Chapter 2
Prospective Models of Society's Future Metabolism: What Industrial Ecology Has to Contribute

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Abstract Scientific assessment of sustainable development strategies provides decision-makers with quantitative information about the strategies' potential effect. This assessment is often done by forward-looking or prospective computer models of society's metabolism and the natural environment. Computer models in industrial ecology (IE) have advanced rapidly over the recent years, and now, a new family of prospective models is available to study the potential effect of sustainable development strategies at full scale.

We outline general principles of prospective modeling and describe the current development status of two prospective model types: extended dynamic material flow analysis and THEMIS (Technology-Hybridized Environmental-Economic Model with Integrated Scenarios). These models combine the high level of technological detail known from life-cycle assessment (LCA) and material flow analysis (MFA) with the comprehensiveness of, respectively, dynamic stock models and input/output analysis (I/O). These models are dynamic; they build future scenarios with a time horizon until 2050 and beyond. They were applied to study the potential effect of a wide spectrum of sustainable development strategies, including renewable energy supply, home weatherization, material efficiency, and light-weighting.

We point out future applications and options for model development and discuss the relation between prospective IE models and the related concept consequential LCA (CLCA).

The prospective models for industrial ecology can answer questions that were previously in the exclusive domain of integrated assessment models (IAMs). A debate about the relation between the two model families is necessary.

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We find that IAMs have a more comprehensive scope than the prospective IE models, but they often do not obey central IE principles such as the life cycle approach and mass balance consistency. Integrating core IE principles into IAMs would increase the scientific quality and policy relevance of the scenarios of society's future metabolism generated by IAMs, while placing industrial ecology concepts more prominently at the same time. We provide a sketch of what this integration could look like.

Keywords Socioeconomic metabolism • Socio-metabolic transition • Sustainable development strategy • Prospective model • Industrial ecology • Integrated assessment model • Policy assessment • Dynamic material flow analysis • Integrated hybrid LCA

1 Introduction

1.1 The Great Transformation Ahead

Human interference with global biogeochemical cycles has grown to a level that will trigger epochal changes, including climatic change and state shifts in the Earth's biosphere. These changes have substantial impact on humanity; they force humans to adapt or to be proactive and mitigate negative impacts on the environment. The spectrum of options for future action is wide. It includes technology development and deployment, economic instruments including taxes and subsidies, regulation and standards, and changes in consumer choices and lifestyle. Both adaptation and mitigation will lead to a transformation of the biophysical basis of our society, which includes agriculture, industry, infrastructure, building stocks and vehicle fleets, and consumer products, and of the way we build, maintain, and operate this basis.

The coming transformation is the continuation of a historic sequence of *socio-metabolic transitions* of mankind, first from the hunter/gatherer to the agrarian and later from the agrarian to the industrialized society (Fischer-Kowalski and Haberl 2007; Fischer-Kowalski et al. 2014; Krausmann and Fischer-Kowalski 2013). The coming transformation represents a special global challenge, however, because it is likely to happen under environmental conditions that are significantly different from those that enabled the previous two transitions (Barnosky et al. 2012).

1.2 Scientific Response: The Interdisciplinary Systems Approach and Prospective Models

Environmental literacy is a core feature of higher species. It is the "capability [...] to appropriately read, utilize, and adapt to environmental information, resources, and system dynamics" (Scholz and Binder 2011). Today, human environmental literacy is higher than ever before. Humanity uses scientific methods to study the biophysical basis of society, to anticipate future challenges associated with the transformation of that basis, and to offer quantitative and objective assistance to decision-makers.

The scientific approach to studying the transformation faces two major challenges: (1) The transformation affects many different aspects of society and the environment; it ignores traditional boundaries between scientific disciplines. (2) The transformation is a complex process and spans many different scales, which are interconnected: spatial (local biotopes, cities, regions, countries, the globe), organizational (households, companies, sectors, nations, global community), and temporal (from immediate consequences to long-term effects several centuries from now).

The necessity to study different scales follows from the nature of the problem: It is essential to consider the global scale for three reasons: the changes in the environment are global, our global economy is causing these changes, and relocation of production activities happens on a global scale. Smaller scales need to be studied as well because these scales represent the typical scope of decision-making; they form the arena where interventions take place.

To cope with these two challenges, scientists use an interdisciplinary systems approach, where the biophysical basis of human society is seen as a complex self-reproducing (autopoietic) system controlled by human agents (Binder et al. 2013; Fischer-Kowalski and Weisz 1999). The systems approach to studying the biophysical basis of human society is called socioeconomic metabolism (SEM) (Fischer-Kowalski and Haberl 1998); it forms the basis for scientific assessments from the angle of different disciplines (Pauliuk and Hertwich 2015). A major application of the systems approach is to quantify possible future impacts of specific transformation strategies, such as deployment of renewable energy supply or carbon taxation, on different spatial, temporal, and organizational scales. This forward-looking analysis is called *prospective assessment* of transformation strategies. It requires prospective models of socioeconomic metabolism that can capture its future development. These models are being developed in several scientific fields, including integrated assessment model (IAM), econometrics, and industrial ecology (IE).

1.3 Goal and Scope

Unlike IAMs and prospective econometric models, prospective models in industrial ecology were developed very recently, and so far, the community of researchers involved has been rather small. A general overview of prospective modeling in industrial ecology is not available, a gap that we try to fill in this chapter. Our review includes a discussion of general principles of prospective modeling, and it shows how the recently developed prospective IE models relate to the established IE method material flow analysis (MFA), life-cycle assessment (LCA), and input/output analysis (I/O), as well as IAMs.

The remainder of this chapter is structured as follows: First, we describe general principles of prospective models of society's metabolism. Then, we describe the state of the art of prospective models in industrial ecology (IE) and explain the relation of these models to consequential LCA, which is an IE concept that also has a prospective aspect. Finally, we discuss future applications and options for further development of prospective IE models, with special focus on the relation to integrated assessment models (IAMs).

2 Principles of Prospective Models of Socioeconomic Metabolism

2.1 Overview and General Principles

Prospective models of society's metabolism require certain features to be fit for purpose. They need to follow an interdisciplinary systems approach, as explained above, and in Table 2.1, we list salient features of the systems approach and mention briefly how they are commonly implemented.

(1) *Dynamic models* have an explicit time dimension and contain mechanisms to generate the future state of the system from its past and from additional exogenous information. Dynamic models link different time scales with each other, which is necessary to study how changes on short time scales affect the long-term dynamics of the system. For example, large-scale substitution of materials today will alter the recycling system in the future. Combining dynamic models of SEM with other models with an explicit time line, like climate models, allows us to study the interaction between socioeconomic metabolism and the environment over time. Dynamic models allow for flexible handling of time discounting, e.g., an artificial time horizon to calculate the global warming potential is not needed in models where time is explicit. Finally, dynamic models enable researchers to study changes that happen gradually over time, like the introduction of new tech-

Table 2.1 Salient features of prospective models of socioeconomic metabolism and common ways of implementing them

Feature	Common implementation
Ability to capture different spatial, organizational, and temporal scales	(1) Dynamic models
	(2) Assessment at full scale
Capability to produce results that are relevant for different scientific disciplines	(3a) Multilayer modeling
	(3b) Satellite accounts
Ability to determine future consequences of decisions in the past	(1) Dynamic models
Ability to deal with the indeterminacy ("uncertainty") of future development	(4) Scenario modeling with exogenous model parameters
Adherence to generally accepted scientific principles such as mass and energy conservation or economic balances	(3c) Balancing constraints for processes and regions

The numbers refer to the paragraphs below, where more detailed explanation is provided nologies and the transformation of in-use stocks that leads to new recycling opportunities, resource depletion, and declining ore grades.

(2) *Assessment at full scale:* The ultimate goal of the coming transformation is to rescale human activity to a level that can be sustained by nature in the long run and that allows for future human development at the same time. Identifying the appropriate scale of human activity requires us to study socioeconomic metabolism on the global level, which was not necessary to understand the previous socioeconomic transitions.

Socioeconomic metabolism is a nonlinear system, which means that the impact of upscaling small modifications to the system is in general not proportional to the scaling factor. The upscaling of certain sustainable development strategies is subject to local and global constraints for, e.g., land, water, or mineral resources. Moreover, large-scale implementation of certain strategies feeds back into the system and causes structural change. Examples include changing recycling systems, technology learning, or rebound and spillover effects (Hertwich 2005). The total system-wide impact of the strategies' potential effect can therefore only be reliably assessed if the latter are studied at full scale, so that constraints and feedbacks can be included in the assessment.

(3a–c) *Multilayer modeling*, *satellite accounts*, and *balancing constraints* allow scientists from different disciplines, like industrial ecologists and economists, to use a consistent framework to describe society's metabolism and to address a variety of research questions. In multilayer modeling, the physical and economic properties of objects are quantified in consistent parallel frameworks (Pauliuk et al. 2015; Schmidt et al. 2012). Satellite accounts, like emissions to nature or labor requirements, contain additional information about how society's metabolism is connected to the environment and to human agents. They form the interface between models of SEM and those from other scientific disciplines, like climate models or environmental impact assessment. Balancing constraints for the physical and monetary layers, like industry or market balances, is the most fundamental way to check the validity of a prospective system description. Prospective models should always respect these fundamental balances.

(4) *Scenariomodeling with exogenous parameters* acknowledges the indeterminacy of future development and reduces system complexity to a manageable level. Only with scenario modeling one can build scientifically credible prospective models of complex indeterminate systems like socioeconomic metabolism. This central aspect of prospective modeling needs some more elaboration.

Socioeconomic metabolism is a non-isolated and non-deterministic complex system. It is not isolated, because it exchanges energy and matter with the inner of the Earth and with space. SEM is non-deterministic, because it is controlled by human agents that use their environmental literacy to intervene and divert the system from its current trajectory in a non-predictable manner. For such a system, there is no deterministic model that can predict its future development. Instead, scientists use *prospective models* of socioeconomic metabolism to compute future trajectories of the system that are considered *possible but not necessarily likely* continuations of historic development. Such possible future trajectories are called *scenarios*. Prospective models use a trick to compute future scenarios for an indeterminate system: First, a number of *exogenous* parameters, assumptions, and model drivers are defined, and then these are fed into a dynamic model of socioeconomic metabolism that is deterministic relative to the exogenous parameters. Parameters like fertility or efficiency improvement rates, model drivers like GDP or population trajectories, and assumptions like "ceteris paribus" or "business as usual" describe the possible future development of certain indicators and system properties on the macro-scale. In a second step, the prospective model applies the exogenous assumptions to the system description and generates a detailed scenario for society's future metabolism. Specification of exogenous parameters not only eliminates indeterminacy from the model, it also reduces the complexity of the system description by fixing those system variables that one else would have to determine by modeling poorly understood feedback mechanisms or those where sufficient empirical data are not available. Scenario analysis is therefore an important way to handle our ignorance of human-environment systems in a productive and transparent way.

2.2 Credible, Possible, and Likely Scenarios

To decide what is a possible future and what is a credible scenario, scientists have established criteria that prospective models and their results need to fulfill. Exogenous assumptions need to be plausible and consistent. Often, they follow a certain scheme or idea that is called *story line*. Criteria for prospective models include process balancing constraints such as monetary, mass, or energy balances; the assumption that certain parameters, like efficiency improvement rates, do not leave empirically determined ranges; assumptions on human behavior; or the ability of the model to correctly determine the actual development from a given starting point in the past, using macro-indicators such as GDP as driver.

Criteria for plausibility, consistency, and properties of exogenous assumptions and prospective models differ across modeling fields, mainly because of different academic traditions. This scientific inconsistency has repeatedly led to criticism across modeling disciplines, like our criticism of integrated assessment models from an industrial ecology perspective presented below.

Are scenarios, or *possible* futures, also *likely* outcomes of future development? This often-raised question about the predictive capability of scenarios needs clarification. Strictly speaking, there cannot be a connection between possibility and likelihood in an indeterminate system, and a scenario can never be a prediction of the likely future outcome. This dogma, however, contradicts our intuition and the way the term scenario is often used. Especially when it covers only a short time span into the future, a scenario for the future development of SEM can appear to have predictive character (Börjeson et al. 2006). We assert that the apparent short-term determinacy of the indeterminate socio-metabolic system is a result of the slow turnover of in-use stocks, such as buildings, infrastructure, and products of different kinds, which adds considerable inertia to the system. The large amount of social and biophysical resources required to transform in-use stocks limits the speed at which the system can deviate from its present state (Pauliuk and Müller 2014). Hence, the spectrum of likely future states of SEM is the narrower the shorter the time horizon. Still, this predictability of an indeterminate system differs from the "absolute" predictions for truly deterministic systems because in indeterminate systems, unforeseen events such as the discovery of new technologies, sudden political changes, or natural catastrophes can substantially alter the trajectory even in the short run. To accommodate for the indeterminacy of SEM in the near future, prospective short-term models of society's metabolism are complemented by risk assessment.

The coming transformation of society's metabolism will require us to rebuild a substantial fraction of society's in-use stocks. The more complete the transformation, the less the future state of SEM is determined by present in-use stocks. Scenarios that cover time scales during which the coming transition may take place are therefore only little constrained by the inertia given by present stocks. Consequently, these scenarios have no predictive but explorative (What can happen?) or normative (How can a specific target be reached?) character (Börjeson et al. 2006). Prospective models in industrial ecology are used to study the transition ahead, and hence, the scenarios they generate are explorative or normative but not predictive.

3 Prospective Modeling in Industrial Ecology: State of the Art

3.1 Prospective Modeling with Established IE Methods

Industrial ecology methods and models, which allow us to study complex industrial systems, have been at the forefront of the interdisciplinary systems approach for more than three decades. Traditional industrial ecology methods include EE-I/O, LCA, MFA, urban metabolism, and industrial symbiosis. They cover a wide spectrum of spatial, temporal, and organizational scales, from static snapshots of the supply chain of local companies to studies of the evolution of aggregated material and energy flow accounts through the last centuries. They offer to decision-makers quantitative information about supply chains, environmental impacts embodied in trade, material and energy stocks and flows, and options for system-wide improvement.

Industrial ecology methods have reached high levels of sophistication and are broadly applied in companies and academia alike, but their use for prospective assessment of transformation strategies has remained a niche application. Prospective scenario exercises for I/O tables have repeatedly been conducted over the last decades (Cantono et al. 2008; De Koning et al. 2015; de Lange 1980; Idenburg and Wilting 2000; Leontief and Duchin 1986; Levine et al. 2007), but this modeling approach has not entered mainstream research on society's future metabolism. The reason may be twofold: (1) constructing I/O tables for future years requires many assumptions to be made and (2) using I/O tables in monetary units to measure interindustry flows, as in the studies above, makes it difficult to include physical process descriptions for specific technologies. Beyond IE, I/O tables form the core of computable general equilibrium (CGE) and prospective econometric models like the E3ME model (Burfisher 2011; Cambridge Econometrics 2014).

Most LCA studies are retrospective and attributional; they use historic data to model the life cycle of product systems and provide timeless indicators for environmental product performance. Prospective LCA (Lundie et al. 2004; Spielmann et al. 2005) and consequential LCA (CLCA) (Earles and Halog 2011; Finnveden et al. 2009; Whitefoot et al. 2011) add a forward-looking perspective to LCA. They typically assess transformation strategies on the small scale.

Prospective MFA studies mostly cover metals and building materials but do not include other layers or satellite accounts (Elshkaki and Graedel 2013; Hatayama et al. 2010; D. B. Müller 2006; Northey et al. 2014; Pauliuk et al. 2012; Sartori et al. 2008; Gallardo et al. 2014).

From the methods above, only MFA has been used to analyze preindustrial societies' socio-metabolic transitions (Krausmann 2011; Schaffartzik et al. 2014; Sieferle et al. 2006). These studies quantified trends in the total energy and material turnover of different socio-metabolic regimes, but they did not assess specific transformation strategies to shift from one regime to another.

3.2 New Approaches to Prospective Modeling in Industrial Ecology

The state of development of the above methods to conduct prospective studies of the next socio-metabolic transition is not satisfactory. The history of IE exhibits several examples for problems that were overcome by combining different IE methods into new frameworks. Examples include hybrid LCA (Suh et al. 2004) and WIO-MFA (Nakamura et al. 2007).

To come closer to the ultimate goal of studying a wide spectrum of transformation strategies at full scale in a common prospective modeling framework, the established IE methods have been combined in novel ways. As a result, a new family of prospective industrial ecology models is available, and we briefly present two of its members, extended dynamic MFA and THEMIS (Technology-Hybridized Environmental-Economic Model with Integrated Scenarios), and their application so far.

In-use stocks of buildings, infrastructure, or products are central in understanding the transition from the present to different possible future states (Pauliuk and Müller 2014). In-use stocks therefore need to be part of prospective models of socioeconomic metabolism. They are commonly represented as dynamic stock or population balance models, which are time series of stocks that are broken down into age cohorts and specific product types or technologies. The items in each age cohort and technology class can have specific material composition, energy efficiency, and other parameters necessary to determine the requirements and emissions of each item in the stock during its useful life.

Next to in-use stocks, prospective models of SEM contain descriptions of the industries to build up, maintain, and dispose of these stocks and markets that distribute products or product mixes across users. In-use stocks, industries, and markets are arranged into a general system description of socioeconomic metabolism (Fig. 2.1). The universal system structure of the socioeconomic metabolism in

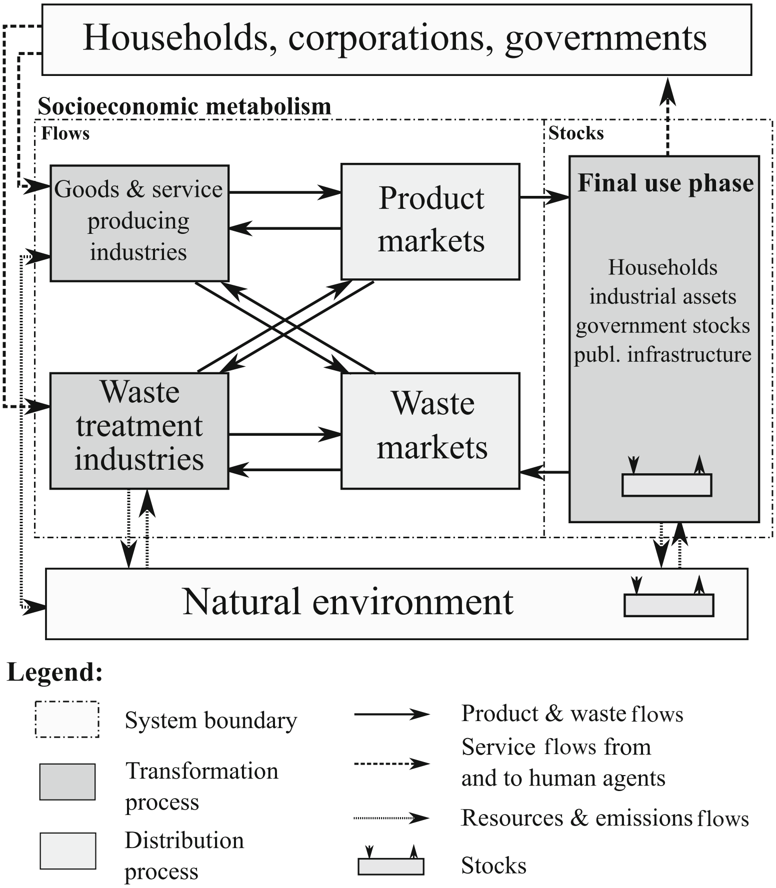

Fig. 2.1 The general structure of the system definitions of the prospective industrial ecology models (Adapted from Pauliuk et al. (2015))

Fig. 2.1 serves as blueprint for the structure of the system definitions of the different prospective models, including CGEs and IAMs (Pauliuk et al. 2015).

3.2.1 Prospective Modeling Using Extended Dynamic MFA

MFA models contain both flows and stocks; they are hence a natural starting point for dynamic and subsequently prospective modeling (Baccini and Bader 1996; Kleijn et al. 2000; D. B. Müller et al. 2004; van der Voet et al. 2002). MFA studies focus on a few materials or product groups at a time, and it was clear early on that prospective modeling with such a limited scope requires exogenous assumptions on the future development of material demand and technological change. In stock-driven modeling, the size of in-use stocks and the lifetime distribution of the different age cohorts are given exogenously, and deconvolution is applied to determine material demand and scrap supply (D. B. Müller 2006). The ability of dynamic stock models to determine future scrap supply from historic material consumption has enabled prospective modeling of mass-balanced recycling systems (Busch et al. 2014; Hatayama et al. 2009, 2010; Igarashi et al. 2007; E. Müller et al. 2014; Murakami et al. 2010; Tanikawa et al. 2002). These models often distinguish between different quality levels of secondary material and contain rules for the substitution of secondary for primary metal that are similar to system expansion in LCA or the by-product technology assumption in I/O (Daigo et al. 2014; Hashimoto et al. 2007; Løvik et al. 2014; Pauliuk et al. 2012, 2013a). Transformation strategies often affect products and the materials contained therein are not directly addressed. To understand the role of materials in different transformation strategies, there hence was a need to include product life cycles into dynamic MFA models, which led to the development of multilayer MFA and the combination of MFA with process-based LCA and life-cycle impact assessment (Milford et al. 2013; Pauliuk et al. 2013b; Sandberg and Brattebø 2012; Pauliuk 2013).

State-of-the-art extended dynamic MFA models comprise these different trends and provide large-scale and long-term dynamic assessments of specific transformation strategies, such as material efficiency (Milford et al. 2013) or passenger vehicle light-weighting (Modaresi et al. 2014). Starting from scenario assumptions on stock size and technology choice, these models apply stock-driven modeling to determine the levels of material production and energy supply that are required to build, operate, and dispose of the product stocks. They contain material-balanced process models of the industrial system and use satellite accounts to track resource consumption, energy supply, and emissions to the environment. A special feature of dynamic extended MFA is the high level of detail of the material cycles in the system, the distinction between open-loop recycling ("downcycling") and proper recycling, and their capability to quantify how changes in material production and recycling systems impact the overall effect of a certain transformation strategy.

3.2.2 Prospective Modeling Using the THEMIS Model

Large-scale deployment of more efficient and renewable energy technology can substantially reduce the environmental footprint of the global economy. It also leads to large changes in the carbon footprint of energy-intensive products and services such as materials or transportation. For example, the environmental superiority of electrically propelled passenger vehicles compared to gasoline-driven ones depends to a large extent on the carbon intensity of the electricity supply (Hawkins et al. 2013). Prospective LCAs of future technologies need to account for these different framing conditions, for example, by conducting a scenario analysis with different mixes of energy carriers and conversion technologies. Possible future mixes are commonly determined by integrated assessment models, such as the TIMES/MARKAL model family (Loulou et al. 2005), which stands behind the Energy Technology Perspectives of the International Energy Agency (OECD/IEA 2010). The technology mixes determined by such models can be used to build future scenarios for LCA databases, so that the market mix for certain products like electricity resembles the mix in the IAM scenarios. A thus modified LCA database can be used to conduct prospective attributional LCAs of future consumption.

The THEMIS model (Technology-Hybridized Environmental-Economic Model with Integrated Scenarios) is a recent implementation of this principle (Gibon et al. 2015). It provides insights into the "comparative environmental impacts and resource use of different electricity generation technologies" (Hertwich et al. 2015). THEMIS has four main features: (1) Its core is a nine-region integrated hybrid LC inventory model, which is a combination of foreground information on the specific technologies studied, a background LC inventory database of generic processes like materials production and transport, and MRIO tables to cover processes not contained in the LC background. (2) The historic technology mixes for electricity generation in the nine model regions were replaced with those obtained from the IEA baseline and BLUE MAP scenarios (OECD/IEA 2010) to build prospective future LC inventory models for 2030 and 2050. (3) The gradual transformation from the current to alternative future electricity mixes until 2050 was modeled with an age-cohort-based stock model of electricity generation assets, so that for every model year, the economy-wide impacts for building up new, operating, existing, and disposing of retiring electricity generation technology can be determined (Hertwich et al. 2015). (4) Exogenous scenario assumptions on the improvement of energy efficiency, capacity factors, and technology in the production of several major materials including aluminum, copper, nickel, iron and steel, and others were taken from a prospective study on efficiency improvement (ESU & IFEU 2008).

3.3 The Relation between Prospective IE Models and MFA, LCA, and I/O Analysis

The prospective IE models are built upon the established IE methods MFA, LCA, and IOA. They are integrated hybrid models of society's metabolism, in the sense that they combine a foreground system with high level of detail and strict adherence to core modeling principles such as mass balance with a generic background system. The background provides the foreground with auxiliary input, such as electricity supply for material production, and uses the products exclusively supplied by the foreground as intermediate requirements in turn.

The foreground of extended dynamic MFA comprises dynamic stock models of the materials and products studied and process models of the industries that are part of the material cycles studied. The foreground system is balanced for the products and material that are within the scope, and the background system supplies energy and other ancillary inputs to operate the stocks and processes in the foreground. Environmental impact assessment is carried out for the satellite accounts of relevant emissions from both foreground and background. Because extended dynamic MFA contains process models, considers the background economy, and uses impact assessment, one can also consider these models as macro-LCAs of the total service provided by the stocks studied, carried out as dynamic studies with scenarios for future development. The foreground model of extended dynamic MFA contains markets at all stages, preserves co-production, and contains rules for substituting secondary material for primary material. It can therefore be reformulated as combination of a physical waste-I/O model with the by-product technology assumption combined with a dynamic stock model of the products studied.

THEMIS integrates LCA and I/O modeling and combines the so-obtained hybrid model of interindustry flows with environmental impact assessment via satellite accounts. It also contains elements that are commonly found in dynamic MFA: THEMIS's foreground system is coupled to a dynamic stock model of electricity generation assets, so that material demand for building new assets and recycling of old ones is determined from the turnover of the capital stock in mass-balanced manner.

3.4 The Relation between Prospective IE Models and Consequential LCA

The desire to study the potential future consequences of a decision has been a long-standing motivation for industrial ecology research, and a few recent examples were cited above. In LCA, this desire has led to the concept of consequential life-cycle assessment (CLCA), which "is designed to generate information on the consequences of a decision" (Ekvall and Weidema 2004). While the concept of a consequential LCA is intriguing, it is also poorly defined and subject of controversy (Brandão et al. 2014; Dale and Kim 2014; Finnveden et al. 2009; Hertwich 2014; Plevin et al. 2014a; Suh and Yang 2014; Zamagni et al. 2012). CLCA was initially defined as a result of the debate on how to allocate emissions and inputs of processes with multiple products to the respective outputs. It focused on the marginal effect of producing an additional unit of output of a specific product or of recycling such a product (Ekvall and Weidema 2004). Such allocation problems are addressed through systems expansion in CLCA, so that the assessment of a product depends not only on the product system of the investigated product but also on the product systems of other products and, in particular, the production volumes of and demand for those products. This dependence on other product systems is most clearly visible when scientists, under the heading of "consequential LCA," address the question of what happens to constrained resources when a product is not produced. In the opinion of some, the consequential life-cycle emissions of a bicycle should include those of combusting the petrol that it does not use because somebody else will combust that petrol as a response of the market to the bicycle not using that petrol (Plevin et al. 2014a, b). One of us (Hertwich 2014) has questioned whether it makes sense to say that the petrol not combusted by the bicycle is part of the product system "bicycle" only because one could have used a car instead. It is also problematic to say that riding the bicycle to work causes petrol combustion somewhere else in the economy due to price elasticity. The petrol combustion is rather the consequence of somebody else's decision somewhere else in the economy.

It is of course a legitimate research questions to ask, e.g., what is the effect of the massive and intended expansion of cycling in Copenhagen on GHG emissions? The question, however, remains ill-defined until one juxtaposes the observed or planned expansion of cycling to some counterfactual possible scenario of increased car or bus transport. In addition, one needs to define the scope and functioning of the system investigated, including the causal mechanisms to be addressed. Mechanisms may or may not include the fuel market response to the petrol demand in the counterfactual scenario, the effect of the inspiration Copenhagen now provides to town planners all over the world and the effect of increased life expectancy of the cyclists on food demand and future economic development. Then one has two scenarios to compare, and one may colloquially argue the difference between the scenarios that indicates the effect of Copenhagen's cycling policy and the enthusiastic popular response it has received. Such causality is an imputed, assumed causality; the assumptions are made in the setup of the systems model and the definition of the scenarios and the imputation in the interpretation of the scenario results as showing the difference. Other system models and scenario assumptions may be equally reasonable; the true consequences are unmeasurable because we do not have a second Earth to run an experiment on.

The early developers of systems expansion as a way of addressing allocation issues fully understood that system expansion involved assumptions about other product systems and that results should be interpreted with these assumptions in mind.

We expand our above argument regarding the predictive capacity of prospective models for indeterminate systems and assert that the hypothetical CLCA approach as described by Plevin et al. (2014a) faces a dilemma: The capability of the hypothetical CLCA model to reliably predict the future outcome is the better the smaller the changes to the system and the shorter the time horizon, because fewer human actors, who are the major source of indeterminacy, are involved if changes are small and local and the inertia represented by existing stocks is larger in the near future.

Modeling on the small scale with short time horizons is the opposite of what is needed for studying strategies for a socio-metabolic transition, however, and for large-scale and long-term changes, prediction remains an illusion. Therefore, we need a practical and scientifically credible implementation of the ideal represented by the hypothetical CLCA approach.

In our opinion, prospective IE models provide such implementation. The scenario approach makes explicit the underlying exogenous assumptions that necessarily accompany any prospective model of an indeterminate system. Several authors, including Zamagni et al. (2012), Plevin et al. (2014a), and Suh and Yang (2014), acknowledge the importance of scenario modeling for the scientific assessment of decision-making in general and the questions posed by CLCA in particular. The use of a comprehensive model of society's metabolism allows us to study the system with the high level of detail and biophysical consistency that is a distinctive feature of industrial ecology methods. The combination of the scenario approach and a detailed model of society's metabolism make prospective IE models a powerful and scientifically credible approach to explore the potential consequences of decisions.

4 Prospective Modeling in Industrial Ecology: Future Development

4.1 Future Applications and Model Development of Prospective Models within Industrial Ecology

A major goal of prospective modeling is to assess bundles of mitigation and adaptation strategies and investigate whether the different strategies together can transform socioeconomic metabolism to a more sustainable state. Studying strategy bundles reveals which strategies may yield co-benefits and which ones counteract each other, which is an important information for decision-makers. Bundled assessment leads to "big picture" scenarios for a feasible future, from which environmental, economic, and social performance indicators for individual strategies can be derived. These indicators can then be monitored during real implementation to ensure that the impact of the strategies is as intended. Performance indicators may be material, product, industry sector, or region specific.

Strategy bundles affect different materials and energy carriers, which are substitutable to some extent. Flexibility in the choice of materials and energy carriers allows us to design a more resilient and potentially more sustainable SEM, but it also represents a challenge for prospective modeling, as models need to provide insights into the potential consequences of a wide spectrum of material and energy supply choices.

The cycles of different materials are tightly coupled at several places: Base minerals of different materials often occur together; they are coproduced, often with fixed ratios on certain sites. At higher stages of fabrication, materials are mixed again into compound materials and alloys, products consist of many different materials, and finally, waste streams contain material mixes. Assessments of individual metals on the small scale can neglect this coupling, as it can be assumed that the rest of the economy is able to supply or absorb ancillary flows and a credit or discredit for this service is given by allocation. In prospective modeling of society's future metabolism at full scale, however, the tight coupling between different material cycles ultimately necessitates parallel modeling of different materials across products and over time. Only then can one assess whether and how system-wide supply can meet system-wide demand for different chemical elements at different stages of the material cycles. Supply-demand imbalances may arise under business-as-usual assumptions, as studies for aluminum (Modaresi and Müller 2012) and rare earth metals (Elshkaki and Graedel 2014) show, which points out the necessity to design future material cycles from a systems' perspective.

For dynamic MFA, several trends that point toward comprehensive assessment of multi-material product portfolios are already emerging. One trend goes toward a higher level of detail of material types (alloys) and products studied to better understand quality issues in the recycling systems of different materials (Løvik et al. 2014; Ohno et al. 2014). Another trend goes toward modeling of co-occurrence, co-mining, and co-production of mineral and metal resources and production systems and energy-ore grade relationships (Graedel et al. 2013; Northey et al. 2014). Finally, there are recent advances in the modeling of the fate of the end-of-life materials from the waste management industries back into new products using Markov chains and supply-driven I/O modeling (Duchin and Levine 2013; Nakamura et al. 2014).

The trend of using I/O models for prospective assessments is also likely to continue. Service-driven modeling, or – if stocks are used as proxy for services – stock-driven modeling, can be used (a) to determine the final demand vector for I/O models (Kagawa et al. 2015) and (b) to determine the Leontief-A matrix from an age-cohort-based model of the productive capital stock (Pauliuk et al. 2015). Multilayer modeling (Schmidt et al. 2012) can be used to cover different materials in a common I/O framework, and when building I/O models of future industrial systems, the by-product technology construct can be applied to avoid allocation (Majeau-Bettez et al. 2014). A major application of the so-obtained I/O models is the prospective attributional assessment of certain quanta of final demand to measure strategy performance and derive policy targets related to specific transformation strategies.

4.2 Linking Industrial Ecology and Integrated Assessment Models (IAMs)

The most prominent contribution to prospective modeling of society's metabolism did not emerge from industrial ecology but from other disciplines, especially integrated assessment modeling. While widely successful in generating integrated scenarios of the society' future metabolism, the biosphere, and the climate system, integrated assessment models were criticized for several shortcomings (Arvesen et al. 2011; Pindyck 2013; Stern 2013). To our knowledge, a detailed criticism of IAMs from an industrial ecology perspective is still lacking; it is also beyond the scope of this chapter; however, below we list central points of critique and propose some ideas for the integration of IE principles into IAMs.

4.2.1 Integrated Assessment Models from an Industrial Ecology Perspective

In general, one can say that industrial ecologists have a more refined notion of industry as a complex system than what is currently characterized in most integrated assessment models. IAMs trace the extraction, refinement, and conversion of energy carriers but lack a description of the life cycle of the conversion technologies. IAMs model energy demand and energy efficiency opportunities in industry, buildings, and transport but lack a description of value chains and hence the interaction of different sectors. IAMs contain a description of material production as the most important industrial energy consumer but lack detail regarding the modeling of waste generation and recycling, co-production, material demand, and associated environmental impacts.

In IAMs, the level of material recycling – if recycling is considered at all – is in general not determined from the turnover of the industrial assets and products in the use phase. Either the material stocks (mostly steel and aluminum) are modeled separately from capital and product stocks and an average lifetime is used, or there is no connection at all between the extent of recycling and historic levels of material consumption. Co-production, substitution of by-products, and industrial symbiosis are only rudimentarily considered, if at all. Due to the focus on climate change, other environmental impact categories, like toxicity or acidification, are generally not taken into account in energy systems models nor are mineral resource depletion and the relation between ore grade and energy demand for extraction commonly considered.

In a nutshell, we assert that integrated assessment models lack several features that are central achievements of industrial ecology research. From the perspective of our field, the scenarios of society's future metabolism constructed by IAMs lack consistency and validity, which may compromise the credibility of the conclusions drawn.

4.2.2 The Link Between the Prospective IE Models and IAMs

Integrating IE principles into IAMs will allow the latter to construct more consistent and realistic scenarios of society's future metabolism. Moreover, this integration can increase the scope of IE research, and as a result, both research fields can move forward. We present some ideas for how this integration could happen.

The general system structure of socioeconomic metabolism acknowledges three types of processes: the industries, the markets, and the final use phase (Pauliuk et al. 2015). There are canonical models for each process type. Industries are modeled by production functions, markets by supply and demand curves, and the use phase by dynamic stock models. We discuss each process type in turn.

(1) *Industries*: Both IAMs and IE models commonly use Leontief-type production functions with fixed technical coefficients and no substitution between inputs to

describe intermediate demand. Technological detail is high in both model families, and in IAMs, industrial assets are often modeled as discrete units to simulate individual plants. Technological change is exogenous in IE models but endogenous in some IAMs. We see three ways in which IE principles can improve the modeling of production processes in IAMs: (1) mass balance consistency between industrial input and output, inclusion of waste generation and recycling; (2) consideration of multi-output processes and industrial symbiosis, that is, joint production of commodities and by-products within and across industrial sectors; (3) separate description of primary and secondary material production. Point (4) is already part of several IAMs, but the way scrap supply is modeled differs substantially across different IAMs, and not all approaches are meaningful from an IE perspective.

(2) *Marketsand products*: In IE models and IAMs, markets balance supply and demand. It is common in IE to distinguish between markets for primary products and waste and to require the models to clear both markets at the same time. Introduction of waste markets into IAMs and the development of mechanisms for how they are cleared would allow for realistic modeling of waste treatment and recycling activities. Detailed descriptions of waste handling, recycling, and substitution of secondary for primary materials are essential in understanding how a transition to a more circular economy could happen; they should therefore be an integral part of future prospective models. More details regarding the quality of materials, for example, by considering different alloys, will be necessary to build scenarios for the use of secondary materials in different products.

(3) *The final use phase* comprises in-use stocks such as products used by households, public buildings and infrastructure, and industrial assets. Both prospective IE models and IAMs use age-cohort-based dynamic models to represent in-use stocks. The age cohort technology composition of industrial assets, vehicles, or buildings determines the overall intermediate energy and material requirements to produce industrial output, drive vehicles, or heat buildings, and modeling this relation is the traditional strength of IAMs. In-use stocks, however, also represent material stocks or "urban mines." Modeling the material layer of in-use stocks along with their economic value and technical coefficients allows us to obtain a comprehensive picture of stocks and to connect the future extent of waste recovery and recycling to the physical turnover of industrial assets and other in-use stocks. The principles for this multilayer modeling of stocks are presented elsewhere (Pauliuk et al. 2015), and to implement them into IAMs, one needs to amend the description of in-use stocks by adding the material composition layer.

IAMs can also be extended regarding the *interaction of SEM with environment and society*. Due to their focus on climate change, IAMs generally focus on greenhouse gas emissions, but other types of emissions, such as particulate matter or heavy metals and other toxic substances, can be readily included (Gibon et al. 2015). IAMs contain detailed descriptions of biotic resources but should be extended to better reflect the depletion of mineral resources, especially metal ores. More details can be added on the social side, too, for example, by capturing direct relations between production activities and society, such as labor requirements at different levels of skill or labor conditions (Simas et al. 2014).

IAMs that fully respect IE principles will generate scenarios that include a wide spectrum of transformation strategies, provide a mass balance consistent and material-specific representation of SEM, and comprehensively cover interactions of SEM with the environment and society. These comprehensive and scientifically credible scenarios of society's future metabolism will then form a common basis for the analysis by different scientific disciplines.

5 Conclusion

Prospective IE models combine central features of the established IE methods into a new framework. They allow researchers to conduct comprehensive and dynamic scenario analyses of society's future metabolism and to study the potential system-wide effect of sustainable development strategies. The development of these models is motivated by the desire to study the coming socio-metabolic transition and to assess the different transformation strategies at full scale and with long-term scope, while maintaining the high level of detail and biophysical consistency that is a distinctive feature of industrial ecology methods. The intellectual framing that comes along with the prospective IE models provides a "new slang" for the field: It broadens the perspective of industrial ecology research because it gives impulses for the development of new and important research questions for further refinement and integration of assessment methods and for the development of a common, model-independent database of socioeconomic metabolism.

The recent development in industrial ecology methods necessitates a discussion about the relation between prospective IE models and IAMs since the latter are the major tool for prospective assessment of transformation strategies. We contributed to this debate by proposing how industrial ecology principles could become an integral part of integrated assessment models and how this integration could strengthen both fields and increase the relevance, robustness, and credibility of scientific assessment of transformation strategies.

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