SIMBIOSES:
Modelling industrial metabolism in a multi-regional economic system

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Abstract

A model framework, SIMBIOSES, is presented which describes economic activities and related material, substance and energy flows in a multi-region and multi-sector economic system. The conceptual design of the framework is discussed in relation to current issues on “dematerialization” and “decoupling”.

Three types of models to implement SIMBIOSES are discussed: a static equilibrium model, a dynamic optimisation model, and a system dynamics model. The static model determines the static equilibrium of extraction, production, recycling, and energy recovery from waste. The dynamic model determines the long-term investment decision that optimises total discounted utility of consumption. The dynamic model incorporates technological change, allocation of resources, and damage costs due to accumulation of substances in the environment. The system dynamic model generates endogenous economic growth and technology development and includes bounded rationality of economic agents.

Keywords

dematerialization, mass balance, integrated models, Environmental Kuznets curve, equilibrium analysis, dynamic optimisation, system dynamics.

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1. Introduction

Like any living system, an economy consumes material and energy inputs, processes them into usable forms, and eliminates the wastes from the process. This can be seen as metabolism and has been referred to as "industrial metabolism" (Ayres, 1989; Ayres and Simones, 1996, Socolow et al., 1994; Greadel and Allenby, 1995). Metabolism in the biological context refers to the internal processes of a living organism. The organism needs energy-rich, low-entropy materials (food) to provide for its own maintenance and functions, as well as to permit growth and reproduction. The organism excretes and exhales waste output consisting of degraded, high-entropy materials. In analogy with biological metabolism we can consider the metabolism of industrial activities as the total of physical processes that convert raw materials and energy into finished products and wastes.

This paper discusses a conceptual framework to study the industrial metabolism of an ecological economic system. This is denoted by the acronym SIMBIOSES, which stands for **S**patial **I**ndustrial **M**etabolism and **B**ehaviour of **I**nput/**O**utput **S**tructures in an **E**conomic **S**ystem. SIMBIOSES refers to symbiosis, a term in ecology that denotes the reciprocally beneficial interaction between different organisms. For example, sea-anemones attach themselves to the shells of hermit crabs. The anemone has the advantage of locomotion, while the crab gains protection and camouflage.

We use the term symbiosis on three levels in the context of industrial metabolism. First, it means that industrial metabolism is related to the development of both the economy and the environment. Second, symbiosis refers to the interactions between regions, for example, through trade in primary and secondary materials. Such regional interactions can be beneficial or damaging to the state of the global environment and the regional economies. Third, on a regional level symbiosis refers to interactions among economic agents, which can improve efficiency. In the context of industrial ecology where firms are located in such a way that they can use waste (material and energy) generated by firms in the vicinity as resources for their own production (Socolow et al., 1994; Greadel and Allenby, 1995).

With SIMBIOSES we aim to determine which types of spatial (re)allocations of economic activities lead to improvements in terms of environmental quality. Environmental quality has many dimensions. Nevertheless, much effort is being spent on defining one-dimensional indicators. Inevitably, each indicator leaves out certain dimensions of environmental quality. An integrated model like SIMBIOSES can provide a tool to analyse the various dimensions of environmental quality and the economic consequences of environmental policy.

We will give a brief overview of models that integrate material balance and economic processes. Although a large number of physically oriented models of the economic system exist integration of physical processes in economic models is rare, notably in a multi-regional setting. An exception perhaps is the current stream of so-called integrated assessment models that focus on CO_2. However, also in this type of models, analytical integration of economics and physical systems is rare. One of the difficulties is that the use of specific modelling approaches leads to a focus on certain aspects and questions of the integrated system. Therefore we propose the use of various modelling paradigms in order to give a balanced picture integration of social and natural systems.

In the next section we discuss in more detail the relations between spatial scales, materials use and industrial metabolism. Section 3 discusses indicators of physical and environmental characteristics of economic systems and development. Section 4 presents an overview of models that integrate material flows and economic processes. In Section 5, the current stream of integrated models for climate change analysis is discussed from the present perspective. Finally, in Section 6 the general structure of SIMBIOSES is discussed. In addition, conceptual models of SIMBIOSES are presented that are based on different modelling types. Section 7 concludes.

2. Spatial Scales and Materials Use in Industrial Metabolism

The concept of industrial metabolism can be usefully applied at many different levels: global, national, regional, sectoral, company, site and household. Industrial metabolism analysis highlights the difference between natural and industrial metabolic processes: in natural systems materials flow in closed loops with near universal recycling, whereas in industrial systems material recycling is not universal. Industrial activities are often very scattered, leading to diffuse waste and pollution. As a result materials concentrations are too low to allow for profitable recycling although they can be sufficiently high to cause problems of pollution. Understanding the pattern of energy and material flows through an economy provides a good starting point for formulating policy goals and developing indicators for sustainability at all spatial levels.

In analogy with bio-geo-chemical materials cycles (the hydrological cycle, the carbon cycle, the nitrogen cycle, the phosphorus cycle, etc.) a general cycle for materials can be identified (Figure 1). Natural cycles are closed, i.e. all nutrients are recycled, whereas industrial cycles are part of the natural cycle, though extraction of high quality materials (fossil fuels, ores) and emissions of these in degraded form to the environment.

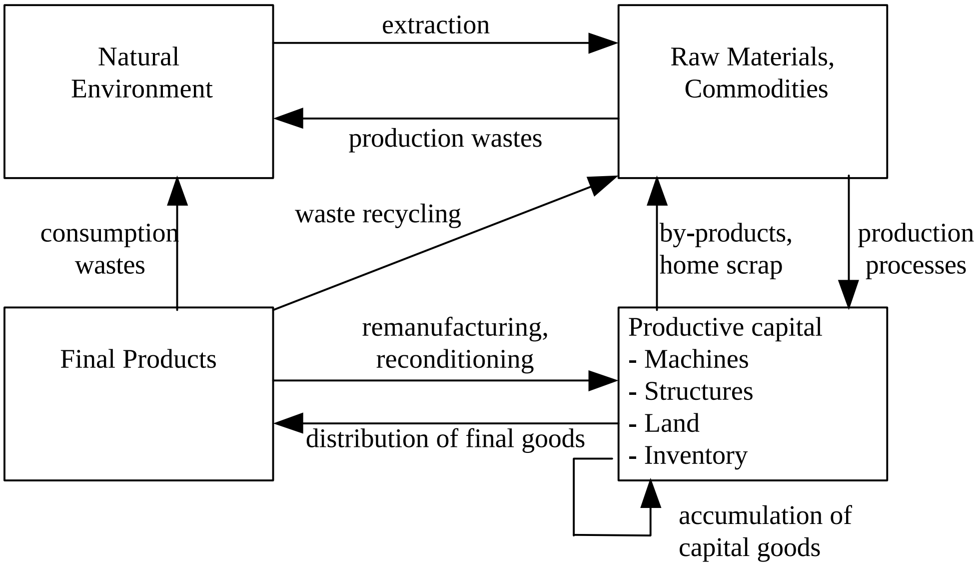

Figure 1: 4-Box Scheme for Industrial Material Cycles (Ayres, 1997).

Industrial metabolism analyses material flows from an integrated perspective that allows studying system-wide effects and problem shifting due to of environmental policies. With industrial metabolism analysis we can thus trace the rebound effects of policies. For example, when cars become more fuel efficient, consumers tend to use larger cars and travel more kilometres, so that the net effect can be less significant. Moreover, reducing waste in one part of the system can lead to larger emissions in another part of the system. For example, end-off-pipe measures to reduce pollution to water and air can lead to highly polluted waste, which has to be burned or dumped in landfills. In addition, the trade-off between energy and material use can be studied. For example, recycling of materials reduces the demand for resources, and recovering of materials requires much energy. Burning of waste paper is in some cases more desirable from an environmental perspective than recycling. Leach et al. (1997) studied the options of waste paper treatment in the UK. This paper is mainly produced in Sweden where renewable energy sources are used in the production (pulp). Recycling in the UK require fossil energy and burning waste paper will generate energy. Finally, production and recycling can shift to other regions. Reduction of the energy intensity of emissions in OECD countries and the increase of energy intensity of economies in non-OECD countries can partly be explained by migration of energy intensive industries from OECD to non-OECD countries (Suri and Chapman, 1998). With the globalisation and the resulting international flows of goods, this spatial dimension is of increasing importance. Therefore, the framework will include a spatial dimension.

In sum, industrial metabolism is an approach to analyse system-wide effects of environmental policies in an integrated fashion. The current debate on dematerialisation and other popular concepts (decoupling, ecological footprint) is dominated by one dimensional perspectives of each concept, as will be discussed in the next section.

3. Dematerialization: Concepts, Theories and Indicators

A number of concepts, theories and indicators of the physical and environmental drivers and impacts of economic activities have been developed. This section offers a short overview of the literature. We will argue that all concepts, theories and indicators focus on specific dimensions of environmental problems and that therefore various approaches should be used parallel to analyse environmental problems and policy making.

Concepts

On a general level, the term (relative) “delinking” is used to indicate that economic growth, i.e. increasing income per capita, goes along with an absolute (relative) decrease of environmental pressure (Hofkes *et al.*, 1998). A more specific notion than “delinking” is “dematerialization”, which can be defined as a reduction of materials in the economy; this can be measured in weight terms or other aggregation schemes. Materials can have different weights in the aggregation process. Some materials with low environmental impacts can increase by substituting materials with higher impacts and still derive dematerialization. One can focus on either flows or stocks of materials, or on a combination. Nevertheless, to arrive at a consistent set of indicators a systems perspective of the links between flows and stocks is essential. “Dematerialization” is a concept that can be regarded at various levels, namely that of a process, product, firm, sector, region, country and the world as a whole. Thus, one can define micro, meso, macro and global dematerialization.

On a micro level dematerialization means that the same service or function can be supplied with less direct and indirect use of substances and materials. This means that products becoming lighter due to use of fewer or lighter materials (e.g., aluminium instead of iron). “Miniaturization” is one way to accomplish this. Just like recycling dematerialization will reduce environmental pressure at the beginning (extraction of resources) and end (waste dumping and emissions) of chains of economic activities. Dematerialization can have impacts on energy use and transport.

On a macrolevel various factors influence dematerialization: economic growth, changes in the structure of the economy (heavy industry to services, demand and supply, including imports and exports), technological innovations, substitution between material and other inputs in processes, substitution among various materials, increasing life times of products, and reuse of products and recycling of materials. In view of the large number of factors an accurate prediction of dematerialization is difficult. For instance, information technology has unexpectedly given rise to a net increase of paper use.

Note that dematerialization is not a goal in itself. An evaluation of and strategy for dematerialization should take into account its environmental impacts and costs and benefits.

Theories

Many authors in "industrial ecology" focus on improving "eco-efficiency" via various technological improvements relating to the design of products, and the organisation and logistics of production processes (Reijnders, 1996). The "factor 4"-approach (previously factor 10) proposed by the German Wuppertal Institute is probably the best known example. It refers to a doubling of wealth (standard of living) given a halving of use of materials and energy (Von Weizsäcker e.a., 1997). This sounds straightforward. Nevertheless, many concrete proposals in the context of factor 4 run the risk of being too optimistic estimations of net-saving on materials at a macro level. This overlooks that a number of "rebound effects" can occur, i.e. indirect and economy-wide effects that compensate the original "eco-effiency" gains. For instance, less use of materials and energy can reduce resource prices and linked product prices, which in turn can stimulate the final demand for those products and the intermediate demand for resources. Economy wide models are needed to study such issues.

In environmental economics a theory that is known as the "Environmental Kuznets curve" (EKC) has received much attention over the last few years. It reflects a relationship between environmental pressure and income per capita that consists of three phases: (1) initially income growth goes along with possibly progressively increasing environmental pressure; (2) next, further income growth leads to a degressive increase of environmental pressure until it reaches a maximum; (3) finally, further income growth leads to a reduction of environmental pressure. An explanation for this pattern is that at higher income levels individuals will attach more value to environmental quality; this means more income spending on less damaging consumption (cleaner products, services), as well as more democratic support for stringent environmental policies. This theory has generated its own body of empirical research (see de Bruyn and Heintz, 1999). The main implication of the EKC is that growth by itself would be able to solve environmental problems. This is regarded as an interesting addition to the traditional view that considered economic growth and environmental conservation as antitheses. It should be noted that the EKC is really not much of a theory, as it describes rather than explains. The empirical support for the EKC hypothesis is very doubtful, as it is based on indicators that are partial, from both environmental and spatial perspectives. Among other things, decomposition analysis techniques are required to understand the specific contribution of various factors that influence and explain particular regularities in the relationship between environmental indicators and income per capita (Rose and Casler, 1996).

Finally, a somewhat neglected issue on a theoretical level seems to be the link between dematerialization and recycling. It is not clear how the trade-off between these two strategies should take place. Moreover, recycling has indirect impacts on energy and material use so that in general its net effect on dematerialization is unclear.

Indicators

Various authors have argued that the selection, construction and aggregation of indicators of dematerialisation should satisfy a number of criteria (Pearce *et al.*, 1998; Gilbert and Kuik, 1999; Huele et al., 1999). Most important from the "spatial industrial metabolism" perspective is completeness in environmental impacts and in space. Whereas the testing of the EKC hypothesis has focused on disaggregate and therefore partial indicators, the research on Industrial Ecology, Industrial Metabolism and Industrial Transformation is aimed at a complete perspective on environmental consequences of economic activities (Ayres, 1998). Either multiple indicators or an aggregate indicator of dematerialization can accomplish this.

Aggregation creates its own problems. By aggregation one will always lose information. It (implicitly) assumes fixed weighting and substitution between different disaggregate inputs. A recently developed indicator, the "Ecological Footprint", aggregates various environmental impacts into a hypothetical land use measure in hectares (Wackernagel and Rees, 1996). There are many drawbacks to such an approach (van den Bergh and Verbruggen, 1999). Factor 4 has been linked to the indicator MIPS: "materials inputs per service unit". This is also an aggregate indicator, which is based on the idea that it is useful to add up the kgs of all types of materials and substances that have been used during the life-cycle of a product or service. This procedure thus generates an aggregate indicator in kilograms that attaches equal weights to substances and materials with completely different environmental impacts (see Von Weizsäcker e.a., 1997).

Jänicke *et al.* (1988) have used a macro-indicator based on steel, energy, cement production and freight transport in an empirical cross-section analyse of 31 countries, in which it was concluded that dematerialization on a macro level occurred during part of the 1970s and 1980s. A follow-up study by de Bruyn and Opschoor (1997) showed that there was no dematerialization trend. Of course, the results are very sensitive to the choice of the macro-indicators and the aggregation procedure. Other efforts to aggregate environmental indicators have been presented in van den Bergh and van Veen-Groot (1998) and Hope *et al.* (1992).

Linking of indicators to models can aid in visualising the consequences of adopting particular concepts and indicators, before using them in practice. This could be useful to address aggregation and weighting as well as completeness from environmental and spatial perspectives.

Which specific indicators should be adopted in the present modelling approach? Dematerialization indicators can be formulated at a process, firm, sector, region, country or global level. This would allow for testing the consistency between dematerialization indicators at various economic and spatial levels. One step further is to require that the aggregate indicators follow from the disaggregate ones. Another choice is related to the distinction between stock and flow indicators. This should be done so as to reflect the time dimension and to avoid double counting. Studying dematerialization in an open system (region, country) should focus on shifting trade and relocation of activities and their impact on dematerialization at a global level. Aggregation over space should take into account the use of materials that have different external effects in different regions.

4. Models of Material Flows in Economic Systems

The tradition of modelling material flows in economic systems goes back to the late sixties (Ayres and Kneese, 1969, Kneese et al., 1970, Georgescu-Roegen, 1971, 1976; Ayres, 1978). Nowadays, a number of approaches exist that try to describe the physical economy.
For a macro analysis we can distinguish the following type of modelling approaches:

- input-output modelling
- cost minimisation models
- equilibrium models
- dynamic optimisation models
- system dynamic models

Input-output modelling:

Input-output models represent flows of money, resources, or products among the various producers and consumers in an economy. Such multi-sectoral models can be used to trace the results of changes in the economy or to do detailed economic forecasts. I-O models require a huge amount of data that creates bottlenecks for empirical applications, notably since data sets are often inconsistent. This problem is especially significant for dynamic analysis (Duchin et al., 1994).

Leontief built the foundation of modern input-output analysis (Leontief, 1936). In the early seventies he expanded the original focus of inter-industry flows of money and goods to environmental issues by including flows of energy and pollution (Leontief, 1970). This was further extended by inclusion of material balances and recycling (Kneese et al., 1970; Ayres, 1978; Duchin, 1992). A drawback of I-O analysis remains the descriptive approach with fixed technological coefficients.

A very useful application of I-O models is the historical analysis of material flows through the economy and the environment. I-O tables can be used to analyse structural changes in economic systems (Rose and Casler, 1996). Another application of input-output analysis is the design approach as developed by Statistics Canada and applied to Canada and Australia (Gault et al., 1987; Poldy and Foran, 1998). This approach generates a computer simulation model that describes in detail the physical stocks and flows in an economic system. Socio-economic developments are quantified as scenarios in co-operation with the various stakeholders, sectors and decision-makers.

Cost minimisation models

Cost minimization models are aimed to select the best decisions (techniques) from a set of clearly defined alternatives to minimize the system costs given certain policy targets. This selection can be enlarged by additional constraints within which the activities must take place. Typical examples of such models are the MARKAL-MATTER model (Gielen, 1999) and the MIMES model (Sundberg, 1993). Both models integrate material flows and energy use.

This approach generates a set of techniques that minimise the costs of a certain system in order to meet environmental induced constraints.

A drawback of this approach is the lack of integration with economic decisions in other areas than material and/or energy use. Furthermore, the demand for materials and energy is exogenous. In fact, there is no direct feedback from changes in the physical system to the economic system.

Equilibrium models

Equilibrium models generate a set of equilibrium prices and quantities of goods. The basic assumptions are market clearing and optimising behaviour of producers (maximization of profit under technical constraints) and consumers (maximization of utility under budget constraints). An equilibrium can be partial (one market; or a closed model with income generation and expenditures based on income) or general (a complete set of markets). Furthermore, the models can be static and dynamic, although dynamic versions are generally difficult to solve. Extending such models with material flows would increase the difficulty.

Externalities, such as pollution, are caused by production or consumption and affect utility or production. In an equilibrium, the (negative) externalities can be optimised by imposing policies. Although equilibrium models are used widely in environmental economics, explicit inclusion of material flows has been rare (e.g. Kandelaars, 1998).

Dynamic optimisation models

This type of models focuses on the temporal allocation of resources. A common formulation is to maximise the discounted sum of utility of consumption over time by choosing investments and policy measures to reduce the external effects. This type of models is mainly used to determine optimal extraction of resources, and normally does not include pollution effects. In contrast with static approaches, this type of models can account for the cumulative nature of many environmental issues, and explicitly model feedback from changes in the environment to the economic system.

A well-known example of this type of models is the climate-economy model of Nordhaus (1994) which is discussed in the next section. According to Kandelaars (1998) few general material flow models of this type have been developed and applied.

System dynamics models

System dynamics models describe systems as a set of interacting feedback loops. The changes in stocks and flows are simulated by non-linear differential equations. Studies in this tradition have focused attention on model structure, while relatively little effort has been put into parameter estimation. The purpose of system dynamics models is to study the dynamic behaviour of systems of cause-effect chains.

Since the well-known study by Meadows et al. (1972) many system dynamics models of environmental have been developed. Integrated models with materials flows in economic system remain rare. An interesting model that is close in spirit to some of SIMBIOSES goals is the Metals model of van Vuuren et al. (1999). This describes mineral flows in a multi-regional world. Although the model simulates economic processes of mineral flows in a rather detailed way, it is not integrated with economic mechanisms (markets, individual behaviour). This is needed to analyse the issue of dematerialization and decoupling. Another approach that uses system dynamics is the ECCO (Evaluation of Carrying Capacity Options) approach (Slesser et al., 1997). ECCO models measure physical stocks and flows in terms of their embodied energy. Van den Bergh and Nijkamp (1994) have developed a model that incorporates mass balances into a dynamic economic model of multiple sectors and environmental feedback to the economy.

5. What can be learned from integrated models of climate change?

The recent attention for human induced climate change has led to a number of models that integrate the biophysical cycles and economic activities. These models are interesting in relation to material flow modelling because much effort have been spend all over the world on integrating social and natural science into formal models. What can we learn from these efforts for developing an integrated framework for spatial industrial metabolism?

The integrated models capture the physical and economic aspects of the “material” CO_2 , the main greenhouse gas. Since the global amount of carbon is fixed, mass balance can be usefully applied. Human activities disturb the carbon cycle by extraction (fossil fuel resources), storage in products (wood, plastics), recycling (biomass energy) and emitting (emissions to the atmosphere). There are many possible classifications for the large number of integrated models. One is to distinguish between process-oriented models, rooted in natural science, and policy optimization models, rooted in economics (Weyant et al., 1996). For overviews see Weyant et al. (1996), Rotmans and Dowlatabadi (1997) and Janssen (1998). Here, we will briefly discuss some important models that are typical of this field.

One of the main process-oriented integrated models is IMAGE 2 (Integrated Model to Assess the Greenhouse Effect). The IMAGE 2 model (Alcamo, 1994; Alcamo et al., 1998) presents a geographically disaggregated, global and dynamic picture of a linked society-biosphere-climate system. It consists of three linked subsystems; the energy-industry system, the terrestrial environment system, and the atmosphere-ocean system. The energy-industry models computes the emissions of greenhouse gases in 13 world regions as a function of energy consumption and industrial production. End use energy consumption is based on various economic driving forces. The terrestrial environment models simulate the changes in global land cover on a grid scale, based on climatic and economic factors. The role of land cover and other factors are taken into account to compute the flux of CO_2 and other greenhouse gases from the biosphere to the atmosphere. The atmosphere-ocean models calculate the build-up of greenhouse gases in the atmosphere and the resulting zonal-average temperature and precipitation patterns. The model includes many important feedbacks and linkages between models in these subsystems.

The economic drivers, captured by GDP and sectoral value added, are exogenous. In the current version these economic drivers a re based on scenarios from WorldSCAN, a world economic model developed by the Netherlands Bureau for Economic Policy Analysis (CPB) (Bollen et al., 1998; de Vries et al., 1999). The IMAGE model is thus a linkage of various submodels for scenario analysis.

By extending a traditional optimal growth model with a climate sector, Nordhaus (1994) derived a dynamic integrated model of climate and the economy (DICE). The objective is to maximise the discounted value of utility from consumption. In DICE, population growth and technological change yield productivity growth. Both of these factors of population are exogenously specified and assumed to decline asymptotically to zero.

The global commoner consumer maximises discounted present value of utility of future consumption subject to a Cobb-Douglas production function that includes a climate damage factor. Emissions per unit output are assumed to decline exogenously at a fixed rate and can be further reduced by costly emission-control measures.

The regionalized version of DICE, RICE (Nordhaus and Yang, 1995), divides the world into a number of regions. Each is endowed with an initial capital stock, population, and technology. The capital market clears through equalisation of the real interest rate across regions.

Although the DICE and RICE model are fully integrated in terms of causes and effects, the description of economic and physical processes is limited in detail and sometimes invalid (Price, 1995; Kaufmann, 1997; Janssen, 1998). The mathematical framework needed in order to solve the optimisation problem leads to very drastic simplifications. In relation to our discussion of indicators, it is worthwhile to mention that Nordhaus uses a one-dimensional indicator: % loss of GNP, in which all costs and benefits of climate change policies and impacts are integrated.

These examples of IMAGE and DICE show that finding a balance in integrated modelling is difficult. The IMAGE model explicitly incorporates the mass balance of carbon, whereas in DICE not the whole carbon cycle is included. DICE is an analytically integrated model, whereas IMAGE couples modules but excludes important feedbacks. IMAGE is aimed to describe the system in a rather detailed way in order to project scenarios of climate change, whereas DICE is aimed at generating optimal control policies by balancing costs and benefits of mitigation. Both models are incomplete, but can be complementary if used together.

Similarly, instead of focusing on one model of spatial industrial metabolism, we will consider a framework that covers a set of models. This framework, SIMBIOSES, is described in the following section.

6. SIMBIOSES: a framework for spatial industrial metabolism

6.1 General Features

SIMBIOSES describes the metabolism of materials in a multi-regional and multi-sectoral economic system formulated as a series of activities in a material-product chain. Both the physical material cycles and the economic activities are modelled.

The material cycle is described through stocks and flows (in physical units). Three main groups of raw materials are minerals and ores, fossil fuels, and biomass. The resource dynamics differ between stocks: minerals, ores and fossil fuels are non-renewable stocks, and biomass is a renewable stock.

We consider in each region a number of stocks like non-renewable and renewable material resources, processed material, material incorporated in the capital stock, material incorporated in consumer goods, accumulation of materials in landfills, and accumulation of materials in different compartments of the environment.

The economic system consists of different sectors, related to the different flows in the material sector: extraction of resources, production of intermediate goods, production of consumption goods, recycling, waste management, and energy production. These sectoral activities are influenced by technological development, economic activities in other sectors and regions, and changes in the environmental system.

Figure 2 presents a general scheme of SIMBIOSES. It shows the many interactions between sectors and regions of energy, material and monetary flows. Each economic sector contains material and energy for production. Material is extracted from the resource, and accumulates in the environment depending of the degree of recycling. Goods, energy and materials can be traded between the regions. Environmental degradation can also cross the borders and affect economic activities in other regions.

The SIMBIOSES framework is aimed to generate insight about the relationship between materials use and economic development about the possibility of decoupling economic growth from materials use, about the effectiveness of environmental policies, about the inter-regional aspects of environmental policies, and about the implications of technological changes on the economic structure.

The above description of the SIMBIOSES framework is general. Details can be specified once the framework is operationalised in concrete models. As discussed before, none of the existing modelling approaches will cover all the aspects that we want to study. In order to allow for a broad approach three modelling approaches are elaborated here:

- a static general-equilibrium model
- dynamic optimisation
- system dynamics

Each of these is subsequently described.

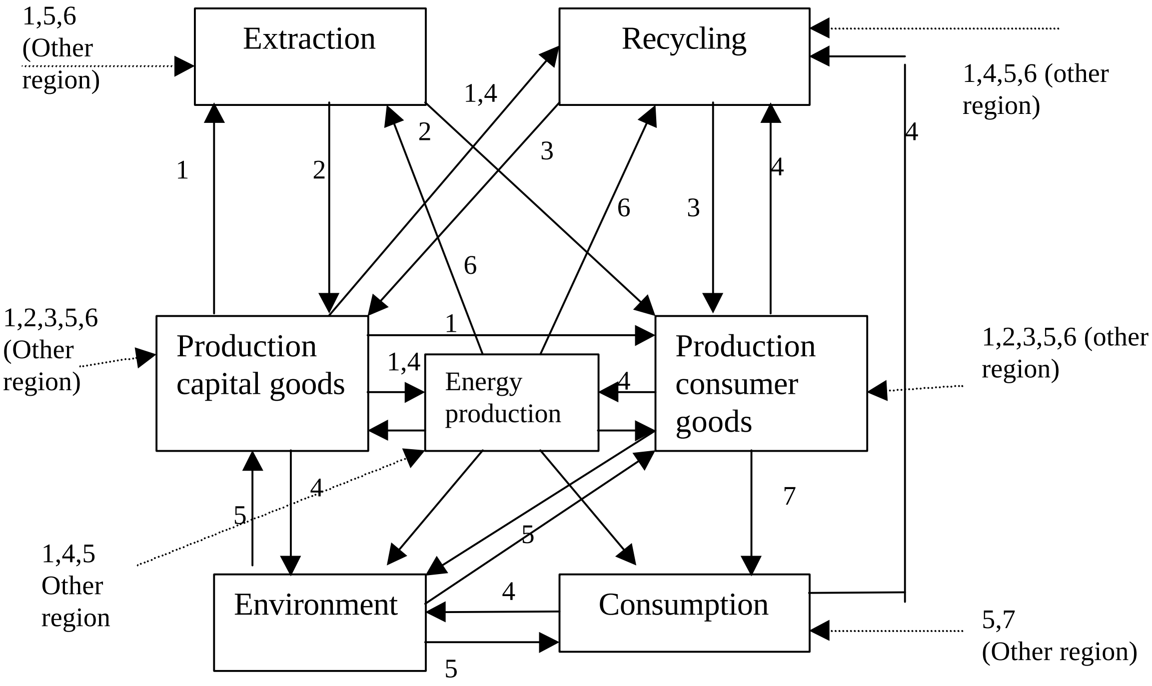

Figure 2: A flow diagram of SIMBIOSES with flows denoting capital (1), new material (2), secondary material (recycled) (3), waste material (4), external costs (5), energy (6) and consumer goods (7).

6.2 Implementation in a static general equilibrium model

The aim of the static general equilibrium model is to determine the optimal allocation of capital, labour and material resources among over the various sectors in the different regions. Furthermore, it can analyse the sensitivity of this equilibrium for key assumptions of the model, like the level of externalities, differences between regions in production characteristics, resource availability, and policies?

The static general equilibrium model includes two regions and material balance constraints. A general equilibrium model is especially useful to study problem shifting between regions, stocks and materials.

Decisions are made in five basic activities in each region: four types of production: extraction of resources, manufacturing of capital goods and consumer goods, and recycling of material, and consumption of products. These producer-related activities are represented in an equilibrium model via separate profit formulations, and technical and material restrictions. Consumers maximise utility of consumption given the available budget. Two regions can trade capital goods, consumption goods, and new and recycled material. Waste that is not recycled will be used for energy production or end up in the environment possibly causing external costs to producers and consumers.

The production functions include technology factors, capital inputs, externalities and quality of material inputs (per unit more recycled material can be required than virgin material). Furthermore, mass balance conditions and material flows are explicitly modelled.

6.3 Implementation in a dynamic optimisation model

The rationale for adopting a dynamic approach is that materials accumulate in the economy, investment decisions trade-off current and expected future consumption, and technological changes over time affect the investment decisions. An optimisation model can determine the allocation of resources by maximizing the discounted value of utility of consumption. The questions we want to address with the optimal control model are: What are the trade-offs between (primary and secondary) inputs from different regions? What does decoupling mean in a multi-sectoral and multi-regional model? What policies should be implemented to realise this? And what are the trade offs between material recycling and energy generation of waste?

The dynamic model will describe two regions. Due to the complexity of a dynamic optimisation problem, the sectoral disaggregation of the model is limited. The model will be solved numerically and generate optimal investments, labour, and waste treatment.

6.4 Implementation in a system dynamics model

The system dynamics approach is the third type of implementation of SIMBIOSES. It simulates interactions between agents, endogenous technological change, satisfising instead of optimising behaviour, diversity in preferences among agents and external surprises affecting the evolution of the system.

The general framework as described before is used as a starting point where each agent, economic sector, is equipped with a set of rules for each agent. These rules are based on the literature (Sterman, 1985; De Vries and Janssen; 1997). Simulation models are not severely confronted with constraints of mathematical methods. Therefore, a simulation model is suitable to add details and comprehensive dynamics. The system dynamic model of SIMBIOSES will describe in detail the different environmental compartments, economic sectors, material characteristics, and so on.

The model can be used to analyse the following questions: How does technology influence economic structure, substitution between materials, between materials and energy, and regional interactions? How can we stimulate desirable technological changes? Under which assumption does a economy decouple economic growth and environmental pressure? What are effective policy measures if we include all kind of possible feedbacks and rebound effects?

6.5 Trade-offs in modelling

In Table 1 we summarise the main differences between the three complementary modelling approaches to implement SIMBIOSES. Technology is treaded differently among the different approaches. In the equilibrium model, technology levels are fixed, whereas in the dynamic optimisation model the technological changes are exogenous. The system dynamics model has the most comprehensive treatment of technology by endogenous implementations of learning by doing dynamics. Another important difference among the modelling approaches is the treatment of agents. All approaches consider consumers and industrial sectors, but the equilibrium approach assumes agents to maximise their utility or profits, whereas the dynamic optimisation model allocates the sectoral investments in such a way that the social welfare is maximised. The inclusion of the environment is different among the various approaches as well. The equilibrium approach includes the environment indirectly by externalities. The dynamic optimisation model described the dynamic changes of the material cycles and possible consequences on the economic sectors, like the system dynamics model that can include some more detail in dynamics and compartments. The policy instruments of the equilibrium and optimisation models are mainly based on financial instruments, where in the system dynamics version of SIMBIOSES we will also be able to include technology stimulation programs.
In sum, the equilibrium model has as advantage that it includes consistent market behaviour, although the limited (dynamic) complexity of structure of the model is considered as an disadvantage. The optimal timing of investments is a clear advantage of the optimisation approach, although the complexity of deriving an optimal solution is considered as a disadvantage. The system dynamics approach is able to include a lot of interesting dynamics. However, that makes the model difficult to analyse.

Table 1. Characteristics of the different modelling approaches (partly based on Kandelaars, 1998).

	General equilibrium	*Dynamic Optimisation*	*System Dynamics*
Focus	Allocation, markets	Optimal allocation over time	Dynamic feedbacks, cause-effect chains
Technological change	Comparative analysis	Exogenous change	Endogenous change
Agents	Optimising utility and profits	Decisions of agents lead to maximisation of social welfare	Bounded rationality
Environment	Static externalities	Dynamic externalities via accumulation of materials in environment which feed back to production and utility	Accumulation of materials in different compartments of the explicit cause effect chains in the environment affecting economic processes.
Policy instruments	Financial policies	Financial policies	Stimulation of technology, financial policies, behavioural changes of consumers
Advantages	Consistent market behaviour	Timing of investments	Feedbacks; technological change; alternative behaviour models
Disadvantages	Limited complexity	Difficult to solve (numerically) the optimisation problem	Difficult to interpreted the model, arbitrarily in assumptions.

7. Conclusions

In this paper the modelling framework SIMBIOSES is presented. It will integrate material flows and economic activities for a multi-regional and multi-sectoral setting. The purpose of SIMBIOSES is to analyse suitable strategies that improve environmental quality at minimal costs. It will provide allocation of investments, labour, goods and materials over time, space and sectors. The goals for environmental and economic targets are multi-dimensional, and cannot be caught in one indicator. SIMBIOSES can be a tool to test the mutual consistency of various indicators. Focusing on one indicator can lead to undesirable effects as measured by other indicators.

SIMBIOSES will be operationalised through various model types. The reason is that each modelling approach frames a problem in a certain way, so that only one perspective on the problem is analysed. We have proposed to use three different modelling approaches: a static general equilibrium model, a dynamic optimisation model, and a system dynamics model. Implementation of these models will be reported in separate papers. The models will first be implemented for a hypothetical economy, so as to study general system and policy characteristics. A next step will be the implementation of SIMBIOSES for a number of case studies on spatial industrial metabolism.

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