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International Trade from a Societal Metabolism Perspective

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Abstract

This presentation discusses the role of international trade in the study of material and energy cycles on country, regional, and global scales. With the growing trade flows, the societal metabolisms of different regions have become increasingly interconnected. Understanding trade flows is therefore essential for understanding and shaping the metabolism of our economies to increase resource efficiency and reduce environmental impacts. The basic method for the study of the societal metabolism, Material Flow Analysis (MFA), provides a language that allows scientists to describe physical stocks and flows in natural as well as anthropogenic systems, which is a prerequisite to integrate ecology and economy. The use of MFA is illustrated with an example of the historic iron cycle in the United States. The study shows that international trade of iron units has increased significantly over the last couple of decades, with a net import of iron embodied in goods upstream of the use phase and a net export of downstream products. The present trade balance of iron units shows a net import that is theoretically large enough to establish an iron, steel and scrap industry that is entirely based on recycling. However, there are large uncertainties with respect to the end-of-life fate of products, such as exports of used and discarded products and accumulation in obsolete stocks or landfills. More reliable trade data for used and discarded products could significantly improve our understanding of the iron metabolism and the policy options for resource and environmental management.

1. Societal metabolism and Material Flow Analysis (MFA)

The basic principle of any study of the metabolism of a system is the law of the conservation of mass[1], which is generally attributed to Antoine Lavoisier (1743-1794), who provided experimental evidence that the mass of a system of substances is constant, regardless of the processes acting inside the system, or, in other words, that matter changes form, but cannot be created or destroyed[2]. In 1855, physician, physiologist, and philosopher Jacob Moleschott (1822-1893) defined metabolism as "exchange of energy and substances between organisms and the environment"[1].

The concept of metabolism has been applied to the study of cells and organisms (biology), but also inspired ecologists to study energy conversions and nutrient cycling in ecosystems. What is common to these notions of metabolism is the idea of metabolism being a complex self-organizing process of autopoietic systems, dependent on the characteristics of this system, vis-à-vis highly variable environments[2].

But also economists used the concepts of metabolism to describe the supply of consumer goods. Richard Cantillon (1680-1734) and François Quesnay (1694-1774) used the mass balance principle to develop primitive models of their economies (which were closed systems without trade), and thereby laying the groundwork for Wassily Leontief's Input-Output Analysis [3, 4]. Input-output analysis is today an established tool of national economic accounting to study transactions (monetary and/or physical flows) among different sectors. However, it usually ignores (i) stocks of natural resources as well as products in use, (ii) the end-of-life phase of products (e.g., waste management), and (iii) interactions with the environment, such as emissions and waste production. Although there are recent attempts to enlarge the system boundaries of national accountings to include waste management and emissions [5, 6], there are currently no input-output models that describe the stocks and flows of an entire national economy with its links to the environmental compartments of air, soil and water.

Karl Marx and Friedrich Engels [7] had in this sense a broader conception of economy, and explicitly applied the term 'metabolism' to society. They recognized that the metabolism between man and nature is effected by human labor: labor (mediated by technology) transforms nature's material … to the wants of man [2].

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[1] The law of conservation of mass fails for nuclear processes, where the equivalence of matter and energy, and hence conservation of energy, applies. The law also fails for relativistic situations, where it is similarly necessary to consider the equivalence of matter and energy. However, it is to a very high accuracy applicable in chemical reactions, since in every case the mass-energy of the reactants is huge in comparison to the energy absorbed or released when they react.

[2] The law was first clearly and unambiguously formulated by Antoine Lavoisier, who is often referred to as the father of modern chemistry. However, other scientists (e.g., Mikhail Lomonosov (1748)) had previously expressed similar ideas.

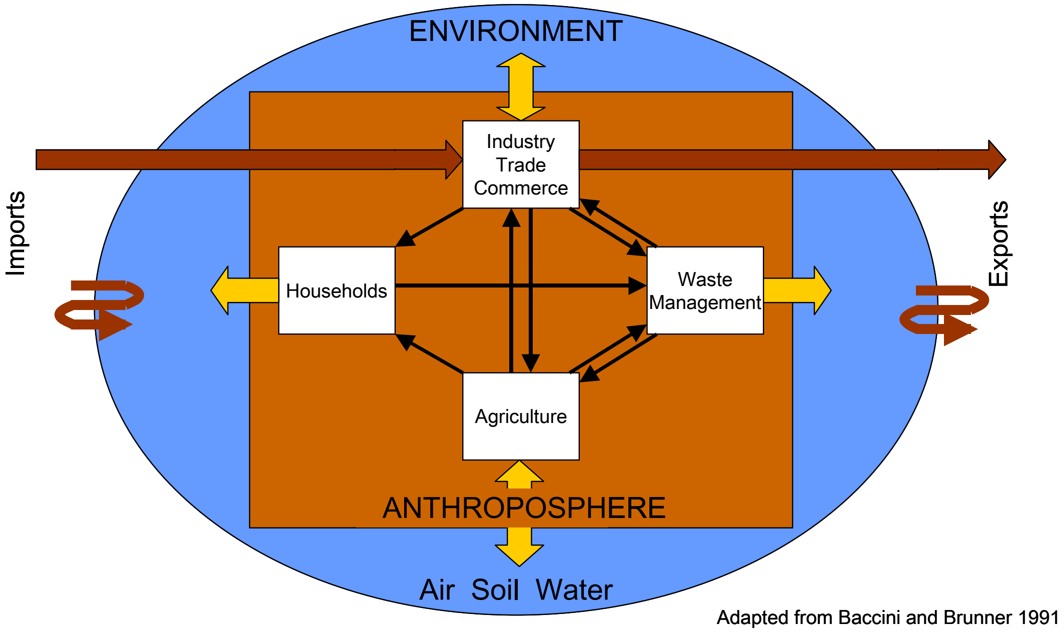

Figure 1: Schematic representation of a regional metabolism according to Baccini and Brunner 1991 [8]. Regions are considered to be open systems: they exchange materials and energy with other regions in the form of trade flows (straight arrows) as well as geogenic flows (curved arrows).

However, it was only in the second half of the 20th century that scientific methods were developed to describe the way human activities effect natural and anthropogenic material cycles. The method that evolved with these studies is called Material Flow Analysis (MFA) or Substance Flow Analysis (SFA)[3]. The first MFA studies in the field of resource conservation and environmental management appeared in the 1970s. The two original areas of application were the metabolism of cities [9, 10] and the analysis of pollutant pathways in regions such as watersheds or urban areas [11-14]. In the following decades, material flow analysis (MFA) became a widespread tool in many fields, including process control, waste and wastewater treatment, agricultural nutrient management, water-quality management, resource conservation and recovery, product design, lifecycle assessment (LCA) and others [15].

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[3] While SFA specifically refers to the study of single substances (e.g., phosphorus, cadmium), the term MFA is used more broadly to describe cycles of single substances as well as bulk flows, such as gravel or timber, which may be constituted of several substances.

2. The Stocks and Flows (STAF) project

2.1 Goals and big questions

The characterization of cycles of the engineering metals is the core activity of the Stocks and Flows (STAF) project, headquartered at the Yale Center for Industrial Ecology [16]. Its overarching goal is arriving at the answers to several “Big Questions”:

- What is the status of the metals mined in the 20th century? Are they still in use? Is a significant amount in storage? Dissipated?
- What are the spatial distributions of the mobilized metals, in–use or otherwise?
- What are scenarios of use for the next several decades?
- What are the implications of alternative scenarios for supply, development, and the environment?

2.2 The resource cycle

A contemporary cycle for a resource used by our technological society can be constructed in several stages, and pictured in a “stocks and flows” concept. In the traditional scenario of resource utilization, the virgin material was extracted and processed, products were manufactured, and those products were utilized by individuals and/or corporations. When obsolete, the products were recycled or discarded, generally in landfills. Two other dispositions are worth noting as well. Mines, mills, and smelters customarily discarded low-grade ores and processing residues, and some products (processing solutions, metal-based paints, etc.) were designed for uses that resulted in the resources being eventually dissipated into soil or water. Only recently, however, have the products in use and the wastes already discarded been viewed as reservoirs of resources potentially available for future capture and use. Were society to decide to “mine” these reservoirs of materials, the flows involved would be those that efficiently return materials from discard and in-use reservoirs back into the active flows of the technological society.

Temporal factors enter strongly into the determination of the resource contents of different reservoirs. Materials move rapidly through a manufacturing facility, for example, more slowly through the user reservoir, and very slowly through a landfill. The contents of these reservoirs thus represent, to varying degrees, a history of resource flows that are functions of turnover times. As a result, some reservoirs are much easier to assess than others. Further, the location and form of aluminum in both stocks in use and waste deposits is directly tied to when and how the aluminum-containing products were manufactured and how they are being used. This in turn shapes any strategy to mine these reservoirs.

The metal cycles investigated in the frame of the STAF project follow a multi-level approach [17] (see Figure 2). The cycles are first calculated for typically 61 countries, which constitute together at least 80% of the metals produced and consumed. The country cycles are then aggregated to 9 regional cycles, and this information is aggregated into comprehensive global cycles for the metals. Following the mass balance principle, the net trade flows is zero for all commodities on the global level.

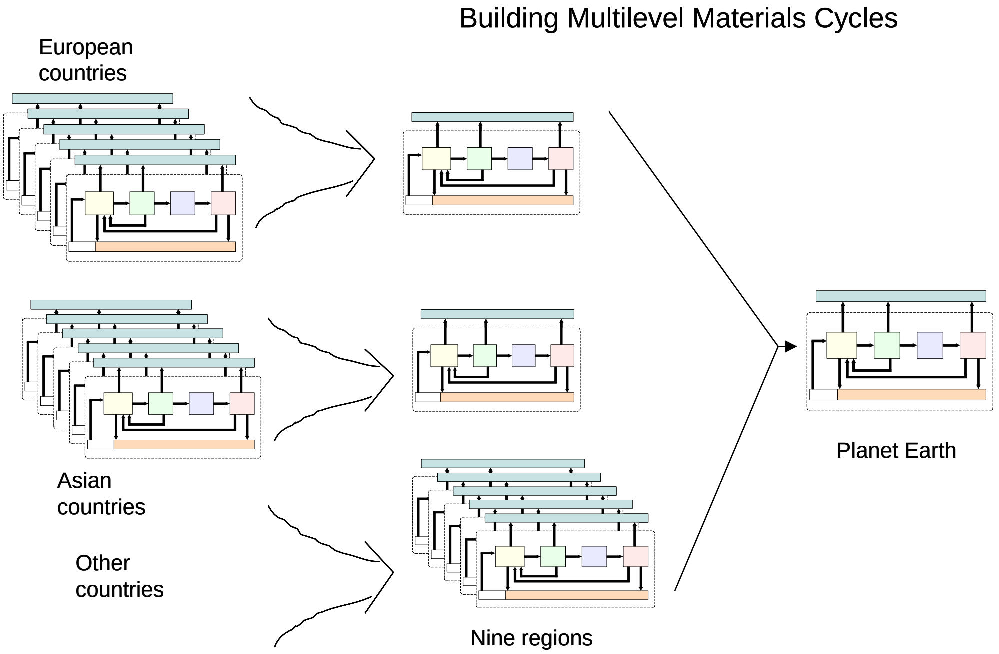

Figure 2: Concept of the multi-level cycle approach of the STAF project

2.3 Status of the STAF Project

We have completed contemporary cycles for copper, zinc, and silver in 61 countries, 9 regions, and the planet as a whole, treating in detail four stages of resource life: *extraction and processing*, *fabrication and manufacturing*, *use*, and *end-of-life*. Multi-level analyses for iron, nickel, and chromium are currently under development and will be completed this year.

3. Case study "historic iron cycle USA"

3.1 Problem and motivation

I will use the historic U.S. iron cycle as an example to illustrate the use of MFA for answering resource management questions and to discuss the role of international trade. This study is in the process of being published [18].

Iron is by far the most widely utilized metal, comprising more than 90% of the metal tonnage produced worldwide [19], and thereby forming the framework around which we have built our modern societies. Although iron is not a scarce metal, there are good ecological and economic reasons to use it more effectively. U.S. iron ore grades have dropped from 50-60% to about 25% since World War II, which causes significant increases in the use of energy and water as well as tailings production in the beneficiation process of the mined ores [19, 20]. The iron and steel industry consumes about 9% of the manufacturing energy use [21]. Steel recycling eliminates the most energy-consuming step of steel making, the blast furnace, thus reducing primary energy consumption by about 75% [22]. This can significantly reduce production costs, considering that energy costs account for about 15-20% of the production costs. Furthermore, scrap that is not recycled needs to be deposited in landfills.

These reasons illustrate that it lies in the interest of the iron and steel industry to use iron resources efficiently. While internal recycling of home scrap can be administered by accounting of company-internal flows, an optimization of the overall system of iron use in the U.S. requires a much broader approach that includes all stages of the lifecycle. MFA can provide the framework for such a national accounting.

3.2 Methods and data

Figure 3 shows the system of the U.S. iron cycle. The large blue boxes symbolize transformation processes, and the small yellow boxes signify market processes. Transformation processes may contain significant stocks, which are market with white boxes inside the blue boxes (e.g., lithosphere, use, or landfills). Smaller stocks, such as manufacturer inventories, are neglected in this study. The arrows designate flows between two processes. For the sake of simplicity, import and export flows are illustrated using one arrow with two heads: one on the (domestic) market side, and one on the system boundary (which would be the corresponding market in other regions).

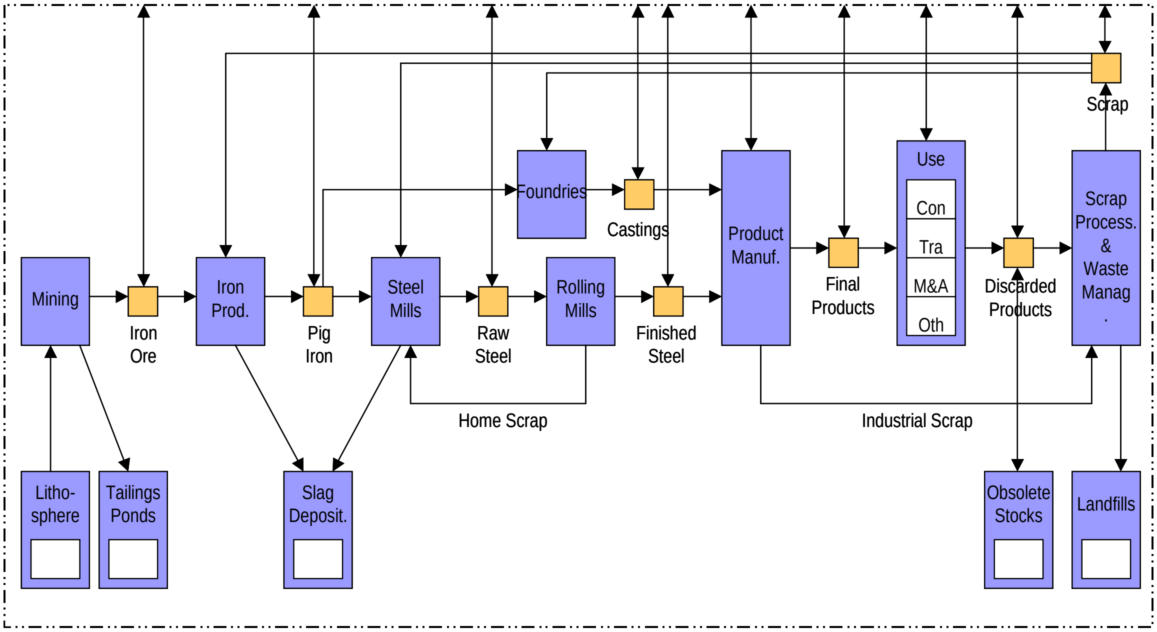

Figure 3: System of the U.S. iron cycle. The large boxes symbolize transformation processes, the small boxes signify market processes.

Economic activities move iron from the lithosphere through various transformation processes (mining, iron production, steel and rolling mills, foundries, and product manufacturing) and market processes (iron ore, pig iron, raw steel, finished steel, castings, final products) to the end user, which uses iron in the form of constructions (Con), transportation vehicles (Tra), machinery and appliances (M&A), and Others (Oth). After the useful service life of the products, discarded products are either accumulated in obsolete stocks (e.g., abandoned buildings, obsolete infrastructures, cars and appliances in junk yards), or they enter a process of scrap processing and waste management, where the iron is either recycled as recovered scrap or landfilled. Scrap is used as a secondary raw material in iron production, in steel mills, and in foundries. Usually not recovered "losses" of iron units can occur in tailings, in iron and steel slag[4], in obsolete stocks, and in landfills. Iron "losses" that are recovered take place in the form of home scrap and industrial scrap.

The iron stocks and flows in this system were quantified using a wide variety of methods and data sources. The most relevant approaches were the following:

1. In an ideal situation, the flows of a particular good as well as its average iron concentration is reported, for example in national statistics of the U.S. Geological Survey. The iron flow can then be calculated as the product of these two values. This approach works relatively well on the left side of the system. The more one moves to the final products, the more extensive and complex the data gathering, and the less data is generally available.
2. For each process, the mass balance can be formulated (net stock accumulation = sum of all inputs minus sum of all outputs), and if only one flow is unknown, it can be computed with this formula.
3. Data about the split of finished steel shipments to different manufacturers are available from the American Iron and Steel Association (AISI). However, the end use of these flows is often not clear. For example, more than 30% of the steel shipments are going to steel service centers, but there are no data about the shipments of steel service centers to other sectors. For these cases, the split of the produced and imported steel to different manufacturers was estimated based on expert interviews.
4. Imports and exports of parts and final products were calculated using Comtrade statistics (SITC-1 for historic data, HS-96 for data in 2000). In case that no mass flows were reported, they needed to be estimated based on price estimates that were obtained from other countries[5]. The total number of product categories that contain iron was about 1000 for the HS-96 system. The iron concentration was estimated only for the largest overall fractions, which constitute together about 70-80% of the overall mass, which reduced the number of product categories to less than 100. This approach assumes that the iron concentration of the remaining

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[4] Iron and steel slag may be recovered for applications in cement production or road fillings etc, but since these uses are do not make use of the metallurgical iron content, they are not tracked further here.

[5] This is probably the largest potential source of errors in the determination of trade flows, because prices can vary significantly between different countries. This is particularly relevant for product categories with large fractions of used products trade.

product categories, which constitute together about 20-30%, have in average the same iron concentration as the product categories that were included. Because the iron concentration of the included product categories was high (typically between 60 and 80%), the error resulting from this simplification is moderate.

5. Trade in used products, which is not reported separately in the harmonized system, was estimated using 10-digit level data published in USA Trade Online. Since only a few percent of these 10-digit level product categories distinguish between new and used products, the product categories that do make this distinction were assumed to be representative for all others within the categories of Transport Vehicles, Machinery and Appliances, and Others. This assumption is standing on weak footing, but was used due to a lack of alternatives. The error is probably larger for exports of used products, because they are significantly larger than the imports.
6. No data are available for iron flows in discarded products. These numbers were calculated using a model simulation that calculated discards based on historic inputs into use and assumed lifetime distributions of the different product categories.
7. In-use stocks were computed based on historic inputs (apparent consumption of new products) and outputs (generation of discarded products).
8. Trade flows in discarded products are not reported at all with exception of “ships for scrapping”, which are suspiciously low. The net trade flow was therefore calculated using the mass balance of the processes “scrap market” and “Scrap Processing and Waste Management”.

3.3 Results

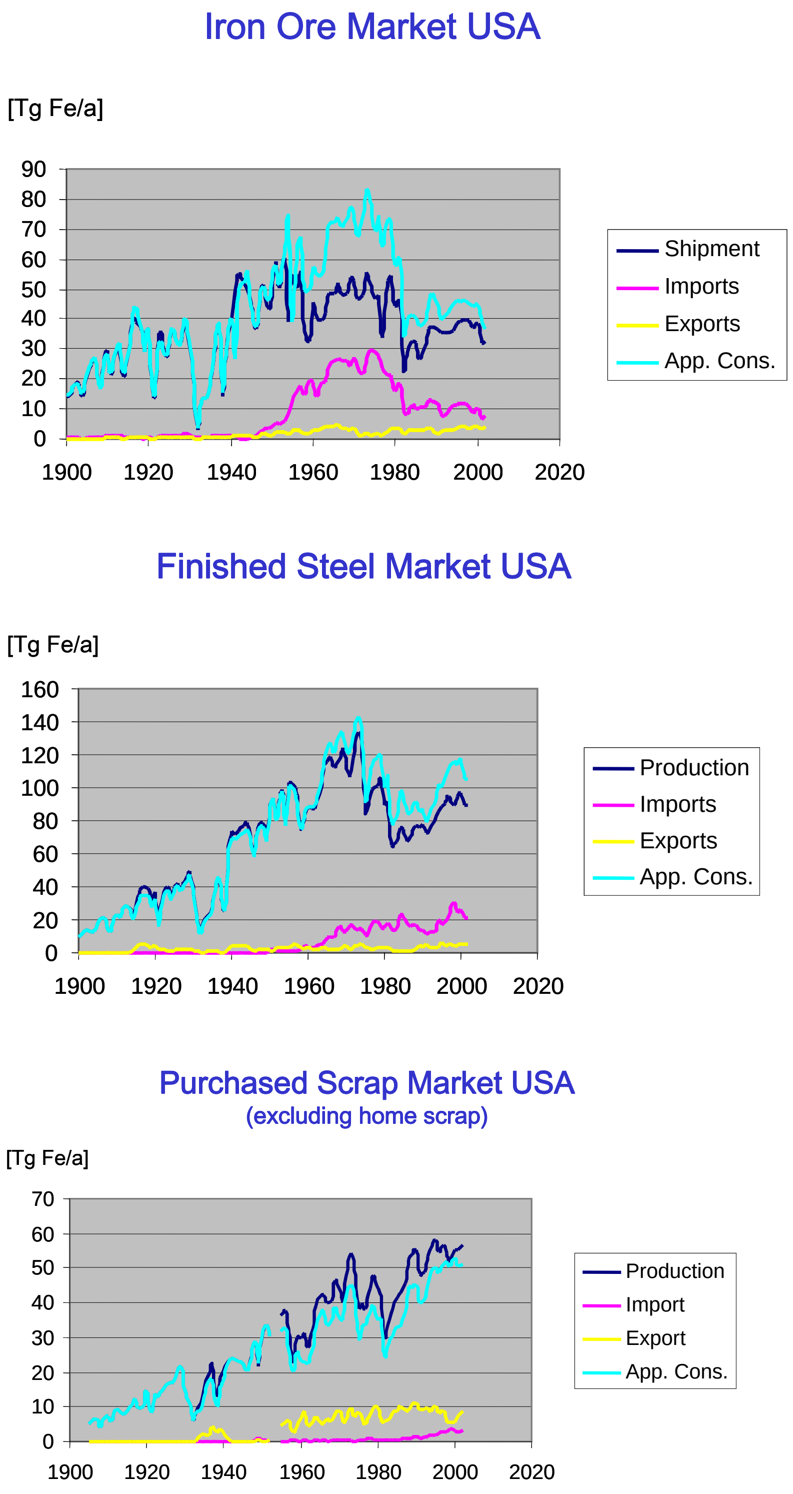
The historic iron flows are shown in Figure 4 exemplarily for iron ore, finished steel, and scrap. The graphs show the annual flows into these markets (production and import) and out of these markets (export and apparent consumption).

Apparent consumption of iron ore peaked in the 1970s. However, the large imports between 1950 and 1980 lead to a peak in production and shipment already in the early 1950s, when apparent consumption was still increasing. Apparent consumption of iron ore is currently about half of the level of the late 1970s.

The production of finished steel shows a peak in production and apparent consumption in the late 1970s, then a sharp decline and a recovery in the 1990s. The increasing imports of finished steel after the 1960s additionally impaired the decline in finished steel production, but they did not make up the loss in production.

While the general trend of scrap consumption was continuously increasing in the last century, scrap trade is comparatively small and remained on a more or less constant level since 1960.

In general, trade flows of iron embodied in products have increased significantly since the 1960s, while the imports were growing faster than exports for all commodities prior to use, and exports exceed imports for used products, discarded products, and scrap.



Iron Ore Market USA

Finished Steel Market USA

Purchased Scrap Market USA
(excluding home scrap)

Figure 4: Historic iron flows in iron ore, finished steel, and purchased scrap in the U.S.

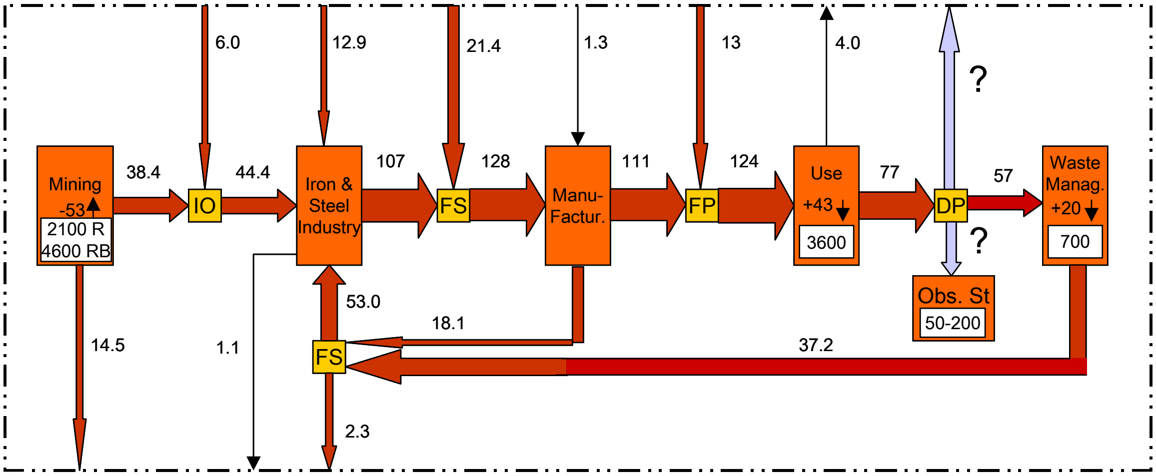


Figure 5: Simplified iron cycle of the U.S. in 2000 (flows in [Tg Fe/a], stocks in [Tg Fe]). Trade flows are shown as net flows. Legend: IO: Iron ore market, FS: finished steel market, FP: final products market, DP: discarded products market, FS: ferrous scrap market.

Figure 5 shows the entire U.S. iron cycle in an aggregated from for the year 2000. It illustrates several important aspects:

The iron incorporated in products in use (3600 Tg Fe) is larger than the domestic reserves of iron ore (2100 Tg Fe), but smaller than the reserve base (4600 Tg Fe). The landfills contain about 5 times less iron than the in-use products (700 Tg Fe). The amount of iron in obsolete stocks is comparatively low with 50-200 Tg Fe. In-use stocks are therefore the most attractive mines of secondary iron for the future.

The U.S. is a net importer for all iron-containing commodities between the mine and the user (iron ore, pig iron, raw steel, finished steel, parts, final products), and a net exporter for all iron containing commodities after the end user (used products, discarded products, and scrap).

Scrap recovery from obsolete or discarded products has a large potential for improvement. Of 77 Tg Fe/a of discarded products, only 37.2 Tg Fe/a are recovered. According to the iron recovery rates determined by the Steel Recycling Institute (SRI), about 20 Tg Fe/a are lost to the landfills, which means that about 57 Tg Fe/a arrive in waste management, leaving a gap of 20 Tg Fe/a. Since the total amount of the obsolete stock is relatively small (50-200 Tg Fe/a), it appears unlikely that the entire amount is accumulated in obsolete stocks. More likely seems to be the possibility of significant exports of iron containing products (used and discarded products) that fall under the category of low value shipments, which are not reported in trade statistics. Another explanation could be that the data of the SRI data underestimate the amount of iron deposited in landfills.

In 2000, the total net import of iron was 48.3 Tg Fe/a (possible export of discarded products not included), and was larger than domestic mining (38.4 Tg Fe/a). Since the net import is slightly larger than the growth of in-use stocks (43 Tg Fe/a), the net import is theoretically large enough to substitute

4 Discussion

With the growing trade flows, the regional metabolisms are becoming increasingly interconnected on a global scale. Understanding these trade flows is essential in order to understand the national and global material and energy flows and to develop policies for resource and environmental management.

MFAs can provide a structure that links trade flows with domestic flows and processes (transformation and market processes). The mass balance principle can be applied for transformation and market processes, which allows us to use trade flows to estimate unknown domestic flows or vice versa, or, to improve the accuracy of the entire system.

In the development process of MFAs for engineering metals, the collection of trade data is the most time-consuming step. At the same time, trade data tend to be very weak for post-primary-user products (used and discarded products), which are low in value, but large in mass.

MFA studies for most mineral resources show that most of the metals mined in the 20th century are still in use, whereby buildings and infrastructures form by far the largest fraction. In-use stocks are therefore the most important "mines" of the future, when the in-use stocks become obsolete. Model simulations show that the flow of demolition wastes is significantly increasing over the next couple of decades, and releasing significant amounts of steel, copper, zinc, and other metals. From a resource management perspective, this means that is becoming increasingly important to understand the paths of these secondary resources in order to design policies for resource and waste management.

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