PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The industrial ecology of metals: a reconnaissance

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The industrial ecology of metals: a reconnaissance

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Industrial ecology involves a systems view of material and energy flows in industry, where industry is thought of very broadly, and between industry and the environment. Closed loop material systems can lighten environmental burdens posed by society, and improve materials sustainability. Fundamental physical and chemical principles, and some experience, suggest that closing material circulation loops is likely to be both environmentally and economically beneficial.

The metal manufacturing system contains complex metal recycling networks involving a variety of actors. Most metal produced as manufacturing 'waste' is recycled, but some wastes containing high concentrations of metals go to landfills for reasons of scale, and the idiosyncrasies of regulation. The greatest loss of manufactured metal appears to be through the disposal of consumer products to landfills.

1. Introduction

From an industrial ecology point of view, industry (indeed, society) is viewed as a physical system in and through which materials (and energy) flow and are transformed into products, and from which wastes and excess materials may 'leak' (or be disposed) and cause environmental or health damage. The consumers buying, using and consuming industrial products are considered to be part of the industrial system for the purpose of product use, but were not included in the study being reported here. They will be referred to, but in this paper, are not a part of the industrial system that we studied.

2. Sustainability

The idea of sustainability is the provision of long term high quality human life in an excellent environment (World Commission on Environment and Development 1987, Brundtland Commission). In this paper we will discuss only the industrial manufacturing piece of the sustainability problem, with reference only to metals

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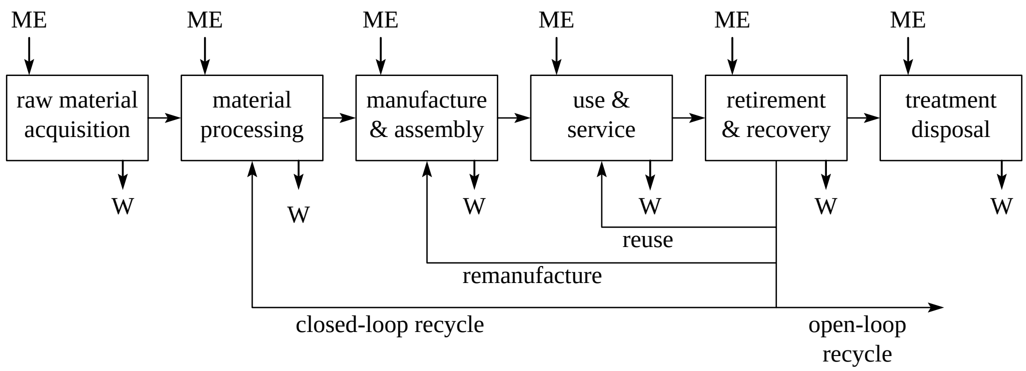

Figure 1. 'Comic strip' diagram of the traditional industrial flow system.

and metal products, i.e. we will not consider other kinds of materials or products, agriculture, etc.

There are two ways for sustainability to fail with materials: we could 'run out of them' (for non-renewables); or their 'leakage' into the environment could result in poisoning of people or failure of the environment as a system providing useful support for life (as sometimes has already occurred locally). 'Running out' of materials seems unlikely with regard to metals, particularly in light of the economic and innovative substitutability of uses and other materials. Poisoning has been the problem from time to time, and now looks like the problem that we need to worry about most.

3. The 'open' system

Traditionally, we have thought of the industrial system as largely an open flow system into which virgin materials come; there may be some reuse and recycling, but generally, products and wastes exit the system: when we're finished with material things we 'throw them out'—the 'throw it in the back yard' solution. The traditional system is illustrated as a 'comic strip' flow system in figure 1 (US Congress, Office of Technology Assessment 1992, based on personal communication with D. Navin Chandra, Carnegie Mellon University) and further simplified into a system cartoon in figure 2 (Frosch 1995).

4. Natural ecological systems and 'closed' systems

Natural ecological systems function as reuse/recycle networks. Excess and wastes, and the living actors themselves, are almost always food for some other actor. Materials, functioning as both material and energy supplies, move around and through the system. There is some waste which is not consumed and digested, or we would not find fossils and fossil fuels, but most of the activity is in use and reuse.

The comparison naturally leads to the questions: are more closed, materials recirculating, industrial systems possible? Would such systems be sensible from thermodynamic, economic, social and environmental points of view?

These questions lead us to reconsider the location of the boundary of the industrial system, and the nature of the responsibilities of the actors inside the boundary, as illustrated in figure 3 (Frosch 1995). In this figure we postulate the incorporation of the cycling of materials into the inside of the industrial system, so that 'disposal'

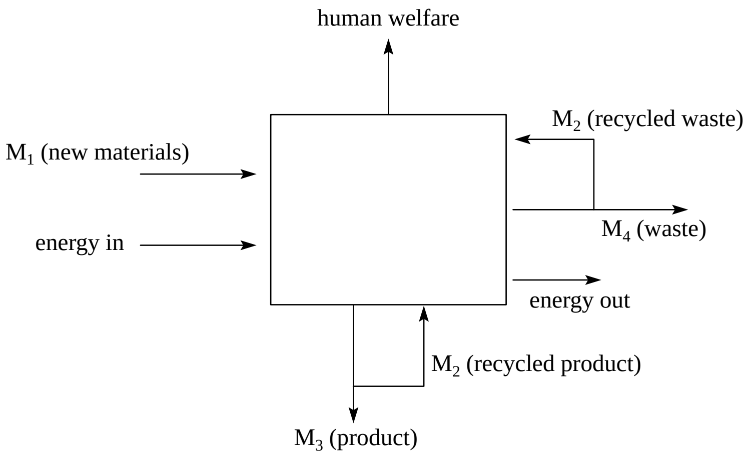

Figure 2. Simplified box diagram of the traditional industrial flow system.

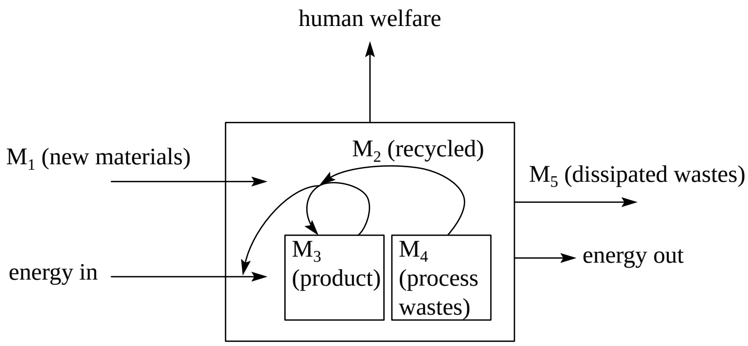

Figure 3. A simplified box diagram of a possible industrial flow system, with a revised boundary showing increased internalization of industrial responsibility for reuse and recycling.

outside the system becomes an exceptional event; the actors in the industrial system use and reuse almost all of their materials.

5. The physics of the system

What is it that the industrial system really does from a physical point of view? The answer is clear: it uses energy to purify, to assemble specific materials, generally purer than when found (or grown): e.g. metals (also, specific molecular structures such as polymers, paper, etc.). Figure 4, known to chemical engineers as the Sherwood plot (Allen & Behmanesh 1994), shows the direct connection between the dilution from which materials must be extracted (more or less equivalent to the separation effort, and hence energy, necessary to extract them) and their economic value. There are presumably materials which would cost a lot of energy to extract, but which we don't want, because we have no use for them, but the correlation for materials we do want is certainly striking over many orders of magnitude.

From this point of view, materials and products are embodied energy, used directly, or through use in capital goods and human labour. Knowledge and system structure are also essential to the process but the energy used in the separation of materials,

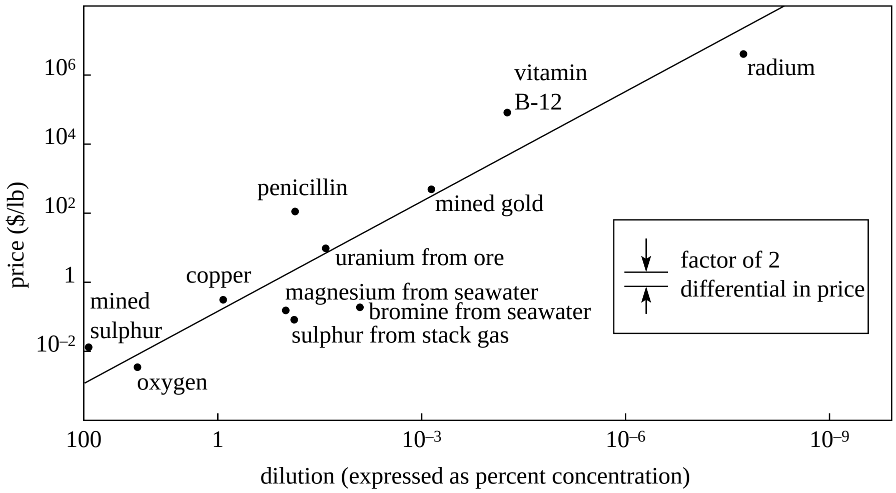

Figure 4. The Sherwood plot: selling prices of materials correlate with their degree of dilution in the matrix from which they are being separated (from Allen & Behmanesh 1994, p. 70).

materials creation by mixing and by chemistry (and sometimes biology) apparently is the dominating economic factor.

In the open system view of the industrial system, the attitude is that we 'consume' and 'throw away'. However, 'waste is waste' (of embodied energy, etc.), and we don't 'consume' metals (or any atoms; transmutation is a rare special case): metals don't vanish. We either have metals in use, or in storage, or we dissipate them by compounding them or mixing them in great dilution with other materials, so that they become 'unavailable' in that the energy cost of getting them back, 'undiluting' them, is too great.

There is thus a *prima facie* case for reuse, as may be seen from table 1 (Sullivan & Hu 1995) and table 2 (Yoshiki-Gravelsins *et al.* 1993).

Metals are the easy case to track since the metal atoms themselves persist, they don't vanish. Metals are not dismantleable molecules, unlike organics, which can be destroyed as molecules with their particular properties by being taken apart. Metals are also important because they can be a big problem due to their toxicity.

6. A reconnaissance

We were thus led to inquire: how does the use of metals really work with companies in the metal using businesses? What actually happens with metals and why? What is the efficiency of the use of metals by the industry? What metal 'leaks' to the environment?

We undertook a reconnaissance into the structure and efficiency of a portion of the industry which manufactures products from metals. We looked at a sample of companies which is mostly centred in the New England states. One of the data sets we have used is solely from companies in Massachusetts. The companies involved in our study mostly manufacture from copper and copper based alloys, and from both the precious and non-precious metal alloys used in jewellery.

We examined several questions as follows.

What does a map of the flow of metal in a piece of this industry look like. What

Table 1. *Material production energy*
(Source: Sullivan & Hu (1995), cited in Keoleian *et al.* (1995).)

	BTU/lb	
material	primary	secondary
steel	17 243	7830
copper and brass	43 000	19 370
zinc	22 813	6850
lead	17 700	3440

Table 2. *The secondary production of metals consumes significantly less energy compared to primary metals*
(Energy savings from recycling is particularly significant for aluminium and magnesium. The table shows this relationship (Yoshiki-Gravelsins & Toguri 1993).)

mineral	energy to recycle as % of virgin energy requirements
aluminium	5%
magnesium	2–5%
zinc	20–25%
copper and steel	30%
titanium	50%

kind of system structure is exhibited? In particular, is there an 'ecology like' structure?

Can we make any useful estimates of the 'efficiency' of the system as a user of metal: how much of the metal used by the firms ends up as 'waste' going to the environment?

What factors drive the decisions made in the individual firms that lead to the behaviour and system structure and efficiency that we find?

7. The data

We developed and used several kinds of data. Inquiring around, we obtained introductions, or introduced ourselves, to various firms and organizations connected with the metals business, mostly around New England. We asked to visit the firms, and to interview them. Having developed a structured interview outline, we then sent our interviewers to the firms and organizations. The results were written as interview reports, and form one body of our data.

The firms interviewed cannot be said to be a random sample, and they are only a small sample of the universe of firms in the industry or the region. Not all interviews were usable; some produced too little data. Some interviews were with organizations that did not directly manufacture or handle metal; they gave background information

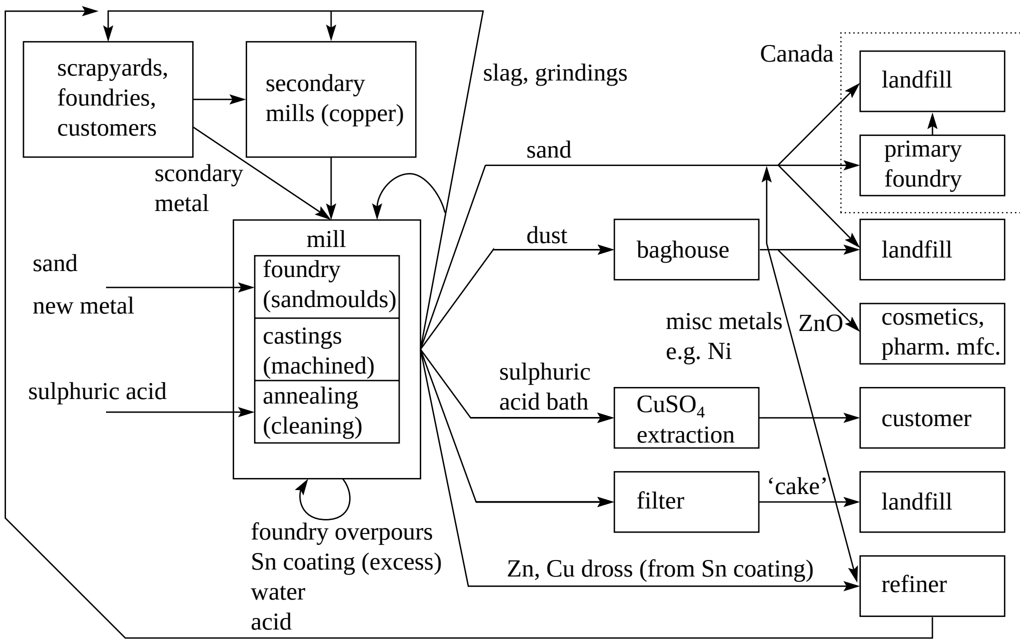

Figure 5. Flow system for a composite mill, showing flows found in the firms which were interviewed.

only. The sample may also be biased, at least in the sense that the firms were willing to be visited and interviewed. These factors explain one reason why we must call it a reconnaissance. It must be said, however, that there were very few refusals, and very few cases where the interview could not be (or was not allowed to be) coupled with a visit to a plant when it was operating.

The second body of data consists of official reports that manufacturing firms (as defined by Department of Commerce Standard Industrial Classification (SIC) codes) are required by either state or federal laws and regulations to provide annually. Under the federally required Toxic Release Inventory (TRI), a firm must report recycled quantities, and emissions and releases of certain materials; those regarded as hazardous (US Environmental Protection Agency 1993). Under the toxic use reduction act (TURA) of the Commonwealth (state) of Massachusetts, firms must report their total use of hazardous materials, and their use in products (Massachusetts Department of Environmental Protection 1993).

A third body of data included telephone questionnaires to some of the firms listed in the TRI–TURA database and listed in state manufacturers' directories under SIC codes, where the SIC codes identify the nature of their business. This information has mostly been used to provide background and to supplement the TURA and TRI information.

8. The industrial ecology of metals

Analysis of these data enables us to draw inferences at various levels of system dissection.

At the level of the individual firm or plant we have an idea of the flow of metal into, inside, and out of the firm. An idea of this flow system can be obtained from

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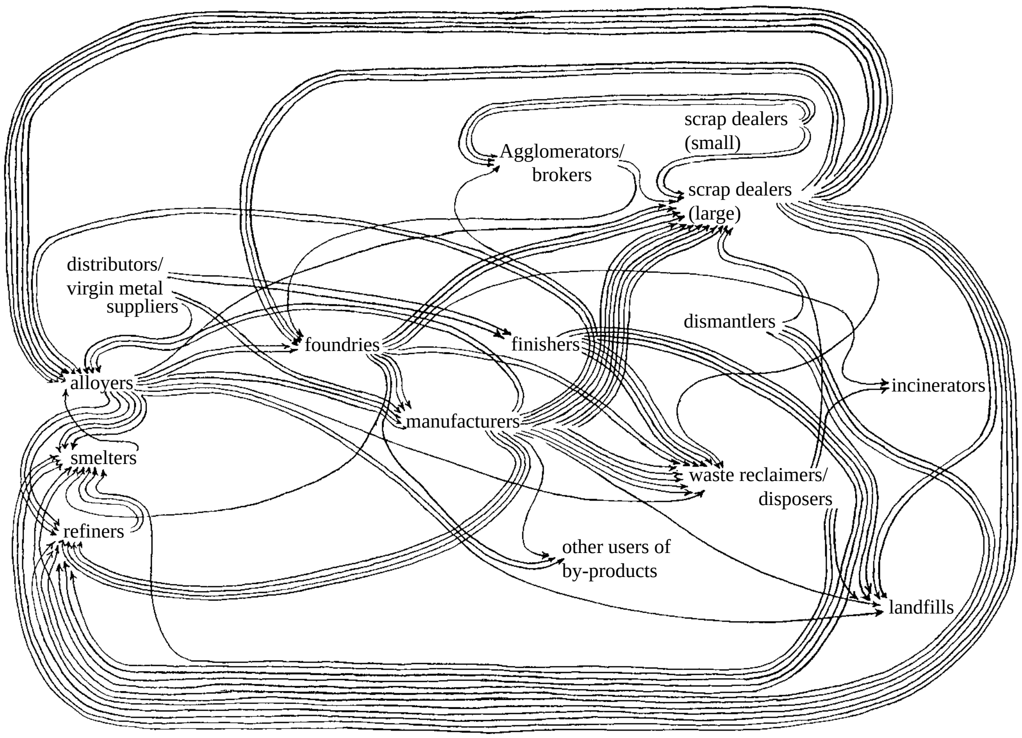

Figure 6. The 'spaghetti' diagram, showing the pattern of metal transfer transactions among the firms. The lines with arrows indicate firm-to-firm transfers of metal or metal-containing material.

figure 5, which shows such a flow system for a composite mill: a fictitious mill which would contain every (or nearly every) flow that we found in some foundry or metal manufacturing firm we interviewed. This gives some idea of the complexity that is to be found in the collection of firms we visited. In effect, some foundry we visited exhibited each flow or loop we had envisioned as a possible metal flow.

At a higher level of system integration, we can consolidate all of the firms of a particular type together (e.g. all the foundries, all the manufacturers of metal pieces and parts by means other than casting, etc.) and examine the metal transferring transactions among them. We constructed a picture of the transaction arrows among firms from the interviews with 35 metal manufacturing firms in our interview database. For example, each time a foundry that we interviewed said they sent metal to a particular type of firm, or obtained metal from a type of firm, we connected the two with a vectored line indicating the direction of transfer. We thus obtained a map of the industry network in terms of the transfers among types of firms, each set of firms of a particular type viewed as a composite block. This produces figure 6, the 'spaghetti diagram'; a picture of the pattern of metal transfer among these firms.

This diagram enables us to identify the types of actors in this simplified industry network, the industry's ecological diagram, and to understand something of the key transactions that make it work.

The important role of scrap dealers, brokers and agglomerators in moving the metal around is apparent, as is that of refiners, alloyers and smelters in the transformations that make the metal recyclable. We can now put names on the actors in the various

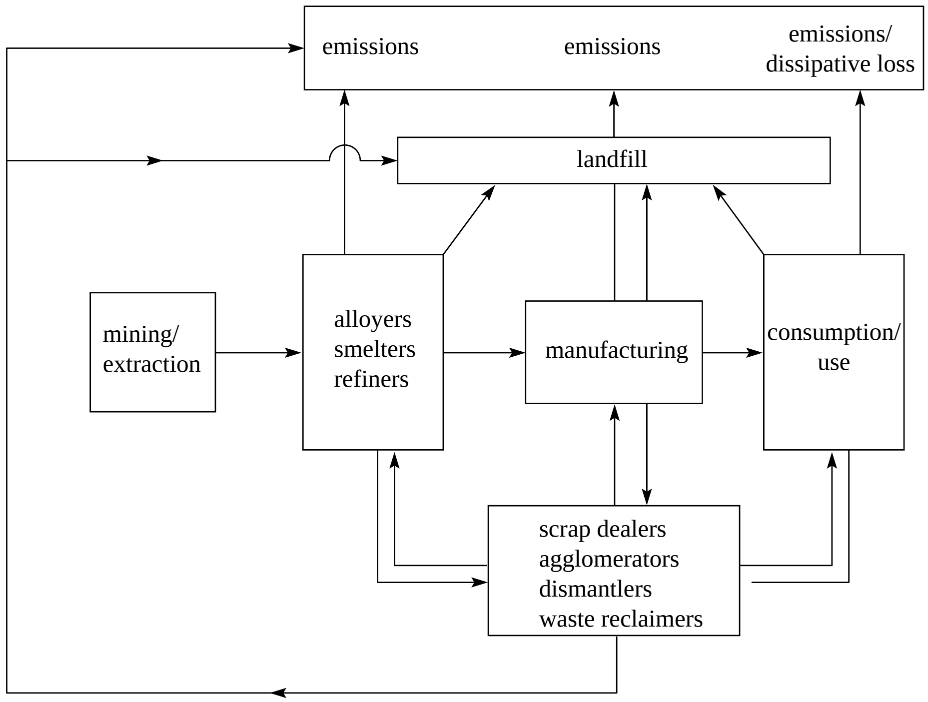

Figure 7. A simplified diagram of the 'spaghetti diagram' system shown in figure 6.

boxes in a simplified system diagram, the one we have seen as figure 7, with the appropriate actors named in their boxes, and the system we studied embedded in its larger system, and in the external environment.

There are two key classes of arrows missing from the spaghetti diagram: arrows representing products that go to the customers of the manufacturers, and arrows that represent scrap coming from other sources than our manufacturers (e.g. post-consumer scrap going to dismantlers and scrap dealers). In effect, we have left the consumers of metal products out of the diagram; we did not study that part of the system.

The system diagram indeed looks like a transaction diagram of an ecological system; like a diagram of the food transactions on the bottom of a lake: who eats what and whom, with metal playing the role of food.

The system is dominated by transactions which move metal around in loops that recycle almost all of the metal which does not go out as product. There are few transactions that 'go to ground', i.e. few transactions that result in putting metal into the environment. As we will see below, this is quantitatively true, by mass, of this part of the metals system as well; like natural ecological systems, it is very good at conserving, and not losing, metal. The industrial part of the system does not 'consume' metal, it generally either transforms it into product or moves it around within the system.

Recycling of metal which is not turned into products by individual firms, is a system property. While individual firms recycle some of the metal internally, the bulk of the metal not immediately turned into product circulates through the system. It is the existence of the self-assembled system that makes possible this circulation and the resulting highly efficient use of the metal.

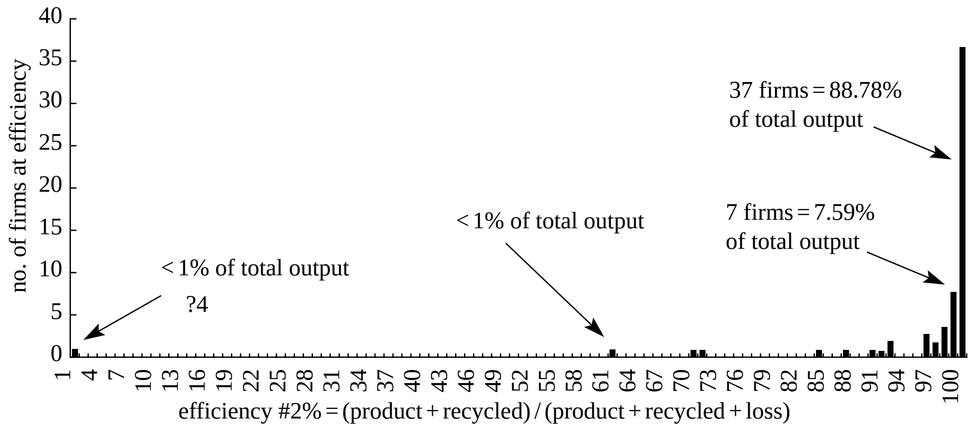

Figure 8. The efficiency of copper use by Massachusetts firms.

9. Efficiency of the system

Since our interview data did not generally result in detailed quantitative information from which we could deduce efficiency, we turned to other sources of information. As noted above, US firms in certain industries, having more than 10 full-time employees, and manufacturing or processing more than 25 000 lbs† of certain materials in the calendar year, must report to the Environmental Protection Agency (EPA) their recycled quantities and releases to the environment (by emission or disposal) of those materials through a system known as the Toxic Release Inventory (TRI). This system does not require reporting of product information, and therefore TRI information by itself cannot be translated into the total quantity of the material used.

In the Commonwealth (state) of Massachusetts (but not in most other states), such firms must also report on certain materials through a system known as the Toxic Use Reduction Act (TURA). Those reports allow a reconstruction of the total amount of such materials exiting the plant every year, but do not allow us to distinguish between material sent for recycling and material entering the environment. By combining data from the two reports (TRI and TURA, and assuming consistency between them) it is possible to construct the distribution of the efficiency of each of the 64 copper-using firms suitably represented in the Massachusetts database. Efficiency is their efficiency in funnelling material into products or into recycling through the system shown above.

There are two ways in which the data from the two systems may be used to deduce the total quantity of metal leaving a firm in a particular year. The result of one of these analyses is shown in figure 8 for copper and figure 9 for lead and lead compounds.

It must be noted that 62% of the metal used by the 64 firms was used by two firms which form ingots into coiled sheets or into wire, and report data which translates into an efficiency of 100%. The top eight copper using firms, all reporting data which translates to 100% efficiency, (which brings us down to firms using 1% or less of the total copper reported by the 64 firms) use 79% of the reported copper. The output-weighted efficiency of the 64 firms in the copper database is about 99%: about 1% of

† 1 lb = 0.4536 kg.

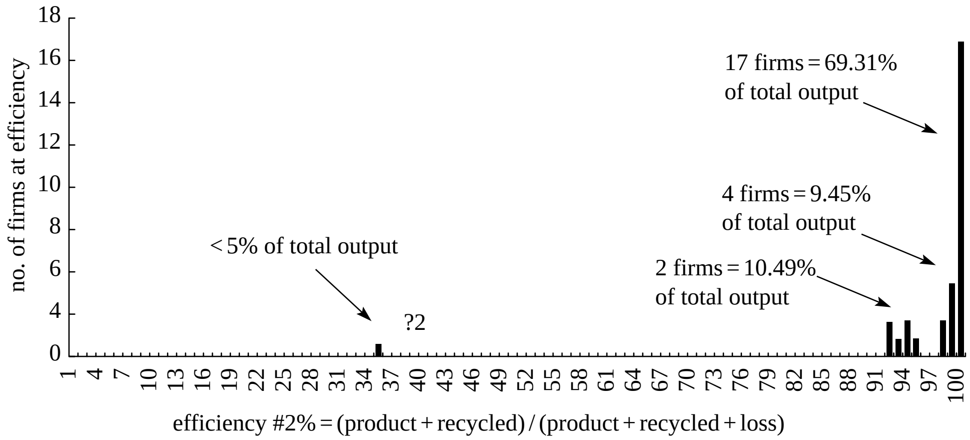

Figure 9. The efficiency of lead use by Massachusetts firms.

the copper used by 64 firms in Massachusetts using more than 25 000 lbs of copper a year is lost to emissions or landfill. (In a couple of cases firms which report are using less than 25 000 lbs of copper, but must report because of a quirk of the regulations.)

Comparison of firm efficiencies using the two methods for estimating annual metal output by each firm shows significant inconsistancies between the two estimates for eight firms, all of which firms show low efficiencies by one of the two measures. Examination of several of these cases suggests that mistakes in filling out the reports result in underestimating the efficiency of the firm. For example, the firm reporting a 1% efficiency reports zero material leaving the firm as product, and the firm reporting only 35% efficiency in the use of lead reports disposal of a lot of lead, but the disposal is to a lead smelter, and is probably being recycled. The report indicates that we 'use' copper and lead but dispose of only a very small fraction of it. The metal manufacturing sector in Massachusetts is more than 99% efficient in copper, and more than 95% efficient in lead, and does not 'consume' much copper or lead. However, depending upon where the material finally goes, even one half of one percent of the 25–30 million pounds of copper in the annual system flow reported by the 64 firms is a potentially significant 100 000 lbs.

There are two other principal possible sources of system leaks. From this investigation, we have no idea of the efficiency of the scrap system in recovering copper from consumer products at the ends of their lives. Several scrap companies to whom we have spoken believe that they are recovering scrap with high efficiency. However, one other estimate of several years ago is only 30% for post-consumer copper scrap, nationally (US Department of Interior, Bureau of Mines 1995).

We also do not have figures for the efficiency of secondary smelters, refiners and alloyers (there are none in the Massachusetts data), although conversations suggest that it is very high. Again, however, since the quantities being handled are very large, even very small percentages of leakage will be potentially significant, depending upon where the metal goes.

10. What does leave the system?

The materials that do leave the manufacturing system include some of the sludges resulting from the polishing and finishing of products (e.g. by 'tumbling' with wet pebbles), some swarf (powder of metal and abrasive resulting from grinding and polishing with abrasives), some metal mixed with foundry sand, and some baghouse dust recovered from the air flow in the plants (particularly from the metal vapor released during foundry 'pours' of molten metal).

However, the metals in these materials are frequently recovered, or the materials themselves are sold for use. Metal polluted foundry sand is sent by some foundries to primary smelters. The sand is a useful flux in the smelting process, and the metal concentration is usually higher than that in primary ore.

Swarf and sludges are also frequently, but not always, resmelted for the metal content. Baghouse dust from brass foundries usually contains quite pure zinc oxide, and this may be (but is not always) sold for use in paint, cosmetics and pharmaceuticals, and, in at least one case, as a zinc supplement for animal feed.

11. What drives this system and how could we ruin it?

In previous publications (Frosch 1994, 1995) we have introduced a classification of factors which influence the environmental performance of firms. These are: technology, economics, information, organization, regulation and liability (or law), which may be remembered by the mnemonic acronym LOITER. This system seems principally to be driven by two of these factors: economics, or cost, and the fear of liability. The liability issue stems from the extremely costly penalties which may be borne by a business found to be (even partially) responsible for contributing to a hazardous waste situation under the 'Superfund' Act (Superfund Amendments and Reauthorization Act (SARA) of 1986, Pub. L. No. 99-499, which amended the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) of 1980 (Pub. L. 96-510).

Many of the firms interviewed make it clear that the combination of the ordinary cost consciousness of business (the value of metal), and the evaluation of potential liability, lead them to behave in such a way that the system conserves metal. They may conserve it even beyond normal cost principles because of the estimate of liability risk, and its potential monetary costs. These firms would not stay profitable, or even in business, if they treated much of their metal, not going into product, as garbage.

The existence of complex, somewhat draconian regulatory systems provide a useful strong pressure to find ways to deal with 'wastes' that will keep the company away from the regulatory system. This provides a useful motivation for reuse and recycling. However, the detailed regulatory treatment of recycling, as a form of disposal, limits how efficient it may be convenient to be, even how efficient it may be economical to be. These details may, generally for reasons of scale, lead a firm to dispose of material rather than sending it for recycling. In some of these cases, however, the disposer may remove and recycle some or all of the metal before landfilling the remaining waste material.

It seems clear that the scrap dealers and the alloyers, refiners and secondary smelters are key actors in the circulation of the metal. Scrap metal is exempt under the regulations that deal with solid waste (Resource Conservation and Recovery Act of 1976 (RCRA), Pub. L. 94-580 and its amendments). By putting strong regulatory administrative barriers into the system, such as by removing this exemption, we could make it difficult to allow this system to function by making it difficult for the scrap dealers to operate.

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12. Recommendations

It seems clear that 'waste' is a poor category for regulation, particularly for an industry, like the segment of the metals industry that we have examined, that lives on the economics and mechanics of recycling of metal. 'Waste' is not a physically definable property, but rather an 'intentional' property defined by what someone intends to do with the material, or, in the end, does do with it. What ought to be managed is the flow and handling of materials.

One consequence of the attempt to manage 'waste' has been that recycling of material not incorporated into product has been treated in US regulatory practice as a form of disposal, on a par with landfilling or incineration. Recycling requires a category of its own, a respectable category.

The largest source of metal entering the environment, as noted above, is probably the disposal to landfill of many consumer products at the ends of their lives. Some of these products are now re-collected, and the metal in them ends up in the metal scrap market. Automobiles, and 'white goods' such as refrigerators, clothes washers and dryers are heavily dismantled and recycled. Circuit boards from old computers and other electronics are heavily recycled and metal from them returns to the metal circulation system.

13. Conclusion

It seems reasonable to view materials in process in industry, and the products of industry, more as transient embodiments of matter and energy in a flow of materials for human use than as 'wastes' with which we must deal.

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Discussion

W. R. Wilson (*Alcan International Ltd, Banbury, UK*). This is more of a comment rather than a question and relates to the 'spaghetti' diagram expressing the movemnet of raw materials, products and scraps in the copper/brass industry. I am very surprised that so few of the businesses involved understood the structure of their industry. It is a long established industry and one driven by the truly entrepreneurial spirit of money making. My own dealings with them directly and through ISRI (US Institute of Scrap Recycling Industries) and with the US Bureau of Mines would suggest that the diagram is well understood. Moreover, similar diagrams have been constructed for their UK equivalents by, for example, ETSU (Energy Technology Support Unit, Harwell).

R. Frosch. I admit that some businesses do understand, but they are in the minority. While most of the businesses interviewed may be aware that they have a role in a larger recycling system, they (particularly the small ones) really are only clear on their immediate transactions. The proprietors of some larger businesses, and certainly ISRI and the Bureau of Mines, understand the general outline of the system, but none seemed to have a clear idea of the overall map. While the Bureau of Mines presumably has the data, it does not express them in 'spaghetti diagram' format. I have subsequently been told that the EPA (US Federal Environmental Protection Administration) once started to create such a diagram, but abandoned the project since they felt that they did not have enough data to finish it. I am not aware of the work of ETSU on the UK system.

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