998). However, several issues cannot be addressed properly with such a descriptive approach, especially the (economic) motivations underlying the actions of the economic agents.

Ayres (1994) noted that the economic system is a metabolic regulatory mechanism that balances 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 can no longer be converted into useful materials or products in an economically feasible way. The materials can come from various stages in the industrial material cycle.

Products of one firm can be used as an input by another. Firms are part of some sort of material cycle. 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, in order to explicitly include the waste treatment sector (Figure 2.1). Materials are extracted from the environment and used to produce final commodities, which in turn are used to produce consumer products. Waste is generated in every step of the material cycle. This waste disappears to the environment, or is collected for reuse or recycling.

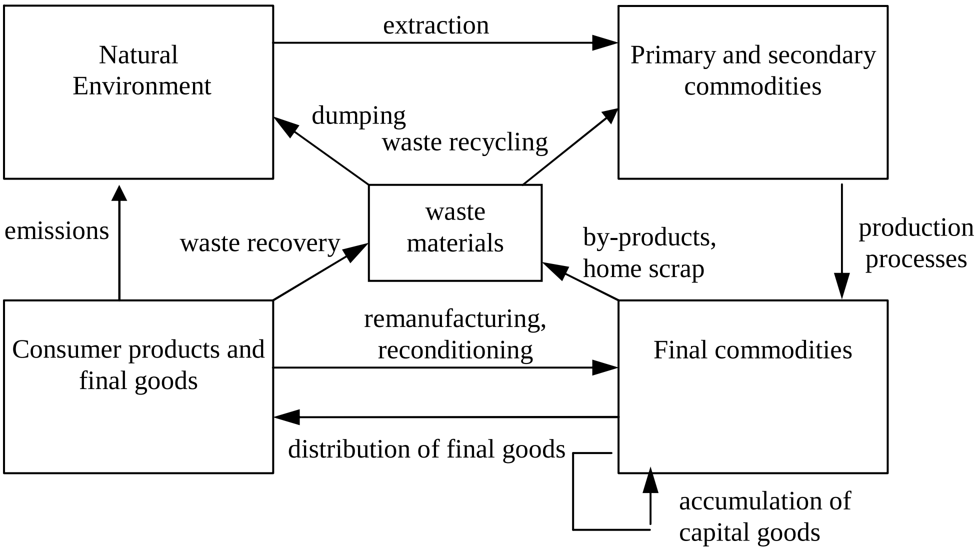

Figure 2.1: 5-Box Scheme for Industrial Material Cycles
Source: Adapted from Ayres (1998).

2.5.3 International material product chains

The relationship between materials flows and international trade has received some attention from economists. An early study is Grace et al. (1978). Van Beukering et al. (2001) discuss a multi-regional version of international material cycles, also known as the international material product chain (I-M-P chain). This combines descriptions of material flows with those of interactions between various economic agents or activities in different countries. The I-M-P chain describes the physical dimension of economic systems in a setting of international interactions.

Figure 2.2 shows a possible I-M-P chain for two interacting or trading countries. Country A represents a developed country that is well-endowed with high-tech capital, skilled labor and recyclable waste materials. Country B represents a developing country that 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. Note that trade can relate to all stages of the chain. Materials and products flow horizontally, diagonally and vertically from one segment to another within the international M-P chain. Horizontal flows reflect intra-industry trade, while diagonal flows indicate inter-industry trade. The traditional M-P chain is represented by the autarchic vertical material flows within each country, given that borders are closed and countries are fully dependent on their own resources.

Traditionally, the immobility of labor and capital has caused natural resource availability to be an important driving factor of inter-industry trade. 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 I-M-P chain. Differences in strictness of environmental policies have caused polluted materials and products to flow to developing countries.

Empirical studies confirm changes in the I-M-P chain (van Beukering and Bouman, 2001). A pattern that links developed and developing countries has emerged. In particular, developing countries have become more important as importers of primary and secondary commodities, and as exporters of commodities to their own region (van Beukering, 2001). A number of other studies also address empirical issues of trade in materials (Byström and Lönnstedt, 1995; Michael, 1998; van Beukering and Duraiappah, 1998; and van Beukering and Janssen, 2001).

Finally, Janssen and van den Bergh (in press) link international trade in materials to the research on environmental Kuznets curves (EKC), which addresses the relationship between economic growth and environmental pressure (see Section 2.4.7). They formulate a numerical optimal growth model with material resource use in two trading countries, and then simulate a number of scenarios. The results can explain some of the patterns obtained by empirical EKC studies.

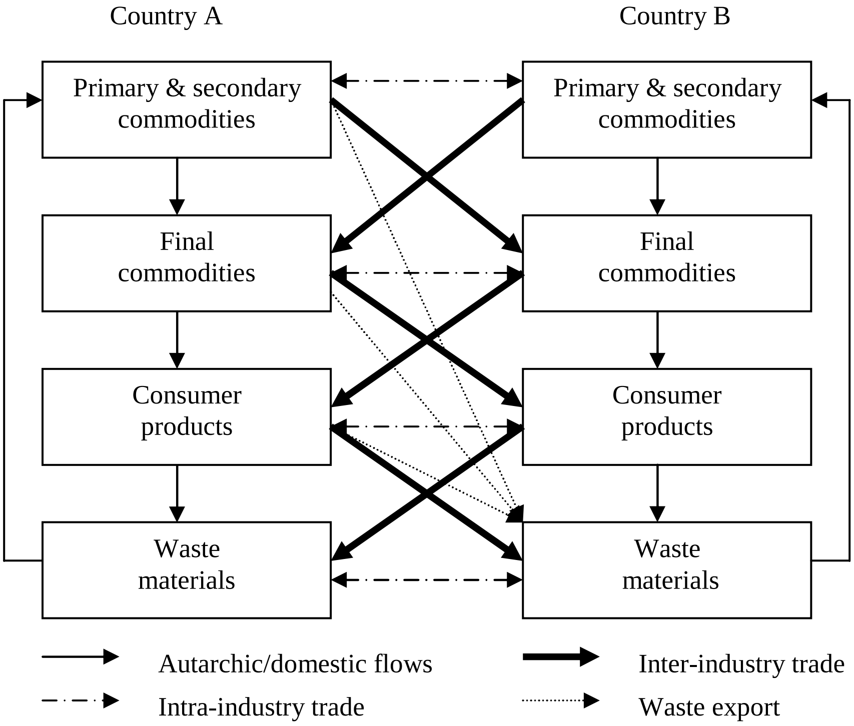

Figure 2.2: An example of the international material-product chain
Source: van Beukering et al. (2001).

2.5.4 Industrial symbiosis

One of the most noticeable topics in industrial ecology is the analysis of “industrial parks”. This relates to the concept of “industrial symbiosis”, i.e. the idea that the negative ecological impact of industrial activities can be reduced efficiently and effectively by stimulating the spatial proximity of location, and cooperation among firms. By stimulating a larger, organized system of industrial relations, it is possible to prevent spillover effects: the possibility that efforts to reduce negative ecological impact in one part of the system create additional/worse impacts in other parts of the system. In a collective approach, firms achieve competitive advantage by physical exchange of materials, energy, water and/or by-products (Chertow, 2000). A prominent example of a successful industrial symbiosis is the industrial park at Kalundborg in Denmark (see Chapter 11 by Jacobsen and Anderberg, in this volume). Even though the term “park” suggests a planned or artificial approach, it can be the outcome of a slow process of self-organization, assisted by a policy environment that is favorable to cooperation and symbiosis. Desrochers (2002) broadens the industrial symbiosis concept from an industrial park to an entire city.

Sager and Frosch (1997) have studied the metals sector in New England (Figure 2.3). They found that this sector has developed into a well-functioning industrial ecosystem, indicated by very low percentages of material loss from the system: 0.5% for copper and 4.5% for lead. They found that larger firms are more efficient, but concluded from a survey for all 35 metal-processing firms that these do not employ an industrial symbiosis perspective. Industrial symbiosis can be regarded as an emergent property of the system of local interactions of individual firms. A critical role in the functioning of the whole system is played by the secondary processors, such as scrap dealers and melters. Sager and Frosch also discovered that a transparent governmental waste policy in terms of prices and regulation stimulates the performance of the industrial ecosystem. In contrast with Kalundborg (which is characterized by fixed interactions among firms associated with particular physical flows), in New England, the metals sector is more flexible due to mobile links among production firms, scrap dealers and melters. Due to these mobile links, the industrial ecosystem has probably a larger capacity to adapt to external stimuli than one characterized by fixed links – the latter being more fragile.

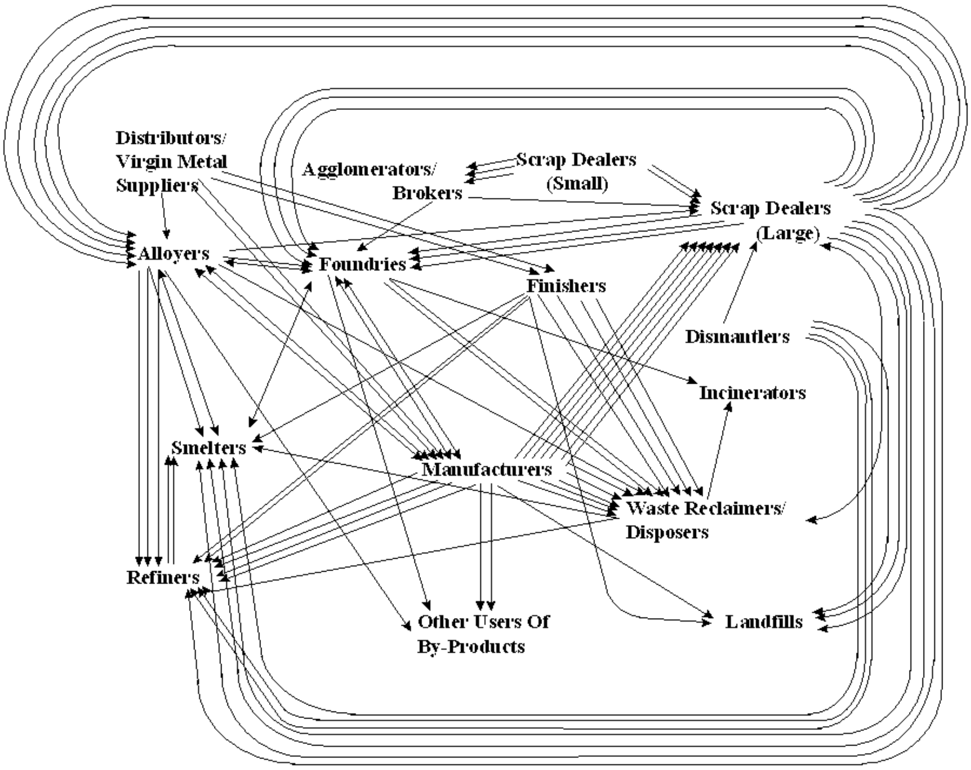

Figure 2.3: Flows of metals among metals processors in New England
Source: Frosch et al. (1996).

Industrial ecosystems can be analyzed at various levels of aggregation, depending on whether the core questions deal with the context or the underlying mechanisms. At the lowest level, concrete people and products come in view. Andrews (2001) argues that the agency level needs to be studied so as to understand the human considerations and motivations – possibly involving profits, welfare, ethics and social norms – that ultimately drive industrial ecology. An important area of micro level analysis is consumer behavior. Current economies are very much focused on the consumption of material goods instead of maximizing the utilization of these goods (Stahel, 1994). Axtell et al. (2002) argue in favor of applying (multi-)agent models in industrial ecology, which they argue are capable of analysing with innovation, cooperation and diffusion processes.

2.5.5 Services and dematerialization

A transition from a consumption economy towards a service economy would emphasize the function or service that products may provide instead of emphasizing the ownership of the product itself. Examples are laundry services, car-pooling or car sharing services, teleshopping, maintenance services, etc. The choice is thus between buying a good or buying its services – for example, buying a washing machine, or bringing your clothes to a laundry service centre. The latter means a more professional approach, economies of scale, better maintenance of machines, and more control of material and waste water flows. Stimulation of services will require a behavioral change of both consumers and firms. For example, by sharing products, service companies will make it more logical to consider the repair or refurbishing of products, thus considering all consumer products as valuable capital goods – as a possible course of action. In order to elicit such a transition, product designs and product services need to change. Products need to be developed in such a way that components can be taken back for re-manufacturing. Re-manufacturing is different from recycling in that it is a form of product prolongation, not a simple material loop-closing (Stahel, 1994). Innovative producers may perceive a possible new market share for alternative dematerialized products, and hence may adopt machines that are more robust, reparable and adjustable qua function. Innovative consumers, i.e. the first individuals that start using alternative products, provide a behavioral example to other consumers.

It is expected that a service economy would be much less material intensive, relative to the satisfaction of human needs, than the present consumption economy (Ehrenfeld, 1997). Technical options like changing product design can significantly reduce material and energy use. The market entrance of such products, however, often fails. One reason is that current production and consumption patterns are “locked-in” (Arthur 1989), indicating that the behavior of agents is interdependent, due to network externalities, social imitation, switching costs, or simply economies of scale. A misunderstanding is the idea that lock-in is permanent. History shows that all kinds of technologies eventually become replaced by a new technology. In the case of text processors, WordPerfect has replaced WordStar and nowadays Word is the dominating text processor. Even the popular lock-in example of the QWERTY keyboard may become replaced one day by another technology: for example, technology related to speech recognition. Janssen and Jager (2002) present a simulation model of coevolution of product choice by consumers and product development by firms. They find that successful introduction of alternative products needs to be accompanied by adequate price shocks to get out of the locked-in situation.

2.5.6 “Factor Four” and rebound effects

Many authors have focused attention on improving “eco-efficiency”, i.e. the environmental performance per unit of useful economic output. Solutions comprise technical design of products and processes, organisation and logistics. The “Factor Four” approach promoted by the German Wuppertal Institute is perhaps the best-known exponent of this. Factor Four denotes that a doubling of welfare is feasible while halving material and energy use (Von Weizsäcker et al., 1997). There is, however, a risk that all concrete “eco-efficiency” suggestions at a micro-level give rise to overly optimistic estimations of net gains on materials at a macro-level. The reason is that indirect effects that run through various markets (resources, products, capital, labor and financial) may be significant. This can stimulate substitution patterns in production and consumption that ultimately may undo part of the first-order eco-efficiency gains. Such indirect effects are now known under various names: general equilibrium, macroeconomic or rebound effects. For example, through less use of a particular material resource due to a new production technology or product design, prices of the respective resource will fall, which in turn can increase the use of the original products or processes, or stimulate entirely new uses of the resource. Only an integration of industrial ecology and economic models (i.e. technical information, material flows and economic mechanisms) will make it possible to solve such difficult issues. Reijnders (1998) in addition argues that in striving for a factor X improvement, achievable values of X will widely vary among economic activities, depending on the specific technological, economic and institutional conditions prevailing. The relevance of institutions for eco-efficiency is stressed by Bleischwitz (2003). Again, models representing a good integration of economics, technology and institutions are needed to address these issues.

2.6 Conclusions

This chapter has shown that there is an overlap of interest and expertise between industrial ecology, ecological economics and environmental economics. Each covers a wide range of approaches to study physical flows through firms, sectors and the economy as a whole. More important, however, is that their methods and insights are largely complementary. This suggests a need for further linking and integration.

Physical flows cover a variety of specific materials and substances, each with unique potential environmental impacts. Especially when addressing larger material flows, materials accounting, using the mass balance principle, is indispensable to arrive at accurate prediction and scenario analysis that can provide useful information for policymaking. Dynamic analysis of the relationship between growth and material flows suggests a number of critical factors: dematerialization at product and production technology levels; recycling of substances, materials and products; and changes in the structure of demand and production.

Environmental and ecological economics offer various conceptual frameworks and techniques to study the contribution of the various factors. They can be linked to ideas coming from the young field of industrial ecology. This, however, emphasizes the risks of transferring environmental problems in systems, space and time. The future promises more linkages between these fields of research. This is particularly useful for studying the design and multidimensional impacts of innovative policies, such as those aimed at chain management, cascading of substances and materials, waste mining, substance deposit-refund systems, and producer lifetime-long responsibility for, and ownership of, final products.

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References

Ackerman, F. (1997). *Why Do We Recycle? Markets, Values, and Public Policy.* Island Press, Washington D.C.

Allenby, B.R. and D.A. Richards (eds.) (1994) The Greening of Industrial Ecosystems, National Academy Press, Washington, DC.

Andrews, C.J. (2001) Building a micro foundation for industrial ecology, *Journal of Industrial Ecology*, 4(3): 35-51.

Arthur, B. (1989). Competing technologies, increasing returns, and lock-in by historical events. *Economic Journal* 99: 116-131.

Axtell R, C.J. Andrews and M.J. Small. (2002). Agent-based modeling and industrial ecology. *Journal of Industrial Ecology* 5(4): 10-13.

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

Ayres, R.U. (1978). *Resources, Environment and Economics: Applications of the Materials/ Energy Balance Principle*. Wiley-Interscience, New York.

Ayres, R.U. (1994) Industrial metabolism. In: R.U. Ayres and U.E. Simonis (eds.), *Industrial metabolism – restructuring for sustainable development*. United Nations University Press, Tokyo, Japan, Chapter 1.

Ayres, R.U. (1995). Life cycle analysis: A critique. *Resources, Conservation and Recycling* 14: 199-223.

Ayres, R.U. (1998). Industrial metabolism: Work in progress. In: J.C.J.M. van den Bergh and M.W. Hofkes (eds.), *Theory and Implementation of Economic Models for Sustainable Development.* Kluwer Academic Publishers, Dordrecht: 195-228.

Ayres, R.U. (1999a). Materials, economics and the environment. In: J.C.J.M. van den Bergh (ed.). *Handbook of Environmental and Resource Economics*. Cheltenham, U.K., pp. 867-894.

Ayres, R.U. (1999b). Industrial metabolism and the grand nutrient cycles. In: J.C.J.M. van den Bergh (ed.). *Handbook of Environmental and Resource Economics*. Cheltenham, U.K.,pp. 912-945.

Ayres, R.U., and L.W. Ayres (1996). *Industrial Ecology: Towards Closing the Materials Cycle.* Edward Elgar, Cheltenham.

Ayres, R.U., and L.W. Ayres (2002) (eds.). *A Handbook of Industrial Ecology*. Edward Elgar Publishing, Cheltenham.

Ayres, R.U. and U.E. Simonis (eds.) (1994). *Industrial metabolism, restructuring for sustainable development*, United Nations University Press, Tokyo, Japan.

Battjes, J.J. (1999) Dynamic Modelling of Energy Stocks and Flows in the Economy (An Energy Accounting Approach, Ph.D. Thesis, University of Groningen, the Netherlands.

Baumol, W.J. and W.E. Oates (1988), *The Theory of Environmental Policy*. 2nd ed. Cambridge University Press, Cambridge, UK.

Beckerman, W. (1999). A pro-growth perspective. In: J.C.J.M. van den Bergh (ed.). *Handbook of Environmental and Resource Economics*. Edward Elgar, Cheltenham.

Berg, N.W. van den, C.E. Dutilh and G. Huppes (1995). *LCA voor beginners – Handleiding milieugerichte levenscyclusanalyse*. Centrum voor Milieukunde Leiden and Unilever Nederland.

Bergh, J.C.J.M. van den (1993). A framework for modelling economy-environment-development relationships based on dynamic carrying capacity, materials balance and sustainable development feedback, *Environmental and Resource Economics* 3: 395-412.

Bergh, J.C.J.M. van den (1999). Materials, capital, direct/indirect substitution, and materials balance production functions. *Land Economics* 75 (4): 547-561.

Bergh, J.C.J.M. van den, and J.M. Gowdy (2000). Evolutionary theories in environmental and resource economics: approaches and applications. *Environmental and Resource Economics* 17(1): 37-57.

Bergh, J.C.J.M. van den, and R. de Mooij (1999). An assessment of the growth debate. In: J.C.J.M. van den Bergh (ed.). *Handbook of Environmental and Resource Economics*. Edward Elgar, Cheltenham: 643-655.

Bergh, J.C.J.M. van den, and P. Nijkamp (1994). Dynamic macro modelling and materials balance. *Economic Modelling* 11: 283-307.

Bergh, J.C.J.M. van den, A. Ferrer-i-Carbonell and G. Munda (2000). Alternative models of individual behaviour and implications for environmental policy. *Ecological Economics* 32(1): 43-61.

Berry, R.S, P. Salamon and G. Heal (1978). On a relation between economic and thermodynamic optima. *Resources and Energy* 1: 125-137.

Beukering, P.J.H. van (2001). *Recycling, International Trade and the Environment: An Empirical Analysis*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Beukering, P.J.H. van and M. Bouman (2001). Empirical Evidence on Recycling and Trade of Paper and Lead in Developed and Developing Countries, *World Development* 29: 1717-1737.

Beukering, P.J.H. van and A. Duraiappah (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

Beukering, P.J.M. van and M.A. Janssen (2001). Trade and recycling of used tyres in Western and Eastern Europe, *Resources, Conservation and Recycling* 33: 235-265.

Beukering, P.J.H. van, F.A. Spaninks and F.H. Oosterhuis (1998). Economic valuation in life cycle assessment: applied to recycling and solid waste management. Report W98/02. Institute for Environmental Studies. Amsterdam.

Beukering, P.J.H. van, J.C.J.M. van den Bergh, M.A. Janssen and H. Verbruggen (2001). International material-product chains: an alternative perspective on international trade and trade theories, discussion paper TI 2000-034/3, Tinbergen Institute, Amsterdam.

Bleischwitz, R. (2003). Cognitive and institutional perspectives of eco-efficiency. *Ecological Economics* 46: 453-467.

Bouman, M., R. Heijungs, E. van der Voet and G. Huppes (2000). Material flows and economic models: an analytical comparison of SFA, LCA and partial equilibrium models. *Ecological Economics* 32(2): 195-216.

Bruyn, S.M. de, and R.J. Heintz (1999). The environmental Kuznets curve hypothesis. In: J.C.J.M. van den Bergh (ed.), *Handbook of Environmental and Resource Economics*. Edward Elgar, Cheltenham: 656-677.

Bruyn, S.M. de, and J.B. Opschoor (1997). Developments in the throughput-income relationship: theoretical and empirical observations. *Ecological Economics* 20: 255-268.

Byström, S. and L. Lönnstedt (1995). Waste paper usage and fibre flow in Western Europe. *Resources, Conservation and Recycling* 15: 111-121.

Chertow, M.R. (2000). Industrial Symbiosis: Literature and Taxonomy, *Annual Review of Energy and the Environment*, 25, 313-337.

Choe, C. and I. Fraser (1999). An economics analysis of household waste management. *Journal of Environmental Economics and Management* 38: 234-246.

Cleveland, C.J., and M. Ruth (1997). When, where, and by how much do biophysical limits constrain the economic process?; A survey of Nicholas Georgescu-Roegen’s contribution to ecological economics. *Ecological Economics* 22: 203-223.

Cleveland, C.J., and M. Ruth (1999). Indicators of dematerialization and the materials intensity of use. *Journal of Industrial Ecology* 2(3): 15-50.

Daly, H.E. (1997) Georgescu-Roegen versus Solow/Stiglitz, Ecological Economics 22: 261-266.

Daly, H.E. and A.F. Umaña (eds.) (1981). *Energy, Economics and the Environment.* AAAS Selected Symposia Series, Westview Press, Boulder, Col.

d'Arge R.C. and K.C. Kogiku (1973). Economic growth and the environment. *Review of Economic Studies* 40(1): 61-77.

Dasgupta, P.S. and G.M. Heal (1979). *Economic Theory and Exhaustible Resources,* Cambridge University Press. Cambridge University Press, Cambridge.

Dellink, R., M. Bennis and H. Verbruggen (1996). Sustainable economic structures: scenarios for sustainability in the Netherlands. IVM-report W96/27, Institute for Environmental Studies, Free University, Amsterdam.

Dellink, R.B. and P.P.A.A.H. Kandelaars (2000). An empirical analysis of dematerialisation: application to metal policies in the Netherlands. *Ecological Economics* 33: 205-218.

Desrochers, P. (2002). Cities and industrial symbiosis. *Journal of Industrial Ecology* 5(4): 29-44.

Dinan, T.M. (1993). Economic efficiency effects of alternative policies for reducing waste disposal, *Journal of Environmental Economics and Management* 25: 242-256.

DTO (1997). *DTO Sleutel Chemie – Zon en Biomassa: Bronnen van de Toekomst*. Interdepartementaal Onderzoeksprogramma Duurzame Technologische Ontwikkeling. Uitgeverij Ten Hagen & Stam, Den Haag.

Duchin, F. (1992). Industrial input-output analysis: Implications for industrial ecology, *Proceedings National Academy of Sciences*, **89**, 851-855.

Duchin, F. (1996). Ecological Economics: The Second Stage. Chapter 14 in: R. Costanza, O. Segura and J. Martinez-Alier (eds.). *Getting Down to Earth: Practical Applications of Ecological Economics.* Island Press, Washington D.C.: 285-299.

Duchin, F. and G.M. Lange, in association with K. Thonstad and A. Idenburg (1994). *The Future of the Environment: Ecological Economics and Technical Change.* Oxford University Press, Oxford.

Ehrenfeld J.R. (1997). Industrial Ecology: a framework for product and process design, *Journal of Cleaner Production* 5(1-2): 87-95.

Faber, M., H. Niemes and G. Stephan (1987). *Entropy, Environment and Resources: An Essay in Physico-Economics*. Springer-Verlag, Heidelberg.

Ferrara, I. (2003). Differential Provision of Solid Waste Collection Services in the Presence of Heterogeneous Households, *Environment and Resource Economics* 26(2): 211-226.

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

Frosch, R.A. and N.E. Gallopoulos, N.E. (1989). Strategies for manufacturing, *Scientific American*, 261(3):94-102.

Fullerton, D. and T.C. Kinnaman (1995). Garbage, recycling, and illicit burning or dumping, *Journal of Environmental Economics and Management* 29: 78-91.

Fullerton, D. and T.C. Kinnaman (1996) Household demand for garbage and recycling collection with the start of a price per bag. *American Economic Review* 86: 971-984.

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

Georgescu-Roegen, N. (1971b). Process analysis and the neoclassical theory of production.In: N. Georgescu-Roegen (1976) *Energy and Economic Myths*. Pergamon, New York.: 37-52.

Georgescu-Roegen, N. (1976). *Energy and Economic Myths*. Pergamon, New York.Graedel, T.E., and B.R. Allenby (2003). *Industrial Ecology*. 2nd edition (1st ed. 1995). Pearson Education, Prentice Hall, Upper Saddle River, NJ.

Grace, R., R.K. Turner and I. Walter (1978). Secondary materials and international trade. *Journal of Environmental Economics and Management* 5: 172-186.

Graedel, T.E., and B.R. Allenby (2003). *Industrial Ecology*. 2nd edition (1st ed. 1995). Pearson Education, Prentice Hall, Upper Saddle River, NJ.

Gross, L.S. and E.C.H. Veendorp (1990). Growth with exhaustible resources and a materials balance production function. *Natural Resource Modeling* 4: 77-94.

Guineé, J.B. (1995). *Development of a Methodology for the Environmental Life-cycle Assessment of Products – With a Case Study on Margarines.* PhD Thesis. Centre for Environmental Science, Leiden University.

Guinée, J.B., J.C.J.M. van den Bergh, G. Huppes, P. Kandelaars, T.M. Lexmond, S.W. Moolenaar, E. van der Voet and E. Verkuijlen (1999). Evaluation of risks of metal flows and accumulation in economy and environment. *Ecological Economics* 30 (1): 47-65.

Heijungs, R. (1997) Economic Drama and the Environmental Stage. Formal Derivation of Algorithmic Tools for Environmental Analysis and Decision-Support from a Unified Epistemological Principle, PhD Thesis, Leiden University, the Netherlands.

Herman, R., S.A. Ardekani and J.H. Ausubel (1989). Dematerialization. In: J.H. Ausubel and H.E. Sladovich (eds.), *Technology and Environment*. National Academy Press, Washington D.C.

Hoekstra, R. (2003). *Structural Change of the Physical Economy: Decomposition Analysis of Physical and Hybrid-Unit Input-Output Tables*. Phd Thesis. Tinbergen Institute Research Series No. 315. Thela Thesis Academic Publishing Services, Amsterdam.

Hoekstra, R. and J.C.J.M van den Bergh (2002). Structural decomposition analysis of physical flows in the economy. *Environmental and Resource Economics* 23, pp. 357-378.

Hoekstra, R. and J.C.J.M van den Bergh (2003). Comparing structural and index decomposition analysis. *Energy Economics* 25, pp. 39-64.

Hong, S. R., M. Adams, and H.A. Love (1993) An economic analysis of household recycling of solid waste: the case of Portland, Oregon. *Journal of Environmental Economics and Management* 25: 136-146.

Ibenholt, K. (2003) Material Accounting in a Macroeconomic Framework: Forecast of Waste Generated in Manufacturing Industries in Norway, *Environmental and Resource Econo*mics 26(2): 227-248.

Jänicke, M., M. Mönch, T. Ranneberg and U.E. Simonis (1988), *Structural Change and environmental impact: empirical evidence on thirty-one countries* in East and West, WZB, Berlin.

Janssen, M.A. and J.C.J.M. van den Bergh, Into the black box of environmental Kuznets curves: optimal growth and material resource use in two trading countries, *Annals of Regional Science*, in press

Janssen, M.A. and W. Jager (2002) Stimulating diffusion of green products, Co-evolution between firms and consumers. *Journal of Evolutionary Economics* 12: 283-306.

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

Kandelaars, P.P.A.A.H. and J.C.J.M. van den Bergh (1996a). Materials-product chain analysis: Theory and an application to zinc and pvc gutters. *Environmental and Resource Economics* 8: 97-118.

Kandelaars, P.P.A.A.H., and J.C.J.M. van den Bergh (1996b). A dynamic simulation model for materials-product chains: An Application to gutters. *Journal of Environmental Systems* 24: 345-371.

Kandelaars, P.P.A.A.H., and J.C.J.M. van den Bergh (1997). Dynamic analysis of materials-product chains: An application to window frames. *Ecological Economics* 22: 41-61.

Kandelaars, P.P.A.A.H. en J.C.J.M. van den Bergh (2001). A survey of material flows in economic models. *International Journal of Sustainable Development* 4(3): 282-303.

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

Linderhof, V., P. Kooreman, M. Allers and D. Wiersma (2001) Weight-Based Pricing in the Collection of Household Waste; the Oostzaan Case, *Resource and Energy Economics* 23: 359-371.

Lovelock, J.E. (1979). *Gaia: A New Look at Life on Earth*. Oxford University Press, Oxford.

Lusky, R. (1975). Optimal taxation policies for conservation and recycling. *Journal of Economic Theory* 11: 315-328.

McClain, K.T. (1995). Recycling programs. In: Bromley D.W. (ed.), *The handbook of Environmental Economics*, Blackwell, Oxford: 222-239.

Michael, J.A. (1998). Recycling, International Trade, and the Distribution of Pollution: the effect of increased U.S. paper recycling on U.S. import demand for Canadian paper. *Journal of Agricultural and Applied Economics* 30(1): 217-223.

Mirada, M.L., and J.E. Aldy (1998). Unit Pricing of residential municipal solid waste: lessons from nine case study communities. *Journal of Environmental Management* 52(1): 79-93.

Moll, H.C. (1993). *Energy Counts and Materials Matter in Models for Sustainable Development*. Ph.d. Thesis. STYX Publications, Groningen.

Molenaar, S.W. (1998). *Sustainable Management of Heavy Metals in Agro-ecosystems*. Ph.D. Thesis, Wageningen University.

Morris, G. (1994). The economics of household solid waste generation and disposal. *Journal of Environmental Economics and Management* 26: 215-234.

Noorman, K.J. (1995). Exploring Futures From an Energy Perspective: A Natural Capital Accounting model to study into the long-term economic development of the Netherlands, Ph.D thesis, University of Groningen, the Netherlands.

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

Odum, E.P. (1963), *Ecology*, Holt, Rinehalt and Winston, New York.

Opschoor, J.B. (1994). Chain management in environmental policy: analytical and evaluative concepts, in: Opschoor, J.B. and R.K. Turner (eds*.), Economic incentives and environmental policies*, Kluwer Academic Publishers, Dordrecht, pp. 197-227.

Palmer K. and M. Walls (1997) Optimal policies for solid waste disposal taxes, subsidies, and standards. *Journal of Public Economics* 65: 193-205.

Peet, J. (1992). *Energy and the Ecological Economics of Sustainability*. Island Press. Washington D.C.

Perrings, C. (1986). Conservation of mass and instability in a dynamic economy-environment system. *Journal of Environmental Economics and Management* 13: 199-211.

Perrings, C. (1987). *Economy and Environment*. Cambridge University Press, New York.

Powell, J.C., R.K. Turner and I.J. Bateman (2001). *Waste Management and Planning.* Vol. 5 in "Managing the environment for sustainable development" series. Edward Elgar, Cheltenham.

Reijnders, L. (1998). The factor X debate: setting targets for eco-efficiency. *Journal of Industrial Ecology* 2(1): 13-22.

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

Rose, A. (1999). Input-output decomposition analysis of energy and the environment. In: J.C.J.M van den Bergh (ed.), *Handbook of Environmental and Resource Economics,* Edward Elgar, Cheltenham. pp. 1164-1179.

Rose, A. and S. Casler (1996). Input-output structural decomposition analysis: A critical appraisal. *Economic Systems Research* 8: 33-62.

Rose, A., C.Y. Chen and G. Adams (1996). *Structural decomposition analysis of changes in material demand*. Working paper, The Pennsylvania State University.

Rotmans, J. and B. de Vries (1997). Perspectives on Global Change: The Targets Approach. Cambridge University Press, Cambridge, UK.

Ruth, M. (1993). *Integrating Economics, Ecology and Thermodynamics*. Kluwer Academic Publishers, Dordrecht.

Ruth, M. (1995a). Technology Change in US Iron and Steel Production: Implications for Material and Energy Use, and CO_2 Emissions, *Resources Policy*, 21 (3), 199-214.

Ruth, M. (1995b). Thermodynamic implications for natural resource extraction and technical change in US copper mining. *Environmental and Resource Economics* 6: 187-206.

Ruth, M. (1998). Dematerialization in five US metals sectors: implications for energy use and CO_2 emissions. *Resources Policy* 24(1): 1-18.

Ruth, M. (1999). Physical principles and environmental economic analysis. In: J.C.J.M. van den Bergh (ed.), *Handbook of Environmental and Resource Economics*. Edward Elgar, Cheltenham: 855-866.

Ryan, G.J. (1995) Dynamic Physical Analysis of Long-Term Economy-Environment Options, Ph.D. Thesis, University of Canterbury, U.K.

Sager, A.D. and R.A. Frosch (1997) A pespective on industrial ecology and its application to a metals-industry ecosystem, *Journal of the Cleaner Production* 5:39-45.

Shinkuma, T. (2003). On the Second-Best Policy of Household's Waste Recycling. *Environmental and Resource Economics* 24**:** 77–95.

Simon, J. and H. Kahn (1984) (eds.). *The Resourceful Earth: A Response to the Global 2000 Report.* Basil Blackwell, New York.

Slesser, M., (1990). ECCO, Simulation software for assessing national Sustainable Development. Part II, User's Manual. Resource Use Institute, Edinburgh, Scotland.

Slesser, M., J. King, and D.C. Crane (1997) The Management of Greed, a Bio-Physical Appraisal of Environment and Economic Paradigm, Resource Use Institute, Ltd. Dunblane, Scotland.

Socolow, R., C. Andrews, F. Berkhout and V. Thomas (eds.) (1994). *Industrial Ecology and Global Change.* Cambridge University Press, Cambridge.

Stahel, W (1994) The Utilization-Focused Service Economy: Resource Efficiency and Product-Life Extension. In: B.R. Allenby and D.J. Richards (eds.*) Greening of Industrial Ecosystems, National Academy of Engineering,* Washington D.C., pp: 178-190.

Starreveld, P.F. and E.C. van Ierland (1994). Recycling of plastics: A material balance optimisation model. *Environmental and Resource Economics* 4: 251-264.

Stern, D.I. (1997). Limits to substitution and irreversibility in production and consumption: A neoclassical interpretation of ecological economics. *Ecological Economics* 21: 197-215.

Sterner, T. and H. Bartelings (1999) Household waste management in a Swedish municipality: determinants of waste disposal, recycling and composting. *Environmental and Resource Economics* 13: 473-491.

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

Turner, R.K. (1995). Waste management. In: H. Folmer, H.L. Gabel and J.B. Opschoor. *Principles of Environmental and Resource Economics: A Guide for Students and Decision-makers.* Edward Elgar, Aldershot.

Vitousek, P.M., H.A. Mooney, J. Lubchenco and J.M. Melillo (1997). Human domination of Earth’s ecosystems. *Science* 277: 494-499.

Voet, E. van der (1996). *Substances from Cradle to Grave.* PhD. Thesis. Optima Druk, Moolenaarsgraaf.

Voet, E. Can der, J.B. Guinée and H.A. Udo de Haes (eds.) (1999). *Heavy Metals: A Problem Solved? - Methods and Models to Evaluate Policy Strategies for Heavy Metals.* Kluwer Academic Publishers, Dordrecht.

WCED (1987). *Our Common Future*. World Commission on Environment and Development, Oxford University Press, Oxford/New York.

Weaver, P.M., H. Landis Gabel, J.M. Bloemhof-Ruwaard and L.N. van Wassenhove (1997). Optimising environmental product life cycles: A case study of the European pulp and paper sector. FEEM paper (Nota di lavoro) 88.97. Fondazione Eni Enrico Mattei, Milaan.

Weizsäcker, E. von, A.B. Lovins and L.H. Lovins (1997). *Factor Four: Doubling Wealth - Halving Resource Use, A Report to the Club of Rome.* Earthscan, London.

Wernick, I.K., and J.H. Ausubel (1995). National materials flows and the environment. *Annual Review of Energy and Environment* 20: 493-573.

Wertz, K.L. (1976). Economic factors influencing household production of refuse. *Journal of Environmental Economics and Management* 2: 263-272.

Wier, M. and B. Hasler (1999). Accounting for nitrogen in Denmark - a structural decomposition analysis. *Ecological Economics* 30, pp. 317-331.

WRR (1987). *Ruimte voor Groei.* Wetenschappelijke Raad voor het Regeringsbeleid, rapporten aan de regering 1987/29, Staatsuitgeverij, Den Haag.