Industrial Ecology open online course

IEooc_Background1_Reading1

Quantitative Analysis *of* Industrial Systems:

Intellectual Framing

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Summary

The reduction of natural phenomena into predictable local environments and repeatable processes is the basis of the industrial system and the synthesis of products generated by that system. The industrial system is embedded in the larger social and natural environment, and to tackle major challenges such as sustainable development the reduction and synthesis approach is not sufficient. It needs to be complemented by systems thinking, which is about understanding reality as a set of interrelated and diverse elements and studying complex phenomena from the perspective of different scientific disciplines.

Reality has two spheres: First the biophysical sphere that exists independently of human observers and for which claims can be made that can be empirically verified or falsified. Second, the social sphere of causation that constitutes relations among humans, relations between humans and biophysical objects, and between humans and social institutions.

Those biophysical objects and processes that are controlled by humans form the biophysical basis of society. That basis consists of a structure, or in-use stocks, and a social metabolism to build up and maintain these stocks.

For social systems to function humans need to organize socioeconomic metabolism. The arrangement of stocks and flows in society's biophysical basis, in particular, their distribution across the members and institutions of society, depends on the social rules and frameworks created. The study of the biophysical basis of society follows both physical laws and social mechanisms/rationales. Physical laws such as the conservation of mass and energy guide the tracing of mass and energy flows in society, while social rationales motivate the use of economic models as well as different forms of social, cultural, and psychological inquiry.

When in- and outflows of industrial processes can be described in detail, the process itself can be modeled as a black box whose functioning is defined by the processing of specified inflows into specified outflows. This micro-perspective on the industrial system needs to be complemented by a macro-perspective, where system-wide affects such as price formation, resource stocks and their depletion, and total emissions to environment and subsequent environmental degradation can be studied.

Qualitative arguments are helpful to describe the possible impacts of different sustainable development strategies but are not sufficient for robust decision making. To identify the actual potential environmental and resource impacts of a specific strategy, two things are required: First, a *quantitative analysis* of actual material and energy flows associated with the product, and second, a consistent *systems perspective*. The quantitative systems analysis of human-environment-technology interactions, with focus on material and energy flows, is often labelled as 'industrial ecology'. Industrial ecology is a systems science that offers a framework for knowledge integration from different scientific fields. Industrial ecology researchers study specific system linkages, including the service-stock-flow-impact linkage and global supply chains.

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1) Why thinking in systems?

Two basic scientific principles, reductionism and synthesis: Climate change mitigation and the more widely framed sustainable development are commonly seen as 'wicked problems',[2] meaning that problem framing and solution are intertwined and there are no right or wrong solutions to them. Solutions to wicked problems are hard to test and, once implemented, will profoundly change the system, for better or worse. Science has a hard time dealing with those problems, as reductionism, a core scientific principle, does not work well with wicked problems. Reductionism in science means that complex phenomena are separated into many parts or components so they can be studied in isolation from their environment. Reductionism is also the basis of model development. Using scientific models of parts of reality, we can redesign and optimize those parts, create processes or products that emulate specific functionalities, combine these products, and apply them in new environments. In a passenger car, for example, fire was tamed and it is now applied in tamed form in the combustion engine, lightning was engineered into a spark that ignites the fuel-air mixture, and petroleum was turned into the plastic cover of the seats and into the fuel that keeps the car running.

By *reducing* the complexity of problems by limiting their scope, scientists have extracted knowledge about a multitude of mechanisms from the world around us, and engineers have taken this knowledge to *synthesize* new products and processes. As a consequence of this development, humans have developed highly specialized yet diverse skills related to different mechanisms to be able to design, produce, and maintain the different products and processes. The famous dictum: '*no one knows how to make a pencil*' illustrates the division of labor and the organization of specialized processes, products, and jobs into complex supply chains (Fig. B1R1.1).

[2] https://en.wikipedia.org/wiki/Wicked_problem

Figure B1R1.1: "I, pencil."

The phrase can be traced back to a 1958 Essay 'I, pencil', written by Leonard E. Read. In this essay, Read writes from the perspective of a simple pencil that reflects on the process of its creation:

> "[N]*ot a single person on the face of this earth knows how to make me*. […] Actually, millions of human beings have had a hand in my creation, no one of whom even knows more than a very few of the others. […] There isn't a single person in all these millions, including the president of the pencil company, who contributes more than a tiny, infinitesimal bit of know-how. From the standpoint of know-how the only difference between the miner of graphite in Ceylon and the logger in Oregon is in the type of know-how. Neither the miner nor the logger can be dispensed with, any more than can the chemist at the factory or the worker in the oil field—paraffin being a by-product of petroleum.
>
> Here is an astounding fact: Neither the worker in the oil field nor the chemist nor the digger of graphite or clay nor any who mans or makes the ships or trains or trucks nor the one who runs the machine that does the knurling on my bit of metal nor the president of the company performs his singular task because he wants me. Each one wants me less, perhaps, than does a child in the first grade. Indeed, there are some among this vast multitude who never saw a pencil nor would they know how to use one. Their motivation is other than me. Perhaps it is something like this: Each of these millions sees that he can thus exchange his tiny know-how for the goods and services he needs or wants. I may or may not be among these items.
>
> There is a fact still more astounding: The absence of a master mind, of anyone dictating or forcibly directing these countless actions which bring me into being. No trace of such a person can be found." (Read 1958)

Cleary, in industrial societies Read's description applies to virtually any product.

The limit of scientific reductionism and the systems approach: The combination of reductionism and synthesis forms the basis of what is commonly called 'modern society', or, a bit narrower, the industrial society. We reduce the complexity of natural phenomena to distill knowledge from them and synthesize the different industrial operations and products that then serve our needs.

But synthesis creates more than a collection of individual industrial processes: From Read's vivid description we learn that the creation of even seemingly simple products like pencils involves a multitude of pre-stages that together form a complex value chain. Many of these pre-stages require natural resources or emit process waste to the environment, but these upstream interactions are not visible in the final product, the pencil. By analyzing the final product, the pencil, alone, one cannot identify the amount of working hours put in it, nor the amount of carbon emissions released for its production, nor the types of industrial capital required at the different stages of the value chain. The connection between synthesized products and environmental and social impacts is invisible, but it is present. The different industrial and societal processes are not isolated from another; they are in relation to each other as they are linked by material and energy flows, by value chains, by ownership relations, by employment relations, by competition on the markets, and by their exploitation of commonly used natural resource pools. The man-made processes and flows of goods between them are more than just a collection of individual sectors or plants, they form a system, the industrial system (Fig. B1R1.2).

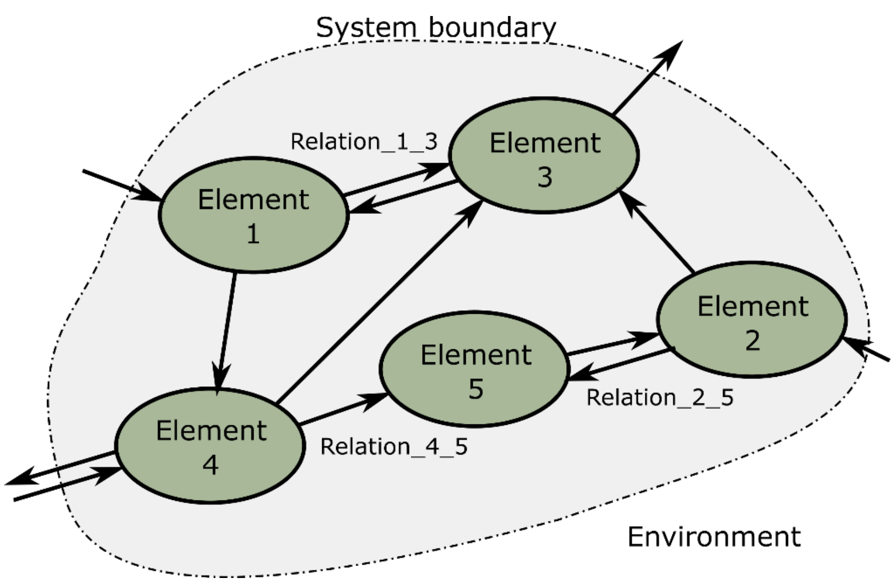

Figure B1R1.2: Sketch of a system, with elements, relations, and the system boundary.

The systems approach allows us to capture linkages (or relations) between individual elements, including: industrial processes, products, environmental processes, and human agents. An industrial process depends on a multitude of precursor products, which are bought on markets. A product has a complex supply chain, and environmental processes are impacted by emissions from the anthroposphere. Human agents play several roles in the industrial system: they supply labor and capital, consume industrial products, and control the entire system.

An industrial process is more than the creation of products, it is also a source of emissions, a sink of resources, a place to work, an investment opportunity, and many more. While reductionism looks at these different roles one at a time and often ignores other roles, the systems approach is more comprehensive and provides a stage where a larger set of the processes' roles in the system can be studied simultaneously and from the perspective of different scientific disciplines.

Summary: The reduction of reality into predictable local environments and repeatable processes is the basis of the industrial system and the synthesis of products generated by that system. The industrial system is embedded in the larger social and natural environment, and to tackle major challenges such as sustainable development the reduction and synthesis approach is not sufficient. This approach needs to be complemented by systems thinking, which is about understanding reality as a set of interrelated elements and studying complex phenomena from the perspective of different scientific disciplines.

2. A general theory of analyzing coupled human-environment systems

Two types of reality: social and biophysical: I think, therefore I am. My mind constructs a world around me that fits to my sensual perception. I perceive weather, ambient temperature, space to navigate in with trees, buildings, rivers, mountains, and other landmarks. There are other people in this constructed world that seem to behave in similar patterns as I do, and from that I conclude that these people are like me. I particular, I assume that their mind also constructs the world around them, and when talking to them I realize that we can agree on a lot of things about this world, especially when it comes to the description of matters independent of how we humans value things or events in that world. That leads us to the assumption that this constructed world around us is actually real, meaning that it exists, it is there, whether we perceive it nor not.

We have no definite certainty that the assumption of the existence of the biophysical world around us is true, in the sense that it can be verified by means other than our own experience. That is because all evidence we can ever produce needs to enter our mind via our sensual perception, be it measurement results or conversations with others. Using our own pure reason we cannot prove its reality, as we can easily think of a 'Matrix'-like situation where all what we perceive is dreamt up, is an illusion hiding from us a very different reality or some other world that we cannot or are not supposed to see.

With our own minds only, we can easily falsify the hypothesis of the objective world around us, just by using an imagination that this world is an illusion, maybe a simulated reality. This is the major uncertainty that we have to live with. But this so-called solipsist approach does not take us very far, except maybe to a self-absorbed infant-like state where the rest of our universe seems to be there to please us and we get really upset if it doesn't.

At some early stage in their life, most people conclude that the world around us is real, in the sense that is coherent and exists with or without interference of human beings. Many also realise that different individuals or groups of people can develop their own valuation of and personal relation to the things and phenomena in that world. **We call the objective world around us the biophysical reality and the ambiguity of man's description of it the social construction of knowledge.**[3]

Both, the doubt about the reality of the world around us and the ambiguity of our description of it get constantly mixed up. We can assert that the world around us is empirically real, verified every day by billions of people like us. We cannot assert the absolute reality of that world, however, because we do not have access to some higher-level reference point to make reality and truth statements, like those made from the point of view of a god-like being looking at our universe. We need to distinguish between the uncertainty related to the reality or truth of the biophysical world around us and the variability of us humans in categorizing, describing, and building relations with this world.

Nature, as we observe it, shows discrete features, objects and creatures of a similar kind, and symmetry. The question of whether the categories humans use to capture discreteness belong to the world, whether they are real and precede the instances or the other way round cannot be answered per se.[4] Instead, the answer to that question depends on how we understand the world as a whole, starting from or initial perception of the world around us.

In the field of interdisciplinary research that industrial ecology positions itself in, a specific approach to disentangling the difference between the objective biophysical reality and its perceptions and categorisation by humans is taken (Fig. B1R1.3). Here, reality is seen as subject to two different causation mechanisms, a biophysical one that exists independent of human observation and one that is purely socially mediated, i.e., constructed by humans. The physical functioning of a car, its wear and tear, and its driving behaviour are part of the biophysical causation, while its ownership status, its role as status symbol, and its financial value are part of the social sphere of causation. All material objects and processes within society have this double role: they have a biophysical basis and are subject to social causation at the same time. Society can therefore be described as a 'hybrid' of both the biophysical and the social sphere of causation (Fischer-Kowalski and Weisz 1999).

The two-sphere model of reality offers a specific framework for clarifying the relation between the physical and the social world. To illustrate that framework consider the above-mentioned problem of universals, for example: In the two-sphere model of reality a clear distinction can be made: Natural phenomena, including symmetry and discreteness, are part of the biophysical sphere of causation, and the categories and properties of objects derived from the observed symmetry and discreteness are part of the social sphere of causation. The categories do not exist in the natural world, they are socially constructed. The biophysical reality features discrete states, similarity, and dissimilarity (different animals, for example, can reproduce together or not, defining species), which motivates humans to introduce categories. The biophysical reality shows

[3] Links to established philosophical concepts can be found here: https://en.wikipedia.org/wiki/Critical_rationalism
[4] https://en.wikipedia.org/wiki/Problem_of_universals

sets with discrete numbers of elements that can be counted using natural numbers, but the numbers themselves are human categories. Since the social sphere is part of reality the numbers and all other human categories and assertions are part of reality as well. The biophysical world can exist without a social sphere, in which case the categories, numbers, etc. would not exist.

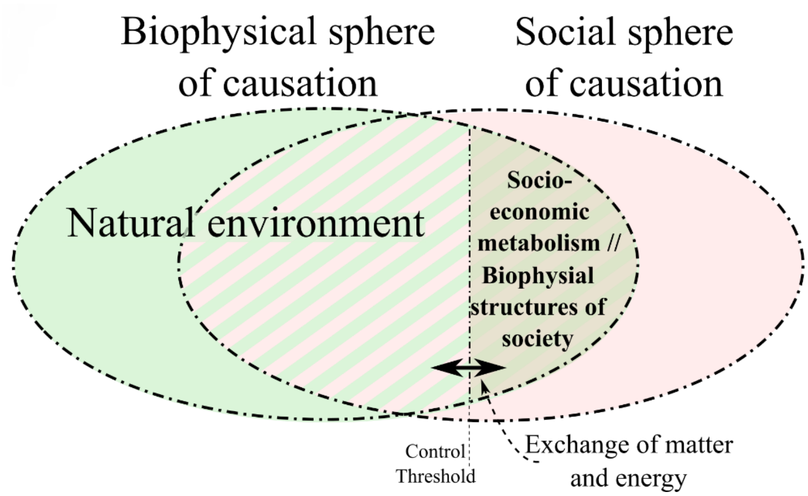

Figure B1R1.3: The two-sphere model of biophysical and social spheres of causation. Society is seen as hybrid of the two spheres (Fischer-Kowalski and Weisz 1999). Figure taken from Pauliuk and Hertwich (2015).

The hybrid approach to understanding reality provides a common framework for studying society from the angle of different scientific disciplines. In particular, it offers an option for combining natural and social sciences into a common framework to describe society. Societies form systems that can be described from the perspective of both: the biophysical and the social sphere of causation. Both spheres are interconnected:

- For social systems to function humans need to organize energy and material flows for their own bodies' reproduction and the reproduction of the built up capital stocks.
- The particular arrangement of stocks and flows in society's biophysical basis, in particular, their distribution across the members and institutions of society, depends on the social rules and frameworks created.
- The particular way in which the biophysical basis of society is operated determines the system's environmental impacts.
- Basic laws of natural science (thermodynamics, mass conservation) also apply to social and economic systems and are to be respected (Ayres and Kneese, 1969).

Social or socioeconomic metabolism: The biophysical objects and processes that are under direct human *control* are called the *biophysical basis* of society. This basis has two components: The first component is the structure, also called in-use stocks, which comprise the buildings, vehicles, industrial assets, and all other assets under direct human control. The second component are all the processes or events that are operated to built up and maintain the biophysical structure of society, and this part is called socioeconomic or social metabolism (Pauliuk and Hertwich 2015; Fischer-Kowalski 1998).

Socioeconomic metabolism, in particular, "*constitutes the self-reproduction and evolution of the biophysical structures of human society. It comprises those biophysical transformation processes, distribution processes, and flows, which are controlled by humans for their purposes. The biophysical structures of society ('in use stocks') and socioeconomic metabolism together form the biophysical basis of society.*" (Pauliuk and Hertwich 2015).

Socioeconomic metabolism can be considered a *paradigm*, meaning that it qualifies as "universally recognized scientific achievement[] that, for a time, provide[s] model problems and solutions for a community of practitioners" (Kuhn 1996). A paradigm prescribes i) what the research is about (object of research), ii) the type and structure of research questions asked, iii) how the research is conducted (research methods), and iv) how the results are to be interpreted. The following list provides the argument for considering socioeconomic metabolism (SEM) as paradigm (Pauliuk and Hertwich 2015):

" [most in-text citations were omitted, references to other parts of original paper were removed.]

• SEM describes an object of research. SEM comprises the processes and flows to build up and maintain the bio-physical structures of society. SEM research necessarily contains a description of these structures. [i]

• The notion of SEM suggests that the study of the biophysical basis of society follows both physical laws and social mechanisms/rationales. Physical laws such as the conservation of mass and energy motivate the tracing of mass and energy flows in society, while social rationales motivate the use of economic models as well as different forms of social, cultural, and economic inquiry. [i, ii, iii, iv]

• The notion of SEM recognizes the interconnection of bio-physical and social realities, which is manifested in multi-layer economic–environmental accounting, the development of integrated economic and physical frameworks to describe and analyze SEM, and the debate about the difference between these models (Majeau-Bettez et al. 2016; Weisz and Duchin 2006). [ii, iii, iv]

• The notion of SEM recognizes the complexity of society-nature interactions, which motivates the study of supply chains with life cycle assessment and input-output analysis, emergent phenomena like industrial symbiosis or complex recycling systems, or feedback mechanisms on different levels. [ii, iii, iv]

• The notion of SEM acknowledges that both biophysical and social reality extend beyond society's biophysical basis [i, ii, iv]

• The notion of SEM acknowledges the limitedness of the natural environment. [ii, iv]

• The notion of SEM acknowledges the importance of conservation laws, which includes mass and energy conservation for physical, and conservation of monetary quantities for economic models. [iii]

• The notion of SEM acknowledges significant human control of his ecological niche, and holds mankind responsible for the events within society and their consequences for the natural environment. This responsibility is well reflected by the introduction of the control threshold, by the current political debate, and by the different methods that study humanity's impact on the environment. [ii, iv]

• The notion of SEM implies the existence of a boundary between human society and nature. The actual specification of that boundary is left to the specific accounting frameworks and system definitions. [i, ii, iv]

• The notion of SEM gives meaning to research questions and approaches that would not make sense under other paradigms. One example is the transfer the concept of allometry (West 1997) from biological organisms to human society (Dalgaard and Strulik 2011). Another example is the application of complex network theory to regional metabolism (Yao et al. 2015) and to energy distribution (Jarvis et al. 2015). [ii]

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Summary: Reality has two spheres: the biophysical sphere that exists independent of human observers and for which claims can be made that can be empirically verified or falsified by human observers, and the social sphere of causation that constitutes relations among humans, relations between humans and biophysical objects, and between humans and society's institutions.

Those biophysical objects and processes that are controlled by society form its biophysical basis. That basis consists of a structure, or in-use stocks, and a social metabolism to build up and maintain these stocks.

For social systems to function humans need to organize socioeconomic metabolism. The particular arrangement of stocks and flows in society's biophysical basis, in particular, their distribution across the members and institutions of society, depends on the social rules and frameworks created. The study of the biophysical basis of society follows both physical laws and social mechanisms/rationales. Physical laws such as the conservation of mass and energy guide the tracing of mass and energy flows in society, while social rationales motivate the use of economic models as well as different forms of social, cultural, and economic inquiry.

3) Thinking big and small

Locally controlled environments and the black box process model: The key to the success of creating products based on reductionism is the creation of locally controlled environments. Consider steel making, for example: Only within a certain temperature range and in the presence of a reduction agent will iron ore, which contains iron oxide, turn into metallic iron which can then be refined into steel. In a computer chip, electric conductors, semiconductors, and insulators are arranged in a special pattern to allow for electric charges to transport, store, and release information. In order to combine different process environments into larger units, such as factories or cities, engineers define interfaces between processes. For example, your computer comes with a power supply unit that is designed for a specific input voltage level. As soon as you have access to a power outlet that fits your device you can operate your machine. As soon as a steel mill can acquire supplies of iron ore, coke, and limestone with a specific grain size and strength, its blast furnaces are ready to go. The interface between a steel mill and a car manufacturer is defined in terms of coils of steel of different alloys and thicknesses, and when the car manufacturer specifies the desired mechanical properties of the steel as well as its thickness and width, he can place an offer on the world market for steel to find a matching supplier. Industrial society is broken down into myriads of industrial processes that create their local operation environments and that offer interfaces, usually in terms of specific products, to their suppliers and users.

The definition of interfaces between processes has an important consequence. It allows engineers to simplify the description of production processes by only referring to their inputs and outputs (Fig. B1R1.4). This *black box* representation of processes ignores the great amount of detailed knowledge required to design and operate processes. Instead, it takes products like iron ore, coke, and crude steel, to implicitly define what happens in the different processes. The black-box-perspective on processes is a crucial aspects of industrial systems and models thereof.

Traditional engineering deals with the development and optimization of locally controlled environments, to deliver black box processes with well-defined safe operation areas and interfaces to services delivered or consumed, and commodities delivered or consumed. This approach to managing socioeconomic metabolism is a crucial component of general progress; it comprises technology development and deployment as well as the principle of reductionism: Sustainable development is broken down into a hierarchy of goals, strategies, and solutions for implementing those strategies, which are then further broken down until they fit the scope of the reductionist engineering approach.

This ‘thinking small’ pathway to a sustainable future captures a great amount of detail, down to individual alloys and specific business models for operating a specific process. Inevitably, this pathway typically ignores the question of scale (to what extent can local solutions be scaled up?) and the question how different technologies and technology pathways can work together.

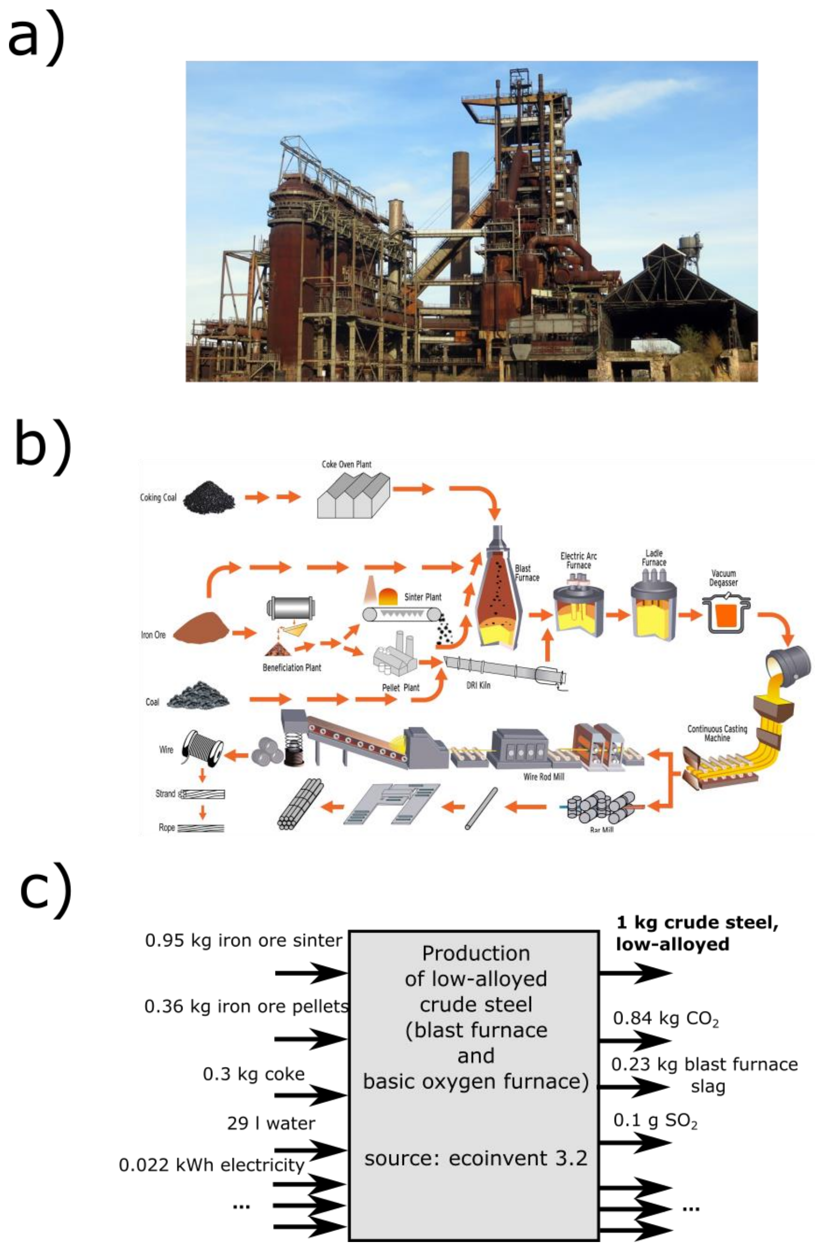

Figure B1R1.4: Three possible descriptions of a steel mill. a) A photo of a steel mill showing a blast furnace and heat exchangers. b) Schematic of the steel making process chain. c) A process inventory for steel making from a life cycle database. Each process representation serves a specific purpose, none of them is complete, but all contribute to a comprehensive depiction of the steelmaking process. [http://www.ushamartin.com/wp-content/uploads/2014/04/Process-flowsheet.jpg]

The 'thinking small' approach needs a complement: the 'thinking big' approach to transforming socioeconomic metabolism, a perspective that tries to match available resources with the expected level of technology scale-up, a perspective from with the overall economic and environmental benefit of competing pathways can be compared, and where system-wide affects such as price formation can be studied. Following the example of steel, the 'thinking-big' counterpart of Figure B1R1.4 would be a visualization of the steel cycle (Fig. 1R1.5), where total stock levels, resources and their depletion, and emissions to environment can be quantified. But this figure is still incomplete: It lacks the economic and employment dimension, and says nothing about the actual services provided by the in-use stocks of steel.

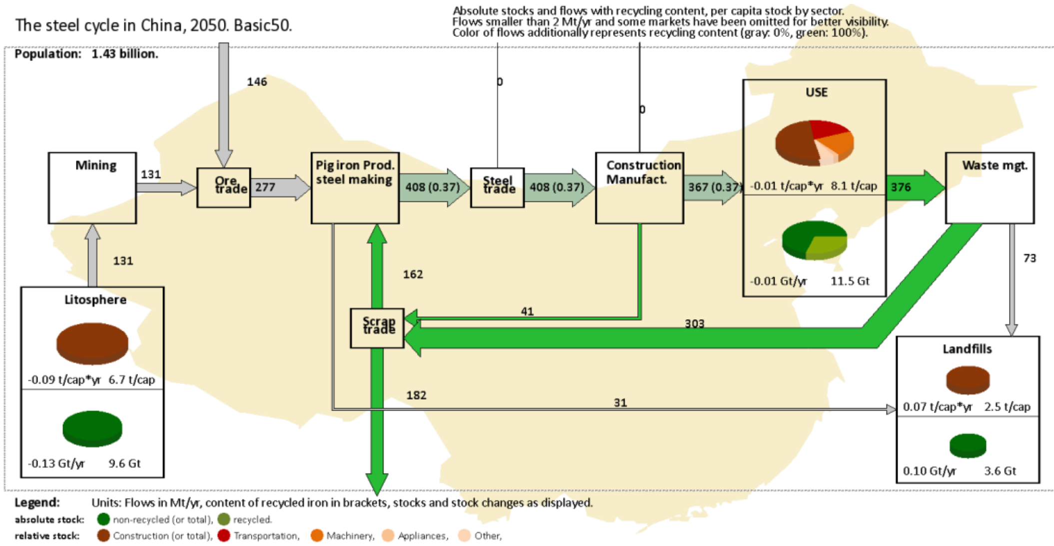

Figure B1R1.5: **The steel cycle in China, scenario for 2050.**

From comparing the two figures above it becomes clear that both perspectives on socioeconomic metabolism are essential.

- Only at the process level one can understand the potential for efficiency gains, for a switch of feedstock, and for productivity gains.
- Only at the system level one can understand the relative contribution of a technology to environmental impacts, resource depletion, and sustainable development goals.

Consequently, interdisciplinary science of sustainable development needs to embrace both perspectives, and below we will see how both perspective come together in the field of industrial ecology.

Summary: When in- and outflows of industrial processes can be described in detail, the process itself can be modeled as a black box whose functioning is defined implicitly by listing the inflows and outflows. This micro-perspective on the industrial system needs to be complemented by a macro-perspective, where system-wide affects such as price formation, resources and their depletion, and emissions to environment can be studied.

4) What is and to which end does one study industrial ecology?

[This section is an amended translation from a blog post originally written in German]

The importance of quantitative analysis from a systems perspective: Should milk be sold in nonreturnable beverage cartons or returnable glass bottles? Are electric vehicles better for the environment? What about biofuels? It is easy to find *plausible qualitative answers* to these questions: Returnable bottles replace beverage cartons and thus save material. On the other hand, returnable bottles need more transport and cleaning, while beverage cartons are lighter and thus save transport energy. The cartons are harder to recycle than glass bottles, and a share of them goes to incineration. The effectiveness of returnable bottles also depends on consumer behaviour. For the other examples electric vehicles and biofuels, analogue examples can be found.

Using qualitative arguments only won't take us very far. To identify the actual environmental and resource impacts of a specific product, two things are required: **First, a quantitative analysis of actual material and energy flows associated with the product, and second, a consistent systems perspective.** Both the quantitative analysis and the systems perspective facilitate the robust scientific analysis of energy supply, transport, manufacturing, and use of products. The quantitative systems analysis of human-environment-technology interactions is often labelled as 'industrial ecology'.

At first glance, industrial ecology appears as contradiction. Aren't industry and nature mutually exclusive? A second glance is needed: 'Industrial' refers to the subject of analysis: the man-made system of resource depletion, material production, manufacturing industries, consumption, consumers, waste management, and recycling. ‚Ecology' does not refer to rests of nature within industrial plants, but to a certain perspective on industrial systems. The perspective is that of a complex man-made ecosystem of material and energy flows, industrial transformation processes, and markets for trading goods. Industrial ecology refers to the quantitative analysis of industrial material and energy flows from a systems perspective. Industrial ecology is a systems science that offers a framework for knowledge integration from different scientific methods and research fields.

The systems perspective includes the analysis of interactions between individual processes (waste heat from power generation is used for drying paper), products (CO_2-emissions from electric transportation are mainly determined by the electricity mix (Hawkins et al. 2013)), materials (substitution of steel for aluminium), or resources (co-production of copper and precious metals). There are a large number of similar couplings in the system of the anthroposphere, which is the part of the world controlled by humans. Only from a systems perspective one can assess whether locally suitable solutions, often labelled as sustainable products, are effective at large scales or suitable for being scaled up. Biofuel usage, while beneficial in some settings, may lead to the destruction of primary forest if deployed at the large scale. Installation of large capacities of intermittent sun- or wind-based electricity sources may lead to grid instability. A technology that requires certain metals to function may lead to dependencies on countries which can supply the raw materials needed.

The systems perspective also allows for studying feedbacks in the system, including an increase of emissions from aluminium production as a consequence of using this material in light-weight vehicles. Another example is the increase of energy consumption in the mining industries, as a consequence of increased copper demand due to the electrification of the energy system.

System linkages that form the core of industrial ecology research: In the 30 years since the inception of ‚industrial ecology' (Jelinski et al. 1992), researchers who gathered under that label[5] identified a number of central couplings in the industrial system and developed and refined methods to study those linkages (Pauliuk et al. 2017):

+ **Global supply chains and the life cycle perspective:** A pump storage plant clearly has much higher local environmental impacts than the corresponding number of household-based battery installations. If the supply chains of the batteries are included in the analysis, the picture is different: The environmental impacts of mining and smelting of battery materials and of manufacturing energy supply are considerable and can change the ranking order of any environmental assessment when compared to the situation where only local impacts are considered. One obtains a similar picture when quantifying the climate change impacts of electric vehicles under different electricity mixes (Hawkins et al. 2013). Without consideration of global supply chains and the respective environmental impacts of the processes involved the trade-offs between emissions in production and in the use phase cannot be determined. Focussing on the use phase only increases the risk of burden shifting, which means that polluting and inefficient production are outsourced to countries with lax or absent emissions regulations and where civil or political resistance to deploying environmentally harmful production facilities is muted. When all relevant processes beyond the use phase, including production and end-of-life management, are considered in an environmental assessments one can say that the assessment is carried out from a *life cycle perspective*.

Life cycle assessment (LCA) is the established method for quantifying resource demand and environmental impacts of products and services from the life cycle perspective. LCA covers the production, use, waste management, and recycling stages of products and services. https://en.wikipedia.org/wiki/Life-cycle_assessment

Input-output analysis (IO), which is an established tool in economics, has become the default method to determine country-specific environmental footprints for land, water, materials, or

[5] https://is4ie.org/

greenhouse gases. Multiregional IO builds upon databases that cover the entire world economy, including bilateral trade. https://en.wikipedia.org/wiki/Input%E2%80%93output_model

+ **The service-stock-flow linkage:** Many of the services we consume daily, including residing, transport, or communication, are delivered by capital stocks such as houses, vehicles, or communication infrastructure. To build, expand, and maintain these stocks material and energy flows are required, e.g., in the form of steel, concrete, copper, or plastics production. Steel production alone accounts for almost 10% of all anthropogenic CO_2 emissions, and those emissions are indirectly linked to the services provided by the steel-containing products like bridges, vehicles, or high-rise buildings. To build up significant in-use stock levels large amounts of material have to be produced, which will then provide service to people throughout their lifetime. In China, for example, produces several gigatonnes of steel and cement every year, which are needed to build up the country's infrastructure and expansion of urban areas. Once per capita stocks of buildings and infrastructure are mature and are close to levelling off, the industrialisation process of a country reaches completion and material input to stocks may decline (Müller et al. 2011; Pauliuk et al. 2012).

Large-scale recycling can only take place once sufficiently high in-use stocks have been built up and are mature enough so that a sufficiently high number of products and buildings need replacement. To understand the development of stock build-up, use, and recycling it is important to keep track of the times when production, use, and recycling occur. The link between new technologies an increased material demand, e.g., the demand for copper in electric transportation, needs to be taken into account. A comprehensive assessment of sustainable development strategies must take into account the impact of those strategies on material production and future recycling. The scientific method to study the service-stock-flow linkage is called dynamic stock modelling (https://en.wikipedia.org/wiki/Dynamic_stock_modelling).

+ **Material cycles** are a core concept to study mining, production, manufacturing, use, waste management, and recycling of materials from a systems perspective. From a material cycle perspective it is clear that recycling is possible only when sufficiently high in-use stocks ('urban mines') are present in the system. It also helps to understand that material cycles can only be closed once in-use stocks have stopped growing, as in the case of stock expansion, primary production or import of secondary resources will always be necessary. For a number of chemical elements, including iron, gold, and copper, the man-made flows are larger than the natural turnover (Klee and Graedel 2004).

Material flow analysis is the tool of choice for modelling and assessing material and energy flows between industries and end-use sectors like households, public institutions, and export (https://en.wikipedia.org/wiki/Material_flow_analysis).

+ **Co-production** occurs when an industrial plant produces several outputs, e.g., electricity and heat. Smart use of co-products helps to save resources and generate additional revenue (https://en.wikipedia.org/wiki/By-product).

+ **Industrial Symbiosis**: Co-products that are difficult to sell often still contain enough energy or valuable materials that their treatment in specialized facilities is economic or desirable from a resource savings point of view. Paper mills, for example, are often located in the vicinity of coal-fired power stations to make use of waste heat for drying paper. Fly ash from incinerators and blast furnace slag can partly or entirely substitute cement. If a larger number of industrial plants is co-located the potential for local utilisation of co-products is often large, while, at the same time, the need for transport is eliminated. Such a local cluster of physically interconnected industries is called eco-industrial park, and the usage of co-products by other industries is called industrial symbiosis (https://en.wikipedia.org/wiki/Industrial_symbiosis).

+ **The connection between urban fabric and transport patterns:** Urban structures, such as the geographical location of living, shopping, working, and leisure activities, and the supply of transport infrastructure determine the transport patterns of residents to a large extent. Proximity and ease of access to those different urban functions determine both: the choice of the means of transport and the time dedicated to transportation. The study of material and energy flows in urban settings is termed 'urban metabolism' (https://en.wikipedia.org/wiki/Urban_metabolism).

Summary: To which end does one study industrial ecology?

The above-described couplings in the system of the anthroposphere strongly influence the actual environmental impact and the effectiveness of the different sustainable development strategies such as electric vehicles, new materials, or biomass products. Existing analysis and assessment tools need constant updating to keep up with the ever-better understanding of these and other relevant system couplings. This tool refinement is necessary to make sure that also in the future, policy makers, industrial stakeholders, and society as a whole can benefit from robust scientific assessments of sustainable development strategies. Industrial ecology researchers are among the leaders of tool and method refinement for sustainability. Industrial ecology is closely linked to related disciplines, including economics, integrated assessment models, sustainability geography, and environmental sciences. Close cooperation between different sustainability sciences allows for integration of scientific progress from different fields into the sustainability assessment methods of industrial ecology, which in turn can be applied both within and outside the field to do justice to the claim to studying sustainability from a systems perspective.

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