Applications of Industrial Ecology: Manufacturing, Recycling, and Efficiency

by

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in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

This work applies concepts from industrial ecology to analyses of manufacturing, recycling, and efficiency. The first part focuses on an environmental analysis of machining, with a specific emphasis on energy consumption. Energy analyses of machining show that in many cases, the energy of actual material removal represents only a small amount of the total energy used in machining, as auxiliary processes can have significant energy requirements. These analyses also show that the embodied energy of the materials that are machined can far exceed the energy of machining. Such energy consumption data, along with material flow data, provide much of the information necessary to evaluate machining on the basis of environmental performance. The second part of this work focuses on material recycling at product end-of-life. In this section, a means of evaluating the material recycling potential for products is presented. This method is based on two measures: the value of the materials used in a product and the mixture of materials used in a product. This simple representation is capable of differentiating between products that are economically worthwhile to recycle and those that are not. Such information can in turn be used to help guide product design and recycling policy. The third part of this work focuses on the effectiveness of efficiency improvements in reducing environmental impact. Historical data from ten activities show that improvements in efficiency are rarely able to outpace increases in production. Thus, the overall impact of each of these activities has increased over time. Specific conditions and policies that do allow for efficiency improvements to reduce impact are identified and explored. Together, the three topics presented here provide information, analyses, and recommendations to help move industrial systems towards sustainability.

Thesis Supervisor: Timothy G. Gutowski
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Introduction

In 1989, in an article in *Scientific American*, Robert Frosch and Nicholas Gallopoulos wrote of a new model for industrial activity (Frosch and Gallopoulos 1989). Instead of the traditional model, a linear system in which large amounts of raw materials are first pulled from the ground, then passed through society, and finally discarded as waste, Frosch and Gallopoulos suggested a new industrial ecosystem model, in which linear material paths are replaced with closed material loops. Many of the ideas behind this new model clearly came from natural ecosystems, in which materials cycle within the system, never actually entering or leaving. While Frosch and Gallopoulos acknowledged that a truly closed-loop industrial ecosystem would be difficult, if not impossible, to realize, it represented a goal for industry and society to work towards.

Almost twenty years later, industrial ecology has evolved into a broad field that covers a wide range of technological, social, economic, and environmental issues. It can be defined as,

> "…the study of technological organisms, their use of resources, their potential environmental impacts, and the ways in which their interactions with the natural world could be restructured to enable global sustainability." (Graedel and Allenby 2003).

This definition clearly casts a large net, although this is perhaps fitting, given the broad system perspective of industrial ecology.

The growth of industrial ecology has paralleled the rise in prominence of environmental issues in the United States. Almost daily, reports about mankind's impact on the earth are released, from articles chronicling the crisis in the oceans to assessments of climate change by the Intergovernmental Panel on Climate Change (Weiss and McFarling 2006, IPCC 2007). At the same time, stories of growing social and political willingness to address mankind's impact can be found, from America's largest retailer, Wal-Mart, committing to more energy efficient stores and delivery vehicles, to recent hearings on Capitol Hill featuring former Vice President Al Gore, among others, speaking about global warming (Gunther 2006, Barbaro 2007, Barringer and Revkin 2007). With this growing buzz regarding green issues, there is also a growing need for information, tools, analyses, and recommendations to address these issues. This is a need that industrial ecology can fill. By accounting for material flows, analyzing energy use, contemplating end-of-life treatments, and evaluating policy options, industrial ecology can help to bridge this gap between awareness of issues and action on issues.

Overview of this Thesis

This thesis focuses on applying concepts from industrial ecology to analyses of manufacturing, recycling, and efficiency. While the three topics presented here all focus on applications of industrial ecology, the issues that are addressed are in fact quite diverse. Thus, each part of this thesis is written to stand on its own, and can be read independently from the others without loss of understanding.

The first part of this thesis provides an environmental analysis of machining, with a special focus on energy consumption. This energy and material flows analysis provides an accounting of process inputs and outputs. Such information can be used to highlight particular aspects of machining that can be improved, as well as to provide a basis for comparison between processes. While the selection of manufacturing processes is currently based primarily on process characteristics such as cost, quality, time, flexibility, and rate, as environmental issues rise in importance, manufacturing decisions will increasingly take environmental factors into account. This chapter provides much of the environmental accounting necessary to begin to make such environmentally-based process decisions regarding machining.

The second part focuses on material recycling at product end-of-life. Recycling of materials is commonly mentioned as a key to converting traditional linear lifecycles into closed loops. By closing such loops, recycling can help to reduce the environmental impact of both upstream and downstream stages of the material lifecycle. The analysis presented here focuses on quantifying both the effort required to isolate pure materials from complex products, and the value that can be obtained in the marketplace for these separated material streams. These two simple measures can differentiate between products that are economically worthwhile to recycle and those that are not. Such information can in turn help to guide design and policy choices related to recycling.

The third part examines the ability of product- and process-level efficiency improvements to reduce overall impact at the system level. This chapter provides a broad historical look at past efficiency improvements and their ability, or rather their inability, to lead to impact reduction. More importantly, this analysis provides insights for both engineers and policymakers as to what conditions and actions may be necessary to bring about impact reductions on a broader system level.

Together, the three topics presented here provide information, analyses, and recommendations to help move industrial systems towards sustainability.

References

Barbaro, M., 2007. Home Depot to Display an Environmental Label. *New York Times*, April 17, 2007.

Barringer, F. and A.C. Revkin, 2007. Gore Warns Congressional Panels of 'Planetary Emergency' on Global Warming. *New York Times*, March 22, 2007.

Frosch, R.A. and N.E. Gallopoulos, 1989. Strategies for Manufacturing. *Scientific American* 261(3): 144-152.

Graedel, T.E. and B.R. Allenby, 2003. Industrial Ecology, Second Edition. Upper Saddle River, New Jersey, USA: Pearson Education, Inc.

Gunther, M., 2006. The Green Machine. *Fortune* 154(3): 42-57.

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007, Fourth Assessment Report. Geneva, Switzerland: IPCC. Available online at http://www.ipcc.ch/index.html. (Accessed April 18, 2007.)

Weiss, K.R. and U.L. McFarling, 2006. Altered Oceans. *Los Angeles Times*, July 30 – August 3, 2006. Available online at http://www.latimes.com/news/local/oceans/la-oceans-series,0,7842752.special. (Accessed April 18, 2007.)

An Environmental Analysis of Machining

Abstract

This work presents a system-level environmental analysis of machining. This analysis considers not only the environmental impact of the material removal process itself, but also the impact of associated processes such as material preparation and cutting fluid preparation. This larger system view results in a more complete assessment of machining. Energy analyses show that the energy requirements of actual material removal can be quite small compared to the total energy used in machining. Also, depending on the type of material machined, the energy of material production can, in some cases, far exceed the total energy of machining.

Keywords: machining, green manufacturing, energy consumption, environmental analysis

Introduction

Machining is a material removal process that typically involves the cutting of metals using a variety of cutting tools. It is a process that is particularly useful due to its high dimensional accuracy, flexibility of process, and cost-effectiveness in producing limited quantities of parts. Among manufacturing processes, machining is unique in that it can be used both to create products and to finish products. However, since it is inherently a process that removes material, machining can be wasteful in its use of both materials and energy. This work focuses on investigating various aspects of the machining process from an energy and material flows perspective. The result is a system-level, environmentally-focused analysis of machining.

In the context of this work, the term "machining" refers to processes such as milling, turning, drilling, and sawing, with much of the analysis presented here focused on milling metals. Other machining activities, such as grinding, along with newer non-traditional forms of machining, such as electrical discharge machining and waterjet machining, are excluded from this analysis.[1]

Background

While a great deal of research has been conducted in the area of machining, much of it has been focused on process-level activities and improvements. Some of these improvements, including optimizing material use, minimizing the use of cutting fluids, and reducing cutting energy, do have important environmental ramifications. For example, cutting fluids, with serious health and environmental issues stemming from their use and disposal, are often studied as an area for potential improvement. Various researchers have examined the benefits, drawbacks, and conditions necessary for both wet and dry machining (Graham 2000, Sreejith and Ngoi 2000, Sutherland et al. 2000, Stanford and Lister 2002). Much research has also been conducted to generate detailed analyses of tool-tip cutting energies, from which energy utilization can be estimated. Such analyses are generally quite well-understood, and simple models can be found in traditional manufacturing texts (Groover 1996, Kalpakjian and Schmid 2001). While these and other process-level analyses lay an important foundation for system-level analyses, few provide complete system views of machining.

Analyses focused on the environmental impacts of machining from a broader system perspective have also been completed. Some such works focus on identifying both important environmental issues related to machining, as well as possible technologies to address some of these concerns (Byrne and Scholta 1993, Gutowski et al. 2001). A more comprehensive system analysis of machining, which addresses energy utilization and mass flow, has also been completed (Munoz and Sheng 1995). This work by Munoz and Sheng explores the sensitivity of environmental impacts to process operating parameters and presents detailed process models that can be used to determine the environmental impacts resulting from the machining of a particular part.

The analysis presented here will assess the environmental impact of machining from a system-level perspective. This analysis will provide energy and material accounting for machining as a means of making a process assessment. In general, such accounting of manufacturing processes is rare. While some process accounting has been done for semiconductor manufacturing, no such accounting has been conducted for many traditional manufacturing processes, including machining (Williams et al. 2002). Such an accounting of resources is often the first step in understanding the environmental ramifications of manufacturing processes, and provides a basis by which to direct future process improvements.

System Diagram

In any system analysis, it is important to first identify the boundaries of the system to be examined. In the case of machining, the overall system includes activities such as tool preparation, material production, material removal, and cleaning, among others. Figure 1 shows a broad system view of machining, with important processes shown in rectangular boxes. While Figure 1 presents a wide array of different activities, specific machining scenarios may include only a subset of the processes shown, or may include other processes not shown. However, Figure 1 strives to represent a general machining scenario.

In the analysis presented here, each of the processes included in the shaded region, and all flows shown in dark text, will be examined in detail. For these primary processes and flows, qualitative assessments will be made. The processes not included in the shaded region, and the flows shown in grey, will be examined briefly in order to provide rough estimates of environmental impact. However, for these secondary processes and flows, detailed qualitative assessments will not be provided.

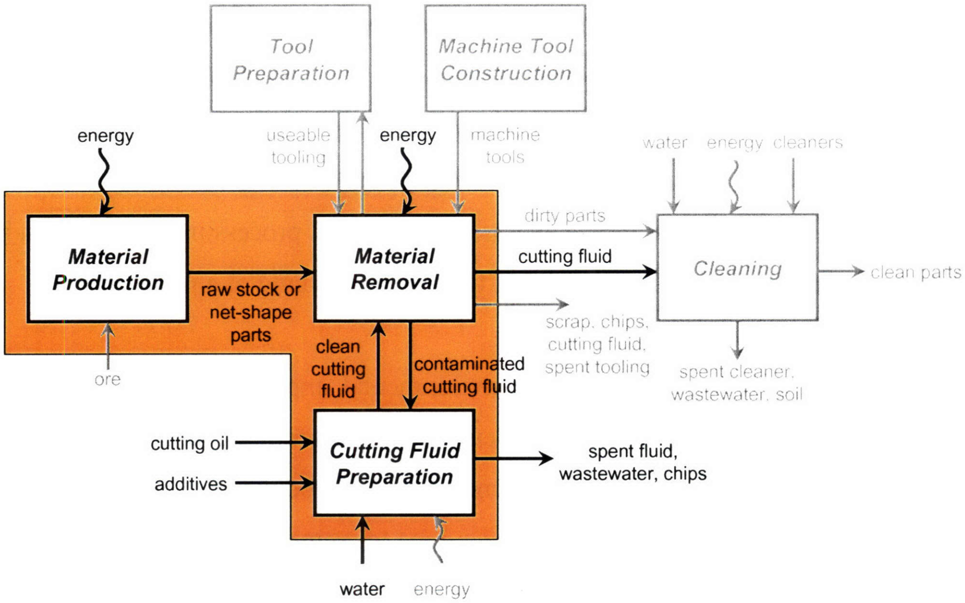


Figure 1: A general system diagram of machining.

Primary Processes

Material Removal

Much of the environmental impact from the material removal process stems from energy use. In estimating the energy requirements for material removal, specific cutting energies are often used. While cutting energies for machining can depend on many factors, including the material properties of the workpiece, the presence of cutting fluids, the sharpness of cutting tools, and the processing variables, ranges of approximate cutting energies in machining are available. For aluminum alloys, specific cutting energies typically range from 0.4 to 1.1 kJ/cm^3, while for steels, specific cutting energies range from 2.7 to 9.3 kJ/cm^3 (Kalpakjian and Schmid 2001). This knowledge of specific cutting energies can help to determine the minimum amount of energy required to remove a certain volume of material. However, this energy requirement is far from the total energy actually required in most machining operations. For example, in production machining, in addition to providing energy to the tool tip, additional energy must be provided to power auxiliary equipment such as workpiece-handling equipment, coolant pumps, chip-handling equipment, tool changers, computers, and machine-lubrication systems. While these additional pieces of equipment may be less common on older and less-advanced pieces of machining equipment, the general industry trends appear to be moving towards more auxiliary equipment on each machine.

In cases where auxiliary equipment is present, the energy requirements of the auxiliary equipment can far exceed the actual cutting energy requirements. Figure 2 shows an energy use breakdown from a large production machining center at a facility run by the Toyota Group.[2] Such a machining center is most likely part of an automated transfer line, with lubrication systems, chip recovery systems, and other equipment all included in the overall system. Figure 2 shows that machining energy, the actual energy used in removing material, is, at most, 14.8% of the total energy used in manufacturing. The remaining 85.2% of the overall energy used is for auxiliary equipment, and is required whether or not a part is being produced. Thus, this constant energy use represents all the energy consumed by the machine that is not directly used in removing material. Clearly, a significant amount of energy is continually consumed in keeping the machine and its auxiliary equipment powered on and ready for use.

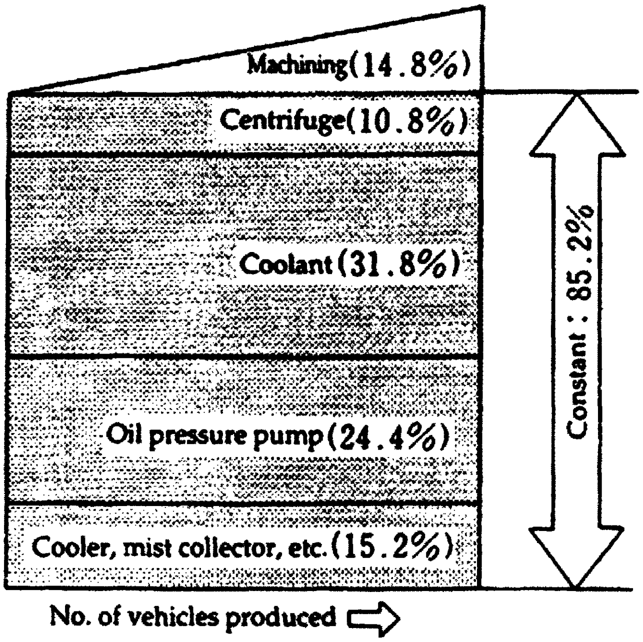


Figure 2: Machining energy use breakdown for a production machining center at a facility run by the Toyota Group. Figure from Gutowski et al. (Gutowski et al. 2005).

While Figure 2 shows the energy breakdown from a modern, highly-automated, mass-production environment, data from smaller, less-automated machines also show a great deal of energy being used in non-cutting operations. Table 1 provides an energy analysis of four different milling machines which fall into three operational classes: production machining centers, automated milling machines, and manual milling machines. Production machining centers, as described previously, are highly-automated machines, typical in mass production. Automated milling machines are also highly-automated, but are generally not capable of as high of throughput as production machining centers. In Table 1, two such automated milling machines are analyzed, namely a 1998 Bridgeport machine and a 1988 Cincinnati Milacron machine. These two machines, although ten years apart in age, are functionally quite similar, both having automated tool changers, coolant pumps, and other auxiliary equipment. The third class of machines examined here, manual milling machines, lack numerical controls (NC) and are often found in small job shop environments or in other shops where limited amounts of machining take place. The actual manual milling machines analyzed in Table 1 are 1985 Bridgeport machines, which lack workpiece handling equipment, tool changers, and other automated equipment.

Of the three classes of machines analyzed in Table 1, manual milling machines are the most common in the United States (American Machinist 1989). However, as new technologies have continued to propagate, the growth in manual machines has slowed, while the growth in automated machines has increased (American Machinist 1989, AMT 1997). Between 1989 and 1994, the number of machining centers in the US almost tripled (Ibid.). While more recent detailed data is difficult to find, overall consumption of machine tools in the US, as measured in nominal dollars, has continued to grow, increasing 5% from 2005 to 2006 (Gardner Publications 2007). For comparison, over the same time period, the rate of growth in nominal dollars in the consumption of machine tools was 20% for China, and almost 40% for India (Ibid.).

Using experimental data and reasonable assumptions, energy consumption models can be developed for the three classes of milling machines. In the "Power Requirements" section in Table 1, experimental power measurements were made for both the automated milling machines and the manual milling machine (Kordonowy 2002). Power data for the production machining center relied upon manufacturer's specifications (Makino 2005). While machine specifications may vary slightly from actual power measurements, they have been shown to provide reasonably accurate estimates of actual power requirements (Kordonowy 2002). The "Power Requirements" section shows how total power demands are distributed among various activities, from constant operations to run-time operations to material removal. "Constant operations" refers to power requirements for computers, fans, coolant pumps, and other such equipment. These constant operations consume energy the entire time the machine is turned on, independent of whether or not the machine is outputting parts. "Run-time operations" include the power necessary to position materials, load tools, and move the spindle. These operations only consume energy when the machine is being used. Finally, "Material removal" refers to the actual power requirements of the spindle motor, the motor that is used for cutting. Thus, "Material removal", as its name suggests, only consumes energy when material is being removed.

To convert these power requirements into energy consumption data, time-based information about machine use is required. In the "Machine Use Scenario" section, assumptions are made about how each class of machines is actually used in practice. Each machine starts with an arbitrary number of available machine time, namely 1000 hours. For the production machining center, it is assumed that in order to purchase such a capital-intensive machine, companies must have sufficient amounts of material to be processed so as to guarantee the machine a steady stream of work. Given this, it is assumed that the production machining center is idle only 10% of the time, resulting in 900 hours of run-time operation for every 1000 hours of available machine time. The assumptions underlying the automated milling machines and the manual milling machines are similar, although these classes of machines, due to their lower capital costs, can afford to be idle for longer periods of time. Thus, the percentage of idle time increases as the capital cost of the equipment decreases, resulting in 650 hours of run-time operation for every 1000 hours of available machine time in the case of automated milling machines, and 350 hours of run-time operation for every 1000 hours of available machine time in the case of manual milling machines.

Of the machine hours spent in run-time operation, not all are spent actively machining a part. Instead, a large portion of this time is spent positioning and loading both the workpiece and the tools. According to Cincinnati Milacron, of the time a part spends on the machine, less than 30% of the time is spent being cut (Kalpakjian 1995). The remaining 70% of the time is spent positioning, loading, and gauging the part (Ibid.). Using these percentages as a guide, the number of machine hours spent actually removing material can be estimated for each class of machine. Assuming that the 30%-70% ratio applies to manual milling machines, it is reasonable to expect that this ratio will be slightly different for the automated milling machines and for the production machining center, again due to the higher capital cost of the equipment. With higher capital costs, machine time is more valuable. Thus, on more expensive machines, much of the positioning, loading, and gauging would be completed before or after the part is placed on the machine. This allows more machine time to be spent machining parts. Because of this, the percentage of time spent removing material increases to 40% in the case of the automated milling machines. In the case of the production machining center, where additional equipment such as tombstones and pallets may be used, machine time spent removing material may be estimated to be 70%.

The "Energy Consumption" section calculates the energy consumption for each of the three activities, namely constant operations, run-time operations, and material removal, as well as the total energy consumption per 1000 machine hours. Multiplying the machine time spent in a given activity by the power required for that activity, results in the total energy consumed by that activity per 1000 machine hours. For example, multiplying "Machine time spent in run-time operation" by the power requirements for run-time operations, results in the energy consumption for that activity per 1000 machine hours. Summing these values yields the total energy consumption per 1000 machine hours. Dividing the energy consumption per activity by the total energy consumption yields a breakdown of energy use, as shown in the "Energy Use Breakdown" section of Table 1, and as seen graphically in Figure 2 for production machining centers. Energy use breakdowns for the two automated milling machines and for the manual milling machines can be seen in Figures 3, 4, and 5. It is important to note that the term "energy", widely used in Table 1, refers to electrical energy, not primary energy. The primary energy requirements of machining are significantly higher than the electrical energy requirements shown in Table 1.

Much like the energy use breakdown shown in Figure 2, the energy distributions shown in Figures 3 through 5 also show a large percentage of energy being devoted to constant operations. Figure 3 shows the energy use breakdown for the more modern automated milling machine, the 1998 Bridgeport machine. Figure 4 shows the energy use breakdown for the older automated milling machine, the 1988 Cincinnati Milacron machine. For each of these machines, the actual energy used in material removal is less than a quarter of the total energy consumed by the machine. In fact, constant operations, which run regardless of whether or not the machine is being used, account for, on average, 45% of the total energy requirement for automated milling machines. While this is less than the approximately 85% consumed by constant operations in the case of production machining centers, it is still a sizeable percentage.

	Production Machining Center		Automated Milling Machine (1998)		Automated Milling Machine (1988)		Manual Milling Machine	
Power Requirements								
Constant operations	76 kW		0.9 kW		3.4 kW		0.7 kW	
Run-time operations (positioning, tool changing, etc.)	7 kW		1.5 kW		3.1 kW		0 kW	
Material removal (maximum power in cut)	22 kW		4.6 kW		6.0 kW		2.3 kW	
Machine Use Scenario								
Available machine time	1000 hours		1000 hours		1000 hours		1000 hours	
Percentage of machine time spent in run-time operation	90 %		65 %		65 %		35 %	
Machine time spent in run-time operation	900 hours		650 hours		650 hours		350 hours	
Percentage of run-time operation time spent in material removal	70 %		40 %		40 %		30 %	
Machine time spent in material removal	630 hours		260 hours		260 hours		105 hours	
Energy Consumption								
Constant operations (per 1000 machine hours)	76319 kWh		920 kWh		3360 kWh		695 kWh	
Run-time operations (per 1000 machine hours)	6327 kWh		956 kWh		2028 kWh		0 kWh	
Material removal (per 1000 machine hours)	6930 kWh		598 kWh		780 kWh		121 kWh	
Total (per 1000 machine hours)	89577 kWh		2474 kWh		6168 kWh		816 kWh	
Energy Use Breakdown								
Constant operations	85 %		37 %		54 %		85 %	
Run-time operations	7 %		39 %		33 %		0 %	
Material removal	8 %		24 %		13 %		15 %	
Energy Consumed per Material Removed								
Material Machined	Aluminum	Steel	Aluminum	Steel	Aluminum	Steel	Aluminum	Steel
Material Removal Rate	20.0 cm^3/sec	4.7 cm^3/sec	5.0 cm^3/sec	1.2 cm^3/sec	5.0 cm^3/sec	1.2 cm^3/sec	1.5 cm^3/sec	0.35 cm^3/sec
Material removed (per 1000 machine hours)	45360000 cm^3	10659600 cm^3	4680000 cm^3	1123200 cm^3	4680000 cm^3	1123200 cm^3	567000 cm^3	132300 cm^3
Energy consumed per material removed	**7.1 kJ/cm^3**	**30 kJ/cm^3**	**1.9 kJ/cm^3**	**8 kJ/cm^3**	**4.7 kJ/cm^3**	**20 kJ/cm^3**	**5.2 kJ/cm^3**	**22 kJ/cm^3**

Table 1: Energy analysis of four milling machines. The term “energy” represents electrical energy, not primary energy.

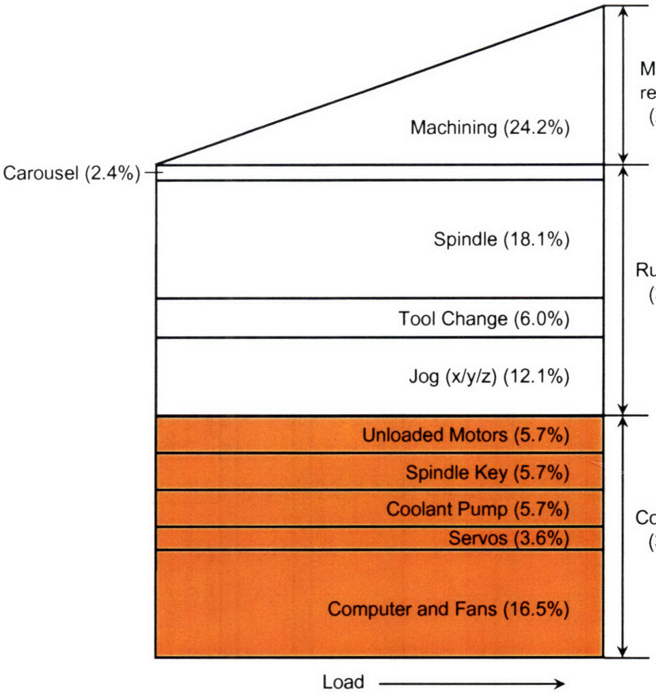


Figure 3: Machining energy use breakdown for a 1998 Bridgeport automated milling machine.

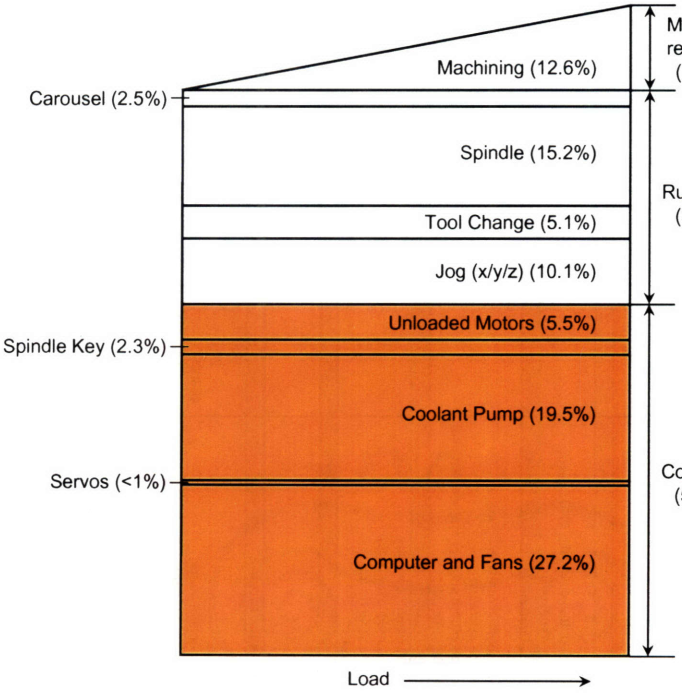


Figure 4: Machining energy use breakdown for a 1988 Cincinnati Milacron automated milling machine.

Figure 5 shows the energy use breakdown for a 1985 Bridgeport manual milling machine. Although this machine lacks auxiliary equipment such as workpiece-handling equipment, tool changers, and coolant pumps, the low usage scenario results in an energy use breakdown similar to that of the most highly-automated machine, the production machining center. In the case of the manual milling machine, 85% of the total energy use is consumed by constant operations.

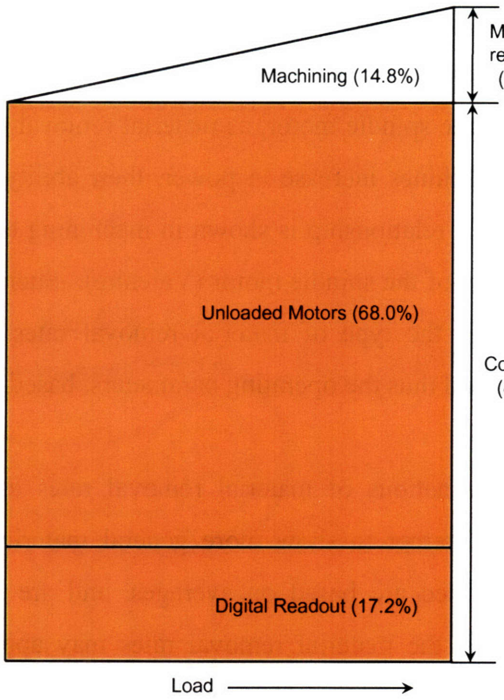


Figure 5: Machining energy use breakdown for a 1985 Bridgeport manual milling machine.

Figures 2 through 5 show that the energy necessary to actually cut the material is only a fraction of the total amount of energy required in machining. Thus, it is clear that detailed models of cutting energies, while useful in some analyses, are not sufficient when attempting to find the total system energy requirements for machining.

It is important to point out that for all four of the milling machines analyzed, the energy required at the tool tip to actually cut the material is the same, assuming operating parameters, material properties, and tool characteristics remain constant. However, the total energy required to remove a given volume of material varies given the different power distributions and usage scenarios of each machine. The amount of energy consumed per volume of material removed is calculated in the last section of Table 1.

The amount of material removed per 1000 work hours can be obtained by estimating a material removal rate. This estimation is difficult, as material removal rates depend on numerous parameters, including tool material (high-speed steel versus carbide), part material (aluminum versus steel), part design (simple versus complex geometry), surface finish (smooth versus rough), processing parameters (wet versus dry machining), and machine parameters (rated capacity of the spindle motor). Using the "Speeds and Feeds" section of a standard Machinery's Handbook, precise material removal rates can be calculated given various operating parameters (Oberg et al. 1996). These calculated material removal rates can then be adjusted further based on the rated capacity of the spindle motor, as material removal rates correlate with machine size. More specifically, as machines increase in power, their ability to apply larger forces at higher velocities improves. This relationship is shown in machining tables that relate material removal rates to the rated capacity of the spindle motor (Valenite). Such tables allow machinists to select appropriate machines for the type of material removal rates desired, or, alternatively, select material removal rates, and thus the operating parameters, based on the machines available.

While such detailed estimations of material removal rates are important for machinists, the models presented here attempt to show more general material removal scenarios. Thus, the material removal rates used are based on averages, and are intended to represent mid-range values. Because of this, the material removal rates may appear higher than typical material removal rates for finishing operations or for operations where complex geometries are involved. However, the material removal rates may appear lower than typical material removal rates for hogging or other operations, where rougher finishes are acceptable.

Using material removal rates, machine use scenarios, and total energy consumption, the amount of energy consumed per volume of material removed can be calculated. These values, ranging from around 2 to 7 kJ/cm^3 of material removed for aluminum, and around 8 to 30 kJ/cm^3 of material removed for steel, provide general estimates of the overall electrical energy requirements for machining.[3] Note that these values are considerably larger than the specific cutting energies mentioned earlier, which apply to only the actual material removal operation. While values for the overall energy requirements of machining will vary some with different machines, machine use scenarios, and material removal rates, the values calculated here do provide good order-of-magnitude estimates.

Material Production

The production of materials is often an energy- and resource-intensive process. While material production may seem to be outside the system boundaries of machining, machining can be viewed as a process that pulls in raw materials, altering them dramatically in the course of producing products. Thus, the energy requirements of the raw materials, in this case aluminum and steel, are examined.[4]

In creating products, machining, being a subtractive process, often uses large amounts of material. In many cases, only a fraction of the total material entering a machining facility leaves in the form of a product. Estimates of scrap production in machining range from 10% to 60% (Kalpakjian and Schmid 2001). While these chips and scraps can be recycled, considerable off-site reprocessing must typically take place before such materials can be reused in the machining process.

In the case of machining aluminum, much of the aluminum used comes from virgin sources. According to a major aluminum producer, the recycled content of machineable aluminum is on the order of 20% (Munster 2004). With aluminum from virgin sources requiring around 270 MJ/kg to produce, and aluminum from recycled sources requiring around 16 MJ/kg to produce, the average aluminum used in machining has an embodied energy of 219 MJ/kg (Chapman and Roberts 1983). It is clear from the large energy difference between virgin aluminum and recycled aluminum that the percentage of recycled content plays a key role in the embodied energy of the material. Using a density of aluminum around 2.7 g/cm^3, the embodied energy per cubic centimeter of input material is around 590 kJ/cm^3, or 80 to 300 times larger than the overall machining energies for aluminum, as calculated in Table 1. Thus, the importance of tracing back material flows to material production is obvious.

For steel, the embodied energy is significantly less than for aluminum, as is the savings from using recycled sources. Producing steel from virgin sources requires 31 MJ/kg, while producing steel from recycled sources requires only 9 MJ/kg (Ibid.). With the density of steel around 8.0 g/cm^3, the embodied energy per cubic centimeter of virgin steel is around 250 kJ/cm^3. Although the material removal energies associated with steel are higher than those for aluminum, the embodied energy of virgin steel is still eight to 30 times larger than the overall machining energy for steel. However, if steel with a high recycled content is used, the embodied energy of the material may be on the order of only twice the machining energy. Again, the percentage of recycled content plays an important role in energy discussions.

A summary of the energy requirements for material production and machining is shown in Table 2. For both aluminum and steel, it is clear that the energy requirements for material production per volume of material produced can far exceed the energy requirements for machining per volume of material removed.

	Aluminum	Steel
Material Production Energies (per cm^3 produced)		
Virgin	730 kJ/cm^3	250 kJ/cm^3
Recycled	43 kJ/cm^3	72 kJ/cm^3
Machining Energies (per cm^3 removed)		
Production Machining Center	7 kJ/cm^3	30 kJ/cm^3
Automated Milling Machine (1998)	2 kJ/cm^3	8 kJ/cm^3
Automated Milling Machine (1988)	5 kJ/cm^3	20 kJ/cm^3
Manual Milling Machine	5 kJ/cm^3	22 kJ/cm^3

Table 2: Material production energy and machining energy for aluminum and steel.

Cutting Fluid Preparation

Cutting fluids are an important part of machining, in terms of both operation and environmental impact. The most widely used cutting fluid, and the one that will be focused on here, is soluble oil. While other types of cutting fluids do exist, including semi-synthetic fluids, synthetic fluids, and straight oils, soluble oils account for more than half of the total cutting fluid market, in large part because they are better at removing heat, safer for workers, and less costly than other types of cutting fluids (Childers 1994, El Baradie 1996a, Stanford and Lister 2002). In use, soluble oils are typically diluted with water, such that around 95% of the cutting fluid, by volume, is water (Becket 1994, Childers 1994, Foltz 1994, El Baradie 1996a, Stanford and Lister 2002).[5] The other 5% is a combination of oil, emulsifiers, and additives, and is often specifically formulated for the machining operations, tool materials, workpiece materials, and machining conditions in which it will be used (El Baradie 1996b).

Despite their name, soluble oils do not dissolve in water. Instead, soluble oils and water form emulsions, in which oil droplets are suspended in water. The most common types of oils for cutting fluids are naphthenic and paraffinic oil, as these types of oils tend to emulsify more easily

(Childers 1994, Stanford and Lister 2002). In order to help with this emulsification process, other compounds, known as emulsifiers, are also added. These emulsifiers include sodium sulfonate, nonylphenol ethoxylates, polyethylene glycol (PEG) esters, and alkanolamides (Childers 1994). Some of these emulsifiers can lead to foaming, thus leading to the use of defoaming additives (Ibid.).

A variety of other additives are also used in order to limit corrosion, improve lubricity, control acidity, and control microbial growth (Childers 1994, Soković and Mijanović 2001). In order to prevent rust, additives such as calcium sulfonate, alkanolamides, and blown waxes can be used (Childers 1994). To improve lubricity, additives ranging from fatty soluble oils, including lard oil and rapeseed oil, to extreme-pressure (EP) soluble oils containing chlorine, sulfur, or phosphorus, are often used (Childers 1994, El Baradie 1996a).[6] To maintain a slightly basic solution, with a pH typically between about 8.8 and 9.3, amines can be added as alkaline sources (Childers 1994, El Baradie 1996b, Stanford and Lister 2002). Maintaining a proper pH is important both to control microbial growth and to protect worker health (El Baradie 1996b, Stanford and Lister 2002). While bacteria rarely grow if the pH is above around 8.8, a pH above 9.3 can lead to skin irritation in workers (Ibid.). Thus, monitoring pH can be quite important. Controlling the growth of bacteria and fungi is accomplished in part through maintaining proper pH values, as mentioned above, as well as through the use of biocides such as formaldehyde condensates, phenols, pyrithiones, and isothiazones (Rossmore and Rossmore 1994, Stanford and Lister 2002). However, the use of biocides is not without debate, mainly due to concerns regarding human health (Soković and Mijanović 2001). In fact, pesticides, including biocides, are regulated by the United States Environmental Protection Agency (EPA) under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). This act requires that all pesticides used in the US are registered by the EPA, and also requires users of pesticides to register their purchases with the EPA (US EPA 2007).

In addition to the many oils and chemicals making up cutting fluid, a large amount of water is also required. Table 3 shows an analysis of the metalworking fluid used in machining. The total sales volume represents an estimate of the amount of metalworking fluid sold in the United States in 1990, and is based on data from both the Independent Lubricant Manufacturers Association and the National Petroleum Refiners Association (Dick 1994, McCoy 1994). These values seem to be in line with older industry estimates found in other texts (Nachtman and Kalpakjian 1985). It is important to point out that "metalworking fluids" typically refers to fluids used in both cutting and grinding (McCoy 1994). The total number of metalcutting machines comes from a 1994 inventory of metalworking equipment by American Machinist (AMT 1997). This number, shown in Table 3, includes milling machines, turning machines, sawing machines, drilling machines, and grinding machines, but does not include non-traditional metalcutting machines such as electrical discharge machines (EDM), laser cutting machines, and waterjet cutting machines.[7]

Metalworking Fluid Sales	
Total sales volume	97 million gallons/year
Metalcutting Machines	
Total number of metalcutting machines	1.856 million machines
Diluted Metalworking Fluid Composition	
Percentage of metalworking fluid	5 %
Percentage of water	95 %
Evaporative losses (water)	1 %
Fluid Use per Metalcutting Machine	
Metalworking fluid (concentrated)	52 gallons/machine/year
Water (including evaporative replacement)	1003 gallons/machine/year
Daily Use (250 work days per year)	
Daily metalworking fluid use per cutting machine (concentrated)	0.21 gallons/machine/day
Daily water use per cutting machine	4.01 gallons/machine/day

Table 3: Metalworking fluid analysis for machining.

In the "Diluted Metalworking Fluid Composition" section, the typical ratio of metalworking fluid to water, namely 5 to 95, is shown. To make up for the evaporative loss of water over time, a small percentage of water must also be added to maintain the proper concentrations. Metalworking fluid mixtures that are either too concentrated or too dilute can lead to problems ranging from rancidity to corrosion to worker health concerns (Foltz 1994).

Using the composition of metalworking fluid, along with the volume of metalworking fluid sold and the number of metalcutting machines, the amount of metalcutting fluid and water used per machine can be calculated on both an annual and daily basis. These calculations assume that the various different types of cutting machines use the same amount of metalworking fluid, a reasonable assumption for the purposes of this analysis. The values generated for water use also assume that all metalworking fluid is mixed with water. This is not entirely true, as some cutting fluids, namely straight oils, are used without dilution. However, straight oils are the least common type of cutting fluid and, due to their health hazards, difficulty in cleaning, and poor cooling properties, are declining in use. In fact, they are seldom used outside of heavy-duty cutting and grinding operations (Sluhan 1994). It is also important to point out that while straight oils are not mixed with water, other cutting fluids, for example synthetic fluids, are sometimes used at dilutions greater than 95% water (Stanford and Lister 2002). Thus, these effects may tend to cancel each other out. With these assumptions, the average metalcutting machine uses around 50 gallons of metalworking fluid and 1000 gallons of water each year. On a daily basis, assuming 50 work weeks per year and 5 work days per week, this amounts to about 4 gallons of water per machine per day.

Once formulated, cutting fluids can be circulated through a system numerous times. However, losses frequently occur, often through vaporization or through chips, workpieces, and handling equipment leaving the working area (Byrne and Scholta 1993, Bell et al. 1999). In fact, some suggest that as much as 30% of the annual total cutting fluid consumption may be lost through these mechanisms (Byrne et al. 2003). Others claim a lower, but still significant, loss rate on the order of 10% (Dick 1994). With either estimate, it is clear that a fair amount of cutting fluid is lost through everyday activities.

While the cutting fluid that remains can be sampled and refreshed over time, there are properties of the cutting fluid that cannot be fixed by simply adding more water, oil, or additives. For example, over time the cutting fluid will pick up contaminants such as metal chips, fines, and tramp oil. Such contaminants can be removed using a separation or filtration process, or, alternatively, the cutting fluid can be disposed of and replaced with fresh fluid. While disposal of spent metalworking fluid was once virtually cost-free, today disposal costs are approximately equal to the cost of the replacement fluid (Sluhan 1997). With increasing environmental regulations, such as the Resource Conservation and Recovery Act (RCRA), disposal of metalworking fluid is becoming more highly controlled and more costly (Ibid.).

Secondary Processes

Tool Preparation

While tooling plays a major role in the machining process, the direct environmental impact of tooling is limited. Due to their relatively long life, the environmental cost of tools and tool maintenance is often amortized over numerous products, thereby making the environmental impact relatively insignificant on a per part basis. However, the effect of tool materials on allowable cutting speeds, and thus on material removal rate, should not be overlooked. Selection of appropriate tools can allow for increased material removal rates, thereby reducing the total machining energy required.

Today, most metal cutting is done using carbide tools (Oberg et al. 1996). A large proportion of these carbide tools are sold as indexable inserts, cutting inserts that attach to specially designed tool holders. These indexable inserts, because they can be repositioned, have multiple cutting surfaces, depending on their geometry. Triangular inserts have six available cutting edges, three per side, rectangular inserts have eight cutting edges, four per side, while circular inserts can be rotated to numerous positions. Once all the cutting edges have been used, the insert is typically discarded (Ibid.). Alternatives to carbide tools do exist, the most popular being high-speed steels. High-speed steels are still used in the majority of drilling applications, as well as in many milling applications (Edwards 1993).

Producing tools does require some energy-intensive materials and processes. Tungsten, with an embodied energy of approximately 400 MJ/kg, comprises most of the mass of carbide cutters (Goldwitz 2002). Some of the manufacturing steps, including sintering, which is used to form carbide tools, and physical vapor deposition (PVD) or chemical vapor deposition (CVD), which is used to coat both carbide and high-speed steel tools, are also quite energy intensive (Gutowski et al. 2007). However, while the energy involved in producing tooling is not trivial, the fact that these cutting tools can be used numerous times on multiple surfaces means that the per part energy contribution from tool production is quite small, and can be more or less ignored in light of the material removal and material production analyses presented earlier.

As mentioned earlier, perhaps the biggest impact with regards to tooling has to do with differences in material removal rates. For example, allowable cutting speeds with carbide tools are much greater than with high-speed steel tools. In the case of end-milling wrought aluminum such as 6061-T6, the optimum cutting speed for high-speed steel tools is 165 feet per minute while the optimum cutting speed for uncoated carbide inserts is 620 feet per minute (Oberg et al. 1996).[8] In the case of end-milling using a 2-tooth, 1-inch diameter tool with a 0.2-inch depth of cut and a 1-inch width of cut, the recommended material removal rate for high-speed steel tools is around 1 cm^3 per second, while the recommended material removal rate for carbide tools is close to 4 cm^3 per second. These examples highlight the drastic changes in cutting speeds and material removal rates that can arise from the use of different cutting tool materials. From Table 1, the importance of material removal rates in the energy consumption of machining is clear; higher material removal rates can lead to drastically decreased machining energy requirements per volume of material removed. Again, it is important to point out that material removal rates are not dependent on tool material alone, as part material, part design, surface finish, processing parameters, and machine parameters are also important.

Machine Tool Construction

Much like tooling, metalcutting machines, which clearly play a critical role in the machining process, have limited direct environmental impact, as most machines are in use for many years. In 1994, almost 60% of all metalcutting machines in the US were more than 10 years old (AMT 1997). These long lifetimes mean that the environmental impact of machine tool construction is amortized over numerous products over many years. Thus, the environmental impact per part is relatively small.

The larger effect of machine tools on machining has to do with energy efficiency. Newer machine tools can, in some cases, be significantly more energy-efficient than older machine tools, thus resulting in energy savings during use. For example, a comparison of energy use by the two automated milling machines analyzed earlier, namely a 1998 Bridgeport machine and a 1988 Cincinnati Milacron machine, may suggest improvements in energy efficiency over time. While these machines are similar in terms of size, capabilities, and auxiliary equipment, they show markedly different energy consumption values, as shown in Table 1, particularly during constant and run-time operations. However, it must be pointed out that there are clearly other factors besides improved efficiency over time that may explain this difference in energy use, including differences in the design and production of these machines and machine components.

Cleaning

Of the many processes that play a role in machining, cleaning is perhaps the one most often cited when discussing environmental impact. However, the importance of cleaning, and the environmental impact of cleaning, is highly dependent on the product being made. High-end painted products must often undergo multiple cleaning steps, while other products may be acceptable with just a simple rag wipe down. This highly diversified cleaning landscape, both in terms of amount of cleaning and type of cleaning, make general qualitative analysis of this process difficult.

The cleaning methods and chemicals currently being used are also changing. Prior to US and international regulations in the late 1980s and early 1990s, metal cleaning was dominated by several large-use chemicals that could be applied in a broad array of different situations (Kirschner 1994). The most widely used of these chemicals was the chlorinated solvent, 1,1,1-trichloroethane (TCA) (Sherman et al. 1998). However, since the phase-out of TCA, and with no "drop-in" replacement available, numerous different cleaning solutions have been implemented (D'Amico 1995, Sherman et al. 1998). Many of these new cleaning processes rely on aqueous cleaners instead of solvent cleaners.

Environmental Concerns

The analysis of machining presented above, and in particular the analyses of the material removal and material production processes, focuses heavily on energy use. In linking this energy use to environmental impacts, following energy back to its sources is critical.

In the case of the material removal process, the energy for this activity comes from electricity from the power grid. In the US, approximately 50% of electricity comes from burning coal (US DOE 2006). Other major sources include nuclear, which provides approximately 20% of US electricity, and natural gas, which provides approximately 19% (Ibid.). In terms of gaseous emissions, an average MJ from the US electric grid is accompanied by 172 g of CO_2, 0.7 g of SO_2, and 0.3 g of NO_x (Ibid.). Many other environmentally important emissions also result from electricity generation, including mercury, chromium, and lead (Graedel and Allenby 1998). It is also important to note the inefficiencies in the electricity generation system. Large coal-fired electricity generation facilities are only around 35% efficient (Smil 1999). Thus, for every 3 kJ of coal that are consumed, about 1 kJ of electricity results. In short, electricity values are heavily burdened.

Material production processes typically rely on a mix of energy sources, including electricity. While the exact energy mix depends on the material being produced, the location of the facilities, and a variety of other factors, this energy must also be appropriately burdened. In some cases, such as the case of aluminum produced in the Northwest, some of the energy may come from less-polluting sources, such as hydropower. Analysis and inclusion of these energy sources is beyond the scope of this paper, but it is important to note the many different sources for both energy and electricity.

While the environmental concerns associated with material removal and material production are focused on energy use, the environmental concerns associated with cutting fluid preparation and cleaning are tied more closely to liquid and hazardous waste. These pollutants raise issues at both local and global levels. While some of the chemicals used in these processes can be harmful to workers, such as some additives to cutting fluids, other chemicals, such as TCA, are associated with high-level ozone depletion. Such environmental impacts further stress the importance of research in areas such as dry machining and aqueous cleaning.

Conclusion

This environmental analysis of machining highlights a few important points. From the energy analysis of the material removal process, it is clear that the actual cutting energy can be quite small when compared to the total energy required for machining. It is also important to note that the energy used to power machine tools typically comes from the electric grid. Thus, electricity requirements for the material removal process must be appropriately burdened to reflect the environmental impact of electricity generation.

Another important point is that the energy involved in the material production process can, in some cases, dominate the energy involved in the machining process. This result is particularly true in the case of aluminum, especially when virgin aluminum is used. However, in the case of steel, or other less-energy-intensive materials, the material production energy and machining energy may be on the same order of magnitude.

With regards to cutting fluid preparation and cleaning, the focus shifts from one of energy to one of liquid and gaseous emissions. While further research must be done in these areas to complete this environmental analysis, it is important to note that these processes will tend to dominate liquid use, liquid waste, and hazardous waste categories, much like material removal and material production dominate energy use categories.

Appendix A

Gathering environmental data for system-level manufacturing models is quite difficult. One important resource for industrial information, the United States Government, does have a large amount of data from agencies such as the US Department of Energy (DOE) and the US Environmental Protection Agency (EPA). The Energy Information Administration (EIA), an agency of the DOE, provides data on industrial energy consumption obtained through its Manufacturing Energy Consumption Survey (MECS), the latest of which was conducted in 2002. While this survey provides a comprehensive look at energy use in the industrial sector, industry information is organized by North American Industry Classification System (NAICS) code or, for data prior to 1997, by Standard Industrial Classification (SIC) code. While some NAICS and SIC codes correspond to specific processes, machining is spread out among numerous different product-specific codes. According to the 1989 Inventory of Metalworking Equipment conducted by the *American Machinist*, 98.2% of all metalcutting machines are distributed among just four major product-specific SIC code groups:

Major Group 34: Fabricated Metal Products, Except Machinery and Transportation Equipment
Major Group 35: Industrial and Commercial Machinery and Computer Equipment
Major Group 36: Electronic and Other Electrical Equipment and Components, Except Computer Equipment
Major Group 37: Transportation Equipment (American Machinist 1989).

While these major groups are known to contain metalcutting machines, and the energy requirements of each of these major groups can be obtained using EIA information, the major groups defined by the SIC code contain far more than simply metalcutting equipment. Therefore, the amount of energy used by one of the major groups listed above cannot be entirely traced back to metalcutting machines. Instead, the energy demand must be divided among metalcutting machines and other machines that are required by that major group. In short, product-specific energy data cannot be easily converted to process-specific data, as required by this analysis.

This inability to link product-specific data to individual processes also prevents the effective use of Toxic Release Inventory (TRI) data provided by the EPA. TRI data, self-reported company data on releases of toxic chemicals, is available at both the level of the firm and at the level of NAICS or SIC codes. However, as in the case of EIA data, TRI data cannot be easily converted to process-specific data. Firms typically have numerous pieces of equipment, not just metalcutting equipment, making the allocation of firm-level TRI releases to specific processes impossible without further information. Likewise, the products contained in product-specific SIC codes are typically made using a variety of different processes, making it impossible to trace any SIC code-specific TRI releases to individual processes without additional information. Even if such TRI data could be linked to specific processes, there is some question as to how representative TRI data is of actual emissions (Williams et al. 2002). Given that TRI data is self-reported, and that not all firms are required to file a TRI, TRI data for an industry as a whole may often be lower than the actual releases.

Outside of government surveys, little system-level industrial information is available. While industrial trade publications such as American Machinist do report on overall industry statistics, environmental issues are rarely included. Also, as there are no requirements to release energy use and environmental data outside of the government requirements, it is not surprising that companies do not release additional, more detailed information. In fact, more detailed information may, in some cases, be seen as a valuable trade secret, particularly in industries such as semiconductor manufacturing, where knowledge of the process outputs may allow one to figure out the process itself. Perhaps contributing to this lack of information is the fact that the industry landscape is constantly changing. With the beginning of the North American Free Trade Agreement (NAFTA) in 1994, the continuing movement of manufacturing offshore, and the rise of contract manufacturers, machining, and the manufacturing sector as a whole, is in constant flux.

An alternative approach to gathering data is to begin with process-specific data. While such data is available, and is already directly linked to the process under investigation, process-specific data can place undue emphasis on a certain machining method or piece of equipment. When relying on process data, it is important that the machining process analyzed is representative of machining processes in general. If it is not, it is important to understand how this process differs from the average process. Much of the analysis presented in this work relies on process-specific data, as opposed to system-level data.

Notes

1. Detailed environmental analyses of waterjet machining and grinding have been completed by Kurd and Baniszewski, respectively (Kurd 2004, Baniszewski 2005).

2. The Toyota Group consists of a number of different companies, the largest and most widely-recognized of which is the Toyota Motor Company.

3. The energy values for machining developed here can be compared to the energy values for machining that appear in life-cycle assessment (LCA) software. For example, the Standard Data Archive from the SimaPro 5.1 LCA software, lists the energy requirement for machining steel as 0.39 MJ/kg removed, or 3.1 kJ/cm^3 removed. For machining aluminum, the same software lists the energy requirement as 0.56 MJ/kg removed, or 1.5 kJ/cm^3 removed. These estimates for machining represent values for the average machining technology found in Western Europe in the late 1980s. Given the lack of details behind the values in the LCA software, it is difficult to know why these values are significantly less than the values developed in this work. Interestingly however, the energy values for machining from the LCA software are either close to or within the range of specific cutting energies for these materials. This fact may suggest that the values used in the LCA software reflect only tool-tip cutting energies, and not the complete energy requirements of machining.

4. While material production is highly energy intensive, it also has other significant environmental implications, ranging from habitat destruction to heavy metal emissions to solid and liquid waste generation (Young 1992, US EPA 1995a, US EPA 1995b).

5. Other types of cutting fluids are also mixed with water, including synthetic fluids and semi-synthetic fluids (Stanford and Lister 2002). Only straight oils are used without dilution.

6. One type of rapeseed is canola, from which canola oil, a popular cooking oil, is made.

7. The total number of metalcutting machines in the US in 1994 was approximately 1.904 million, and included approximately 36,000 electrical discharge and electro-chemical machines, 10,000 laser and thermal cutting machines, and 1,500 waterjet cutting machines (AMT 1997). Subtracting these non-traditional machines from the total number of metalcutting machines, yields approximately 1.856 million metalcutting machines (Ibid.).

8. According to the Machinery's Handbook, "the *optimum* feed/speed data are approximate values of feed and speed that achieve minimum-cost machining by combining a high productivity rate with low tooling cost at a fixed tool life." (Oberg et al. 1996).

References

American Machinist, 1989. The 14th Inventory of Metalworking Equipment. *American Machinist* 133(11): 91-110.

Association for Manufacturing Technology (AMT), 1997. The Economic Handbook of the Machine Tool Industry. McLean, Virginia, USA: The Association for Manufacturing Technology.

Baniszewski, B., 2005. An Environmental Impact Analysis of Grinding. Bachelor of Science Thesis in Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

Becket, G.J.P., 1994. "Corrosion: Causes and Cures," in Metalworking Fluids, ed. J.P. Byers. New York, New York, USA: Marcel Dekker, Inc.

Bell, D.D., J. Chou, L. Nowag, and S.Y. Liang, 1999. Modeling of the Environmental Effect of Cutting Fluid. *Tribology Transactions* 42(1): 168-173.

Byrne, G. and E. Scholta, 1993. Environmentally Clean Machining Processes – A Strategic Approach. *Annals of the CIRP* 42(1): 471-474.

Byrne, G., D. Dornfeld, and B. Denkena, 2003. Advanced Cutting Technology. *Annals of the CIRP* 52(2): 483-507.

Chapman, P.F. and F. Roberts, 1983. Metal Resources and Energy. London, UK: Butterworth and Co Ltd.

Childers, J.C., 1994. "The Chemistry of Metalworking Fluids" in Metalworking Fluids, ed. J.P. Byers. New York, New York, USA: Marcel Dekker, Inc.

D'Amico, E., 1995. Alternatives Finding Way in a Stormy Market. *Chemical Week* 157(17): 54.

Dick, R.M., 1994. "Recycling of Metalworking Fluids" in Metalworking Fluids, ed. J.P. Byers. New York, New York, USA: Marcel Dekker, Inc.

Edwards, R., 1993. Cutting Tools. London, UK: The Institute of Materials.

El Baradie, M.A., 1996a. Cutting Fluids: Part I. Characterisation. *Journal of Materials Processing Technology* 56(1-4): 786-797.

El Baradie, M.A., 1996b. Cutting Fluids: Part II. Recycling and Clean Machining. *Journal of Materials Processing Technology* 56(1-4): 798-806.

Foltz, G.J., 1994. "Metalworking Fluid Management and Troubleshooting" in Metalworking Fluids, ed. J.P. Byers. New York, New York, USA: Marcel Dekker, Inc.

Gardner Publications, 2007. 2007 World Machine Tool Output and Consumption Survey. Cincinnati, Ohio, USA: Gardner Publications, Inc. Available online at http://www.gardnerweb.com/consump/consume.html. (Accessed April 4, 2007.)

Goldwitz, J.A., 2002. Productivity Gains and Environmental Impact of Turning Tools. Bachelor of Science Thesis in Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

Graedel, T. E. and B.R. Allenby, 1998. Design for Environment. Upper Saddle River, New Jersey, USA: Prentice-Hall, Inc.

Graham, D., 2000. Going Dry. *Manufacturing Engineering* 124(1): 72-78.

Groover, M.P., 1996. Fundamentals of Modern Manufacturing. Upper Saddle River, New Jersey, USA: Prentice-Hall, Inc.

Gutowski, T., C. Murphy, D. Allen, D. Bauer, B. Bras, T. Piwonka, P. Sheng, J. Sutherland, D. Thurston, E. Wolff, 2001. WTEC Panel Report on Environmentally Benign Manufacturing (EBM). International Technology Research Institute, World Technology (WTEC) Division, Baltimore, Maryland. Available online at http://www.wtec.org/loyola/ebm/ebm.pdf. (Accessed April 3, 2007.)

Gutowski, T., C. Murphy, D. Allen, D. Bauer, B. Bras, T. Piwonka, P. Sheng, J. Sutherland, D. Thurston, and E. Wolff, 2005. Environmentally Benign Manufacturing: Observations from Japan, Europe and the United States. *Journal of Cleaner Production* 13(1): 1-17.

Gutowski, T., J. Dahmus, A. Thiriez, M. Branham, and A. Jones, 2007. A Thermodynamic Characterization of Manufacturing Processes. Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment, Orlando, Florida, USA. May 7-10, 2007: 137-142.

Kalpakjian, S., 1995. Manufacturing Engineering and Technology, Third Edition. Reading, Massachusetts, USA: Addison-Wesley Publishing Company.

Kalpakjian, S. and S. Schmid, 2001. Manufacturing Engineering and Technology, Fourth Edition. Upper Saddle River, New Jersey, USA: Prentice-Hall, Inc.

Kirschner, E.M., 1994. Environment, Health Concerns Force Shift in Use of Organic Solvents. *Chemical and Engineering News* 72(25): 13-20.

Kordonowy, D.N., 2002. A Power Assessment of Machining Tools. Bachelor of Science Thesis in Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

Kurd, M., 2004. The Material and Energy Flow Through the Abrasive Waterjet Machining and Recycling Processes. Bachelor of Science Thesis in Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

Makino, 2005. Available online at http://www.makinoj.co.jp/english/e_product/e_j55.htm. (Accessed April 4, 2007.)

McCoy, J.S., 1994. "Introduction: Tracing the Historical Development of Metalworking Fluids" in Metalworking Fluids, ed. J.P. Byers. New York, New York, USA: Marcel Dekker, Inc.

Munoz, A.A. and P. Sheng, 1995. An analytical approach for determining the environmental impact of machining processes. *Journal of Materials Processing Technology* 53(3-4): 736-758.

Munster, J., 2004. Alcoa Distribution and Industrial Procuts. Personal communication, May 27, 2004.

Nachtman, E.S. and S. Kalpakjian, 1985. Lubricants and Lubrication in Metalworking Operations. New York, New York, USA: Marcel Dekker, Inc.

Oberg, E., F.D. Jones, H.L. Horton, and H.H. Ryffel, 1996. Machinery's Handbook, 25th Edition, ed. R.E. Green. New York, New York, USA: Industrial Press Inc.

Rossmore, L.A. and H.W. Rossmore, 1994. "Metalworking Fluid Microbiology" in Metalworking Fluids, ed. J.P. Byers. New York, New York, USA: Marcel Dekker, Inc.

Sherman, J., B. Chin, P.D.T. Huibers, R. Garcia-Valls, and T.A. Hatton, 1998. Solvent Replacement for Green Processing. *Environmental Health Perspectives* 106(Supplement 1): 253-271.

Sluhan, C.A., 1994. Selecting the Right Cutting and Grinding Fluids. *Tooling and Production* 60(2).

Sluhan, W., 1997. Trample Tramp Oil. *Cutting Tool Engineering* 49(6).

Smil, V., 1999. Energies: An Illustrated Guide to the Biosphere and Civilization. Cambridge, Massachusetts, USA: The MIT Press.

Soković, M. and K. Mijanović, 2001. Ecological aspects of the cutting fluids and its influence on quantifiable parameters of the cutting processes. *Journal of Materials Processing Technology* 109(1-2): 181-189.

Sreejith, P.S. and B.K.A. Ngoi, 2000. Dry machining: Machining of the future. *Journal of Materials Processing Technology* 101(1-3): 287-291.

Stanford, M. and P.M. Lister, 2002. The Future Role of Metalworking Fluids in Metal Cutting Operations. *Industrial Lubrication and Tribology* 54(1): 11-19.

Sutherland, J.W., V.N. Kulur, and N.C. King, 2000. An Experimental Investigation of Air Quality in Wet and Dry Turning. *Annals of the CIRP* 49(1): 61-64.

United States Department of Energy (US DOE), 2006. "Electricity InfoCard 2005," Electricity, Reports, Energy Information Administration. Available online at http://www.eia.doe.gov/neic/brochure/elecinfocard.html. (Accessed April 7, 2007.)

United States Environmental Protection Agency (US EPA), 1995a. Profile of the Nonferrous Metals Industry. EPA Office of Compliance Sector Notebook Project, Report EPA/310-R-95-010. Washington, DC, USA: US Government Printing Office. Available online at http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/nfmetlsn.pdf (Accessed April 5, 2007.)

United States Environmental Protection Agency (US EPA), 1995b. Profile of the Iron and Steel Industry. EPA Office of Compliance Sector Notebook Project, ReportEPA/310-R-95-005. Washington, DC, USA: US Government Printing Office. Available online at http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/iron&stl.pdf. (Accessed April 5, 2007.)

United States Environmental Protection Agency (US EPA), 2007. "Federal Insecticide, Fungicide, and Rodenticide Act," EPA Home, Region 5, About Region 5, Finding Answers, Major Environmental Laws. Available online at http://www.epa.gov/region5/defs/html/fifra.htm. (Accessed April 5, 2007).

Valenite, undated. *Tools for the Real World,* Shop Slide Rule. Troy, Michigan, USA: Valenite Inc.

Williams, E., R.U. Ayres, and M. Heller, 2002. The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices. *Environmental Science and Technology* 36(24): 5504-5510.

Young, J.E., 1992. Mining the Earth, Worldwatch Paper 109. Washington, DC, USA: Worldwatch Institute.

Sherwood, Shannon, and Material Recycling:

Material Recycling at Product End-of-Life

Abstract

This work focuses on developing a compact representation of the material recycling potential of products at end-of-life. This representation is based on two measures: the value of the materials used in a product and the mixture of materials used in a product. These measures are analogous to those used in the Sherwood plot, which relates the price of an individual material to the concentration of that material in the initial mixture of materials from which it is separated. While the Sherwood plot provides insight into the relative attractiveness of isolating different materials, the work here provides insight into the relative attractiveness of recycling different products. This information can be used to help guide both product design and recycling policy.

Keywords: recycling, material separation, mixing, information theory, product design

Material Separation

The ability to isolate a single material from a mixture of materials is critical to many industries, from metal extraction to pharmaceutical production to pollution abatement. In each of these industries, it is the difficulty in separating a single target material from a mixture of materials that largely dictates the market price of the isolated material. A plot demonstrating this relationship between the difficulty of separation, as represented by the concentration of the target material in the original material stream, and the market price of the target material, was first formulated by Thomas Sherwood in 1959 (Sherwood 1959, NRC 1987). This simple relationship between material concentration and material price has been shown to hold true for a diverse set of materials, from virgin metals to biological materials to pollutants (Phillips and Edwards 1976, Chapman and Roberts 1983, NRC 1987, Grübler 1998). An example of the Sherwood plot appears in Figure 1.

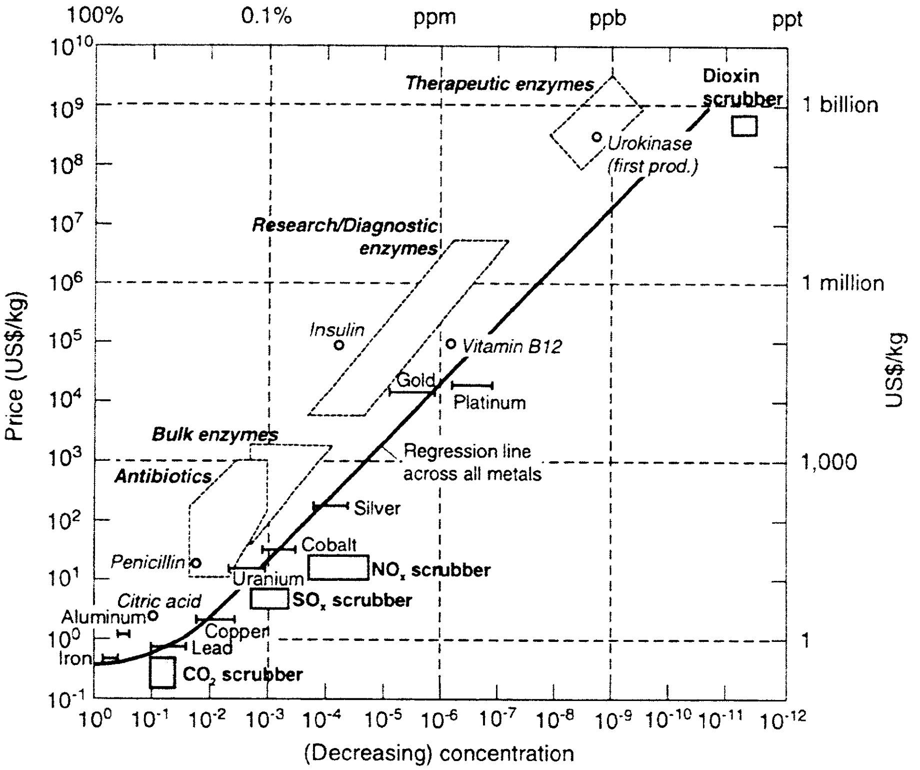


Figure 1: Sherwood plot showing the relationship between the concentration of a target material in a mixture of materials and the market value of the target material. Figure from Grübler (Grübler 1998).

As shown in Figure 1, this simple relationship between the difficulty of material separation and the market price of that material holds true across many different materials and over many orders of magnitude. The underlying explanation is that the market value for a given target material is primarily driven by the amount of material that must be processed in order to isolate the target material.[1] For target materials that occur in low concentrations, relatively large amounts of material must be processed to isolate a given amount of target material. Thus, target materials occurring at low concentrations generally have higher market values. For example, gold, which is found at concentrations on the order of one to five parts per million, has a relatively high market value, as one tonne of ore must be processed to isolate a few grams of gold (Young 1992, Holland and Petersen 1995, Perlez and Johnson 2005). For target materials that occur in high concentrations, relatively small amounts of material must be processed to isolate a given amount of target material. Thus, target materials occurring at high concentrations generally have lower market values. For example, copper, which is found at concentrations on the order of five to ten parts per thousand, has a relatively low market value, as only one kilogram of ore must be processed to isolate five to ten grams of copper (Young 1992, Holland and Petersen 1995, Graedel and Allenby 2003).

The Sherwood plot can also be explained through simple economic models of revenues and costs. In the case of metal separation from ores, profitability requires that revenues from the sale of the target metal exceed the costs of extracting and isolating the metal. Thus, for profitable metal extraction,

$$k_v m_p c_v > k_c m_p \ , \tag{1}$$

where k_v is the market value of the metal ($ per kg of metal),

m_p is the total mass of ore processed (kg of ore),

c_v is the concentration of the metal in the ore (kg of metal per kg of ore), and

k_c is the processing cost per unit mass of ore ($ per kg of ore).

Simplifying (1) yields

$$k_v > \frac{1}{c_v} k_c \ , \tag{2}$$

where the left-hand side of (2) is identical to the ordinate of the Sherwood plot, while the right-hand side of (2) represents the abscissa of the Sherwood plot, $1/c_v$, multiplied by the constant k_c, the processing cost per unit mass of ore.[2] The right-hand side of (2) accounts for the metal extraction costs that scale with the amount of ore processed. In the case of metals, this includes separation costs such as mining and milling costs, but does not include costs such as smelting and refining costs, which do not scale with ore grade (Holland and Petersen 1995). However, as can be seen in Figure 1, the economics of metal separation from ores, and in particular from low-grade ores, is typically dominated by the costs associated with the large material flows required to isolate a given amount of metal.

There are, of course, some exceptions to the Sherwood plot. For example, in the cases of high-grade ores and co-mined metals, metal extraction costs do not scale with the amount of ore processed. With high-grade ores, costs that scale with ore grade do not dominate the cost equation; instead, costs that do not scale with ore grade are of greater importance. For example, the extraction costs for aluminum, which is found in ore grades of 20 to 30%, are dominated not by mining and milling costs, but rather by smelting costs (Young 1992, Holland and Petersen 1995). Thus, aluminum deviates from the other metals on the Sherwood plot, as can be seen in Figure 1.[3] The noticeable curve in the regression line, also shown in Figure 1, captures the fact that at higher concentrations, other costs, besides those that scale with ore grade, are important. With co-mined metals, the fact that multiple metals are extracted from the same ore leads to deviations from the Sherwood plot, as the costs associated with the large material flows are now shared among several metals (Holland and Petersen 1995). For example, cadmium, which is a by-product of zinc refining, has a market value less than what its ore grade would suggest (Phillips and Edwards 1976).[4]

While (1) and (2) focus on the isolation of metals, similar equations can be written for the isolation of other materials, including biological materials and pollutants. Such equations would follow the form of (1) and (2), but would have a different value for the constant k_c, the cost per unit mass of material mixture processed. The Sherwood plot in Figure 1 clearly shows that metals, biological materials, and pollutants all exhibit the same general relationship between concentration and market value. However, the regression line for metals, shown in Figure 1, and the regression lines for other types of materials, are clearly offset from one another. With a regression line above that of metals, biological materials appear to have a higher k_c value; with a regression line below that of metals, pollutants appear to have a lower k_c value.

In short, the Sherwood plot addresses the fundamental relationship between material concentration and material value as it relates to the separation of materials. It can be used to easily assess the relative attractiveness of separating different materials, from mining a metal to isolating a pollutant. The work presented here aims to develop a variant of the Sherwood plot that can be used to assess the relative attractiveness of recycling different products.

Material Recycling for Products

Adapting the Sherwood plot to address product recycling requires some modifications. Unlike scenarios such as metal separation and pollutant extraction, which typically involve the separation of a single target material from a mixture of unwanted materials, the separation of materials from end-of-life products typically involves the separation of multiple target materials, including various metals and plastics. When separating out a single material, as in the Sherwood plot, it is the material concentration that dictates the difficulty of material separation. In separating out multiple target materials, as in the case of material recycling at product end-of-life, it is not the concentration of a single target material, but rather the mixture of materials that determines the difficulty of material separation. In fact, considering common metals and plastics to be target materials, the concentration of target materials in a product is often well over 0.75. Thus, in the case of products, such concentration measurements do not capture the difficulty of material separation, as the difficulty lies both in separating out target materials from waste materials and in separating out target materials from other target materials. For material recycling at product end-of-life, what is needed is a metric, analogous to concentration in the Sherwood plot, that provides a measure of material mixing.

Perhaps the easiest method to measure material mixing would be to simply count the number of materials in a product, M. A product with more materials would have greater material mixing, while a product with fewer materials would have less material mixing. While simple, this metric inevitably leads to questions about how materials are counted, particularly when materials appear in low concentrations. Under this simple counting system, materials that occur in high concentrations are valued identically to materials that occur in low concentrations.

Another means to quantify material mixing is to consider how materials in a product are separated. In most cases, products entering a materials recovery facility (MRF) are first presorted by hand, so that resalable components can be manually removed (US EPA 2005). Following this initial presorting step, sometimes referred to as demanufacturing, products typically undergo a series of shredding and sizing processes, as a means of producing a stream of particles that are uniform in size (Tchobanoglous et al. 1993, McDougall 2001, US EPA 2005). Once these steps are complete, a series of separations take place in order to isolate individual materials (Ibid.). This series of separations can be represented by a branching tree, as shown in Figure 2. Entering the system on the left is a stream of mixed particles; exiting the system are six separated output streams.

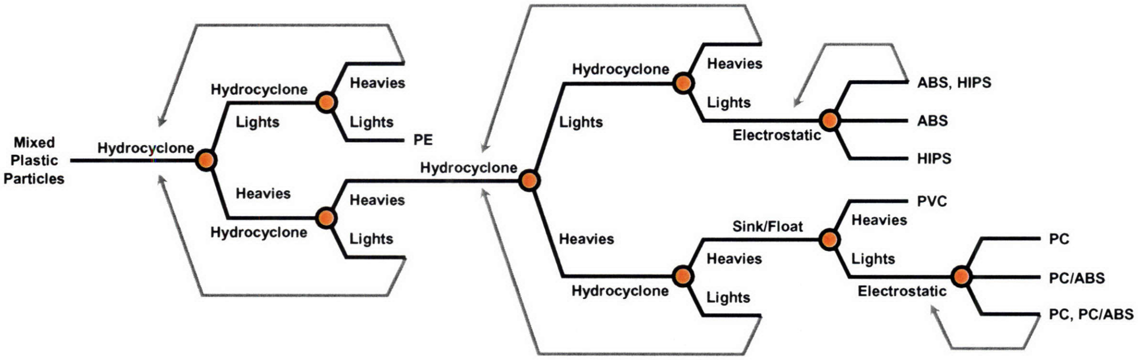


Figure 2: A branching tree showing the material separation steps involved in the plastics recovery module of the Demanufacturing of Electronic Equipment for Reuse and Recycling (DEER2) Project operated by the US Department of Defense. Circles indicate separation steps while arrows indicate reentrant flows of particles of unresolved identity. The plastics that are separated include polyethylene (PE), acrylonitrile/butadiene/styrene (ABS), high impact polystyrene (HIPS), polyvinyl chloride (PVC), polycarbonate (PC), and polycarbonate/acrylonitrile/butadiene/styrene (PC/ABS), a blend of PC and ABS.

While the branching tree shown in Figure 2 deals solely with the separation of mixed plastics, branching trees can also be drawn for the separation of other materials, including metals.[5] It should also be noted that the separation tree shown in Figure 2 represents only one of many possible plastic separation schemes; other schemes, using both different separation steps as well as different ordering of these steps, are also possible (Shent et al. 1999, Sodhi et al. 1999, Jody and Daniels 2006).

In the material separation tree shown in Figure 2, each circle represents a separation step. For any given separation tree, the number of such separation steps could serve as a measure of material mixing. Fewer separation steps would correspond to a product with relatively less material mixing, while more separation steps would correspond to a product with more material mixing. Consider, for example, the case of two hypothetical products with material compositions and material separation schemes as shown in Figure 3. As in Figure 2, in the branching trees shown in Figure 3, shredded materials from end-of-life products enter on the left, while separated materials exit from the final branches. Product A, with two materials, requires only one separation step while Product B, with four materials, requires three separation steps. Thus, using the number of separation steps as a measure of material mixing, the material mixing in Product B would be greater than the material mixing in Product A.

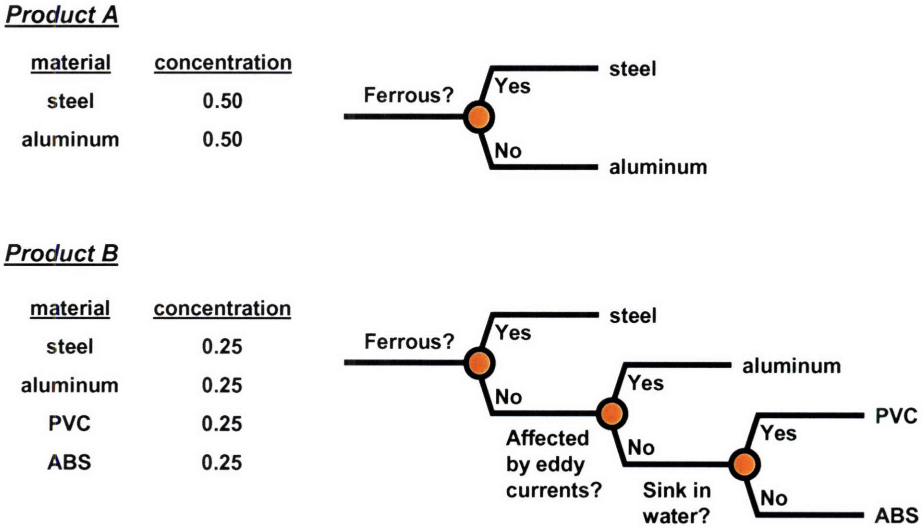


Figure 3: Two hypothetical products along with their respective branching trees for material separation.

In order to use the number of separation steps as a measure of material mixing, a method of counting separation steps must be established. The easiest method would again be based on counting the number of materials in a product; in a product with M materials, $M-1$ separation steps would be required to separate out all the materials. While simple, $M-1$ has the same shortcomings as M. Another approach would be to use the average number of separation steps, $\bar{n}$, calculated using

$$\bar{n} = \sum_{i=1}^{M} c_i n_i \ , \tag{3}$$

where M is the number of materials in the product,

c_i is the concentration of material i, and

n_i is the number of separation steps necessary to isolate material i.

By differentiating between materials, and their associated separation steps, based on their concentrations, this formulation of $\bar{n}$ avoids the material counting problems associated with M-1. At the same time, $\bar{n}$ provides a measure of material mixing.

With this method of measuring material mixing, simple economic models of revenues and costs can be developed to address the economics of material recycling for products at end-of-life. In order for the recycling of a single product to be economically profitable,

$$\sum_{i=1}^{M} m_i k_i > \bar{n} k_n \ , \tag{4}$$

where M is the number of materials in the product,

m_i is the mass of material i (kg),

k_i is the market value of material i (\$ per kg)

$\bar{n}$ is the average number of separation steps, and

k_n is the processing cost per separation step (\$ per separation step).

The left-hand side of (4) represents the revenues from the sale of separated materials extracted from a single product at end-of-life. The right-hand side of (4) represents the processing cost, and is dependent on the average number of separation steps and the processing cost per separation step. Note that (4), which is based on material recycling at product end-of-life, is directly analogous to (2), which is based on the Sherwood plot. In both (2) and (4), the left-hand side is a calculation of material value. The right-hand side is a calculation of processing cost, which is based on both a measure of material mixing ($1/c_v$ and $\bar{n}$) and a cost coefficient (k_c and k_n).

In developing (4), it is assumed that the total processing cost scales with material mixing, as represented by $\bar{n}$. This assumption clearly parallels the critical relationship behind the Sherwood plot, namely that the total processing cost scales with concentration. In the case of material recycling, total processing costs consist primarily of material separation costs and collection costs (Porter 2002). Material separation costs clearly scale with material mixing, as greater material mixing means more capital costs associated with additional separation equipment and more operating costs associated with running such equipment (Ibid.). This relationship between material mixing and material separation costs has also been discussed in the literature (Sodhi et al. 1999). Collection costs can vary greatly, depending on location, infrastructure, and volume. While early cost data suggest that collection costs tend to be slightly larger than material separation costs, these cost numbers generally refer to the collection and processing of relatively simple products, such as cans, bottles, and newspaper, where both material mixing and material separation costs are low (Porter 2002). As the products that are recycled become more complex, and as more material categories are targeted for recovery, material separation costs will increase.

Many of the variables in (4) are relatively straightforward to calculate. Given a bill of materials for a product and material pricing data, the left-hand side of (4) can be calculated. The right-hand side is more difficult to calculate, as it requires information about both the number of separation steps and about the costs that scale with the number of separation steps. While average cost information can be obtained, calculating $\bar{n}$ is more difficult. Calculating $\bar{n}$ for each product requires intimate knowledge of both individual separation processes as well as their sequence within a material separation system. Such information is typically beyond the scope of knowledge for product designers and manufacturers. Furthermore, in many cases, information regarding the sequence of separation steps in a material separation facility is proprietary. Thus, calculating $\bar{n}$ is rarely a straightforward task. However, given a set of reasonable constraints, a result from information theory can provide a simple result that can be used in place of $\bar{n}$.

Information Theory

Information theory was initially developed by Claude Shannon in the 1940s, to better understand and model the behavior of a communication system. A communication system is used to transmit information from a source, where messages are produced, to a destination, where messages are delivered. Between the source and the destination, each message is first encoded into what is known as an object. This object can take many forms, from a series of binary digits in digital communication, to a sequence of dots and dashes in telegraph communication. The object, encoded at the transmitter, is sent through a channel to the receiver, where the object is decoded back into the original message. In this encoding and decoding, some distortions in messages may occur due to noise in the system. A schematic diagram of a general communication system is shown in Figure 4.

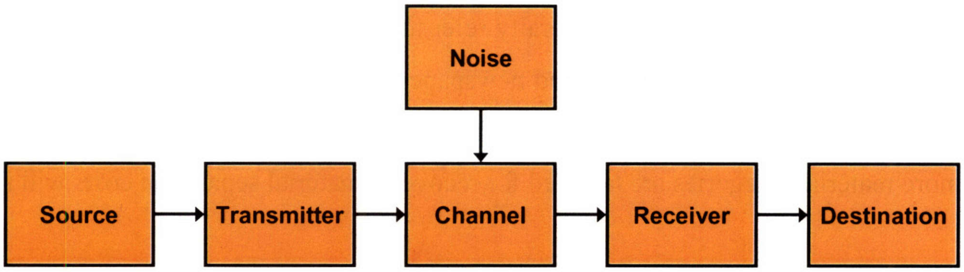


Figure 4: A general communication system. Figure adapted from Ash (Ash 1965).

While the communication system described here may seem to have little to do with recycling, strong analogies can in fact be drawn between the encoding and decoding of messages in communication systems and the manufacturing and recycling of materials in product production systems. In a communication system, messages are encoded into objects at the transmitter; in a product production system, materials are encoded into products at the manufacturer. In a communication system, these encoded messages are passed through a channel, then decoded back into messages at the receiver; in a product production system, these encoded materials are passed through the use phase, then decoded back into materials at the recycler. This analogy is shown in Figure 5. Before further developing this analogy, encoding and decoding in a communication system will first be explained in greater detail.

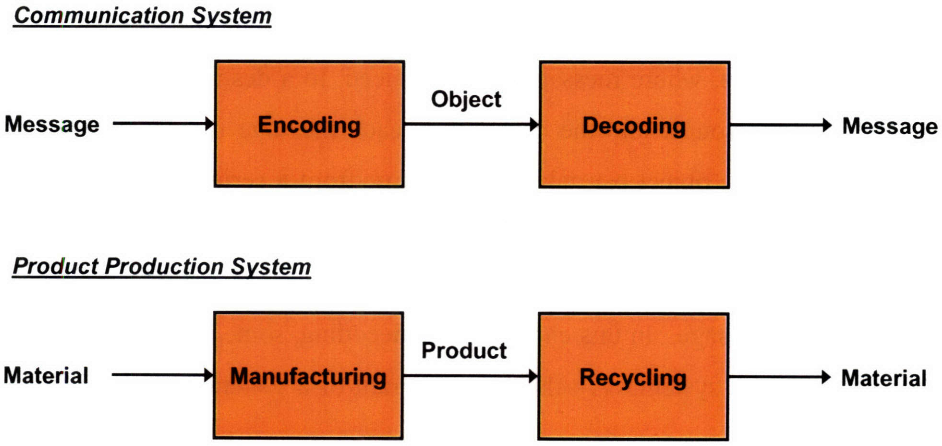
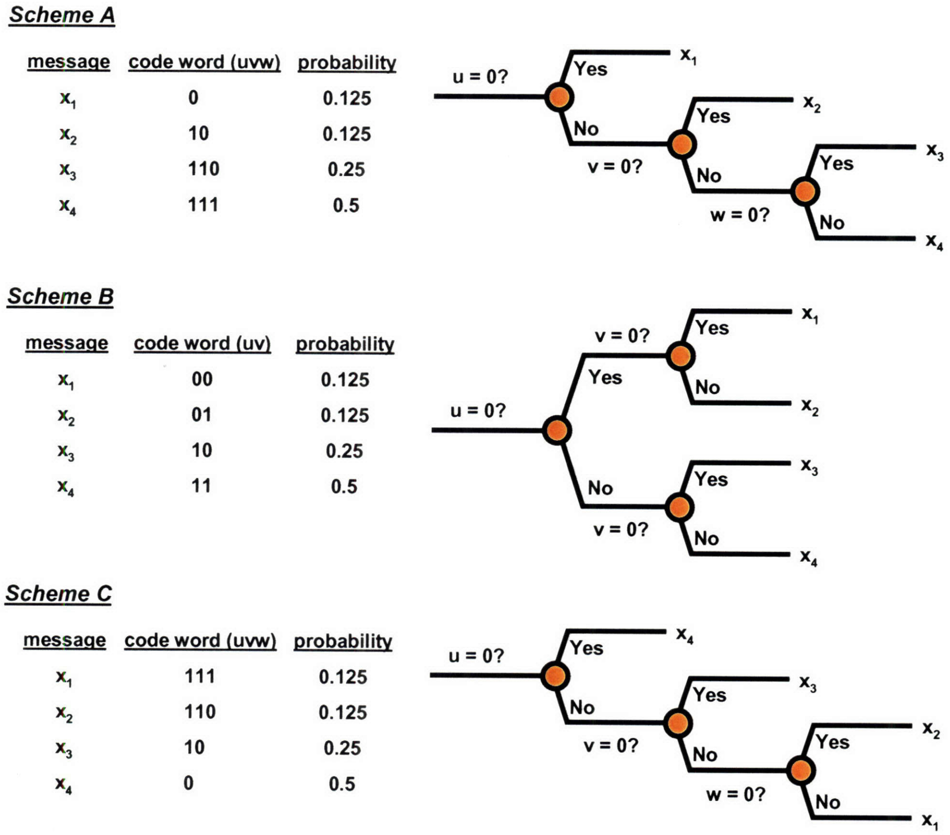


Figure 5: A comparison between a communication system and a product production system.

Encoding and Decoding

Encoding and decoding are critical elements in a communication system, as channel capacity is directly affected by the efficiency of the coding scheme. When messages are encoded for transmission, each message, x_1, …, x_M, is assigned a sequence of code characters. These code characters are taken from a code alphabet, a_1, …, a_D, which can range in size, depending on the code. Each sequence of code characters corresponding to a message is called a code word.

As an example, consider a situation with four messages, x_1, x_2, x_3, and x_4, each of which occurs with a known probability. Using a binary coding scheme, in which the code alphabet consists of only two characters, 0 and 1, each of the messages is assigned a sequence of code characters. Three possible coding schemes, along with their possible decoding trees, are shown in Figure 6.



Scheme A

message	code word (uvw)	probability
x_1	0	0.125
x_2	10	0.125
x_3	110	0.25
x_4	111	0.5

Scheme B

message	code word (uv)	probability
x_1	00	0.125
x_2	01	0.125
x_3	10	0.25
x_4	11	0.5

Scheme C

message	code word (uvw)	probability
x_1	111	0.125
x_2	110	0.125
x_3	10	0.25
x_4	0	0.5

Figure 6: Three possible encoding and decoding schemes used to communicate four messages.

For the coding schemes shown in Figure 4, the average code word length, $\overline{n}$, can be calculated using

$$\bar{n} = \sum_{i=1}^{M} p_i n_i \ , \tag{5}$$

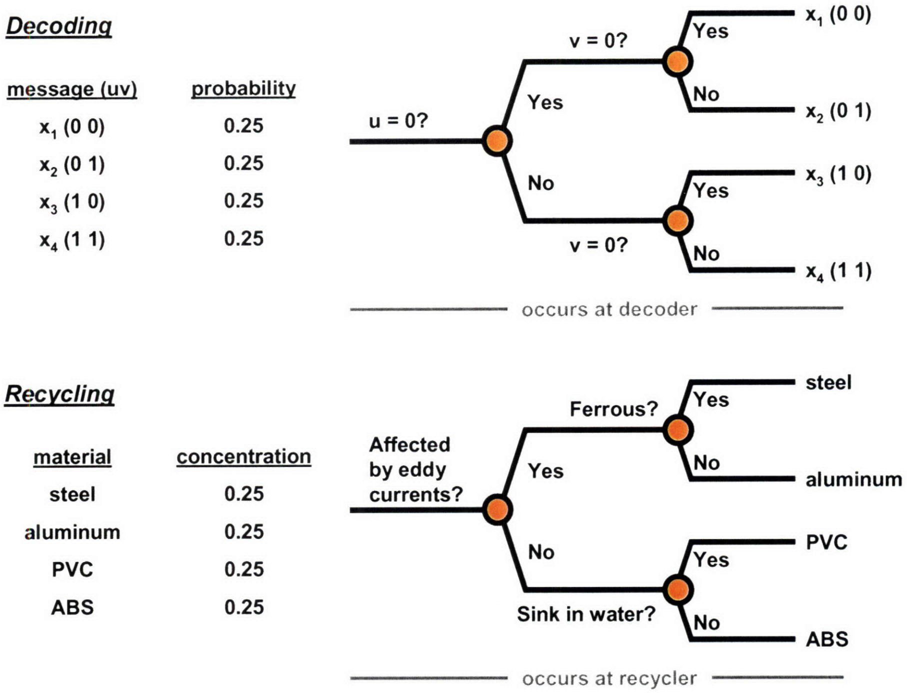
where M is the number of messages,

p_i is the probability of message i, and

n_i is the code word length of message i.

The value of $\bar{n}$ serves as a measure of overall code efficiency. It in fact represents the average number of "yes" or "no" questions necessary to resolve the uncertainty in a message. Thus, for a given set of messages, a smaller $\bar{n}$ indicates that, on average, fewer "yes" or "no" questions are necessary to decode the message. For the three coding schemes shown in Figure 6, $\bar{n}$ is equal to 2.625 for Scheme A, 2.0 for Scheme B, and 1.75 for Scheme C. Thus, of the three coding and decoding schemes shown, Scheme C is the most efficient.

Clear similarities can be seen between (5), which applies to communication systems, and (3), which applies to recycling systems. Both equations determine the average number of binary steps necessary to either decode messages, in the case of communication, or separate materials, in the case of recycling. In both scenarios, branching trees, as shown in Figure 7, are often used to represent the binary steps that occur. In communication, the branching trees represent the procedure necessary to decode messages using a series of "yes" or "no" questions. In recycling, the branching trees represent the procedure necessary to separate materials using a series of binary separation processes. In both cases, a smaller $\bar{n}$ is desirable. In communication, a smaller $\bar{n}$ represents more efficient coding and decoding, and thus greater channel capacity; in recycling, a smaller $\bar{n}$ represents fewer separation steps, and thus lower material separation costs.



Decoding

message (uv)	probability
x_1 (0 0)	0.25
x_2 (0 1)	0.25
x_3 (1 0)	0.25
x_4 (1 1)	0.25

Recycling

material	concentration
steel	0.25
aluminum	0.25
PVC	0.25
ABS	0.25

Figure 7: A comparison of branching trees for message decoding in communication and for material separation in recycling.

Shannon's Noiseless Coding Theorem

Since a smaller value of $\overline{n}$ represents a more efficient coding and decoding scheme, it is important to minimize this value. In attempting to do so, a powerful result known as Shannon's Noiseless Coding Theorem, which provides a lower bound on $\overline{n}$, can be used. Shannon's Noiseless Coding Theorem states that

$$\frac{H}{\log D} \leq \overline{n} \ , \tag{6}$$

where H is a measure of uncertainty,

$\overline{n}$ is the average code word length, calculated using (5), and

D is the size of the code alphabet.

The size of the code alphabet, D, also represents the order of the separation tree. For a binary code alphabet, indicative of separation trees consisting of binary separations, D is equal to two. Given this, and taking logarithms to the base two, (6) can be simplified to

$$H \leq \overline{n} \ . \tag{7}$$

The measure of uncertainty, H, which provides a lower bound on $\bar{n}$, can be calculated using a result from information theory.

As developed in the information theory literature, given a set of possible messages, $x_1, \ldots, x_M$, each occurring with a known probability, $p_1, \ldots, p_M$, the measure of uncertainty, H, about the actual message, should have the following properties (Shannon 1948, Ash 1965):

1. H should be continuous in each probability, p_i.[6]
2. If all probabilities are equal, $p_i = \frac{1}{M}$, H should be a monotonically increasing function of M.[7]
3. H should be additive.[8]

The only equation for H that satisfies these three properties is of the form

$$H = -K\sum_{i=1}^{M} p_i \log p_i \quad , \tag{8}$$

where K is a constant,
M is the number of messages, and
p_i is the probability of message i.

Setting K equal to one, and again taking logarithms to the base two, yields H in bits. A more detailed explanation and derivation of (8) is available in the information theory literature (Shannon 1948, Shannon and Weaver 1964, Ash 1965).

Applying (8) to the encoding and decoding schemes shown in Figure 6 allows the uncertainty, H, of these scenarios to be calculated. For the schemes shown in Figure 6, H is equal to 1.75. Thus, Scheme C, for which $\bar{n}$ is equal to 1.75, is not just the most efficient of the three schemes shown in Figure 6, but is in fact the most efficient coding and decoding scheme possible, given the number of messages and their associated probabilities.

While H provides a lower bound on $\bar{n}$ in communication systems, the goal here is to adapt this result for material systems. Given the analogy between communication systems and product production systems, (8) can be adapted to address material mixing by substituting the probability of a message with the concentration of a material. This yields

$$H = -K\sum_{i=1}^{M} c_i \log c_i \ , \tag{9}$$

where K is a constant,

M is the number of materials, and

c_i is the concentration of material i.

Again, setting K equal to one, and taking logarithms to the base two, yields H in bits. It is interesting to note that the form of (8) and (9) also follows the form of the entropy of mixing equation from thermodynamics, which calculates the entropy generated by irreversibility during the spontaneous mixing of ideal gases under constant temperature and pressure (Gyftopoulos and Beretta 2005). In the entropy of mixing equation, M is the number of gases, while c_i is the mole fraction of material i (Ibid.).

Strong parallels exist between the use of H in communication and the use of H in recycling. In communication, this lower bound, H, represents the minimum average number of "yes" or "no" questions necessary to identify a message. A larger H indicates more uncertainty in the message, and more "yes" or "no" questions to resolve this uncertainty; a smaller H indicates less uncertainty in the message, and fewer "yes" or "no" questions to resolve this uncertainty. In recycling, this lower bound, H, represents the minimum average number of separation steps necessary to identify a material. A larger H indicates greater uncertainty in the material or greater material mixing, and more separation steps to resolve this mixing; a smaller H indicates less uncertainty in the material or less material mixing, and fewer separation steps to resolve this mixing. Thus, in the material analogy to information theory, H is a measure of material mixing.

It should be noted that this measure of material mixing, H, relates to what is perhaps the simplest measure of material mixing, M, the number of materials. In fact, log M is contained in H, and simply represents the case in which all materials occur in equal concentrations. Among the many advantages to using H is the fact that the counting of materials, M, is naturally modulated by the concentration of each material.

Optimal Material Concentrations

As demonstrated above, given a mixture of M materials at known concentrations, Shannon's Noiseless Coding Theorem provides a lower bound on material mixing. However, Shannon's

Noiseless Coding Theorem can also be used to prescribe concentrations for each of M materials so that the mixture is optimal from the standpoint of material separation. Thus, instead of using a mixture of materials to calculate H, H can be used to determine an optimal mixture of materials. This optimal mixture of materials, or optimal code in communication, occurs when equality is reached in (7), meaning that H is equal to $\bar{n}$. Equality occurs when

$$c_i = D^{-n_i} \ . \tag{10}$$

where c_i is the concentration of material i,

n_i is the number of separation steps necessary to isolate material i, and

D is the size of the code alphabet.

Again, for a binary code alphabet, indicative of separation trees consisting of binary separations, D is equal to two.

From (10), it is clear that materials that are easier to separate should be used in higher concentrations, while materials that are difficult to separate should be used in lower concentrations. In fact, (10) provides a guideline for an optimal material mix. For example, for a product containing five materials, x_1, x_2, x_3, x_4, and x_5, with separation steps of n_1, n_2, n_3, n_4, and n_5, the optimal material concentrations, using (10), are given in Table 1.

Materials	Separation Steps n_i	Concentration c_i
x_1	1	0.5
x_2	2	0.25
x_3	3	0.125
x_4	4	0.0625
x_5	4	0.0625

Table 1: Optimal material concentrations for a given set of materials and separation steps.

It is important to note that optimal material mixes and optimal codes are not necessarily feasible. However, these optimal scenarios can serve as targets, allowing information about material separation at end-of-life to influence material selection in product design. In reality, product design typically receives limited input from end-of-life material separation concerns.

Conditions of the Analogy

In applying these results from communication systems to recycling systems, there are a couple of conditions that must be met. The first condition is that the materials that are separated must be of equal interest. This condition is met through the goal of separating out all materials for which recycled material markets exist. With markets for recycled materials growing in both scale and scope, and with landfill tipping fees increasing, the goal of separating out all materials is not unreasonable (Porter 2002). There are of course some scenarios in which only a few select materials from a product are of interest. These cases, as will be explained later, are not addressed by the model developed here. The condition of equal interest is also met in part through presorting steps, in which resalable components or subassemblies that are processed separately are removed from end-of-life products. Once these components are removed, the remaining materials in the product can be separated. While the reuse and resale of components is an important end-of-life option, it is different from the end-of-life material recycling issues addressed by this model. However, it is important to point out that the viability of component recycling is due in part to the viability of material recycling, as the sale of components leaves the remainder of the product to be handled in a cost-effective manner (Isaacs and Gupta 1997).

The second condition involves the nature of the material separation processes used. In order for the analogy with communication systems to work, the costs associated with each separation step must be similar. This condition means that k_n, the processing cost per separation step, as seen in (4), and k_b, the processing cost per bit, as seen later in (11), are indeed constants. While this condition may seem unreasonable given the wide range of material separation processes that exist, a similar condition is used to derive (1) and (2) for the Sherwood plot. In the case of metal extraction in the Sherwood plot, despite the many different types of separation and purification processes, k_c, the processing cost per unit mass of ore, is a constant. Thus, similar conditions are applied here in the case of material recycling. In general, this condition regarding processing costs is reflected in part by the material counting scheme used, which tends to focus on broader material categories, categories that can be isolated through separation methods of comparable cost.[9] This and other issues related to material counting will be addressed later, in greater detail.

Product Data

The results from information theory can now be incorporated into the simple economic models developed earlier for material recycling at product end-of-life. In particular, (4) can be rewritten as

$$\sum_{i=1}^{M} m_i k_i > H k_b \tag{11}$$

where M is the number of materials in the product,

m_i is the mass of material i (kg),

k_i is the market value of material i (\$ per kg)

H is a measure of material mixing, and

k_b is the processing cost per bit (\$ per bit).

In (11), H replaces $\bar{n}$ as a measure of material mixing. For products in which the inequality in (11) is met, material recycling at product end-of-life would be economically profitable. For products in which the inequality in (11) is not met, material recycling at product end-of-life would not be economically profitable.

To test the effectiveness of (11) in determining the recycling potential of products, 23 common products are analyzed. For each product, the potential revenue from recycling the materials in a single product is calculated using the left-hand side of (11), while material mixing for a product, represented by H, is calculated using (9). These values for each product are plotted in Figure 8. Note that Figure 8, much like the Sherwood plot in Figure 1, plots material value versus a measure of material mixing.

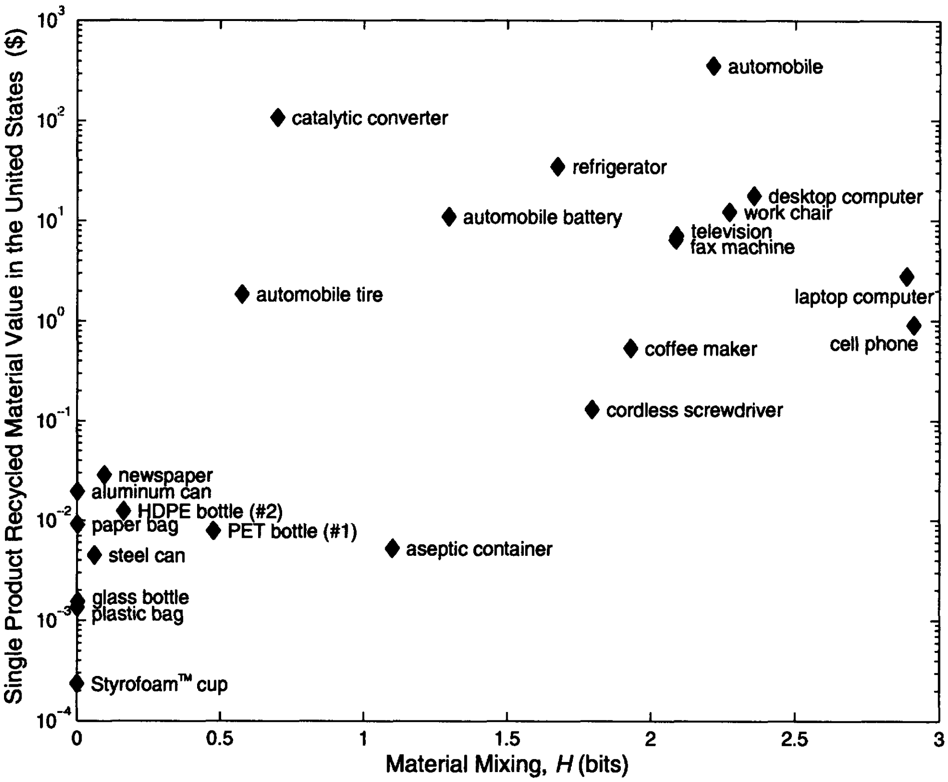


Figure 8: Single product recycled material value in the US ($\Sigma m_i k_i$) versus material mixing (H) for 23 products.

The values used to create Figure 8 are provided in Table 2. The value of the recycled materials in each product, $\Sigma m_i k_i$, is calculated using a bill of materials, which provides m_i, and price data for recycled materials, which provides k_i.[10] Values for H are calculated using the same bill of materials for the product and (9). Thus, calculating the values plotted in Figure 8 requires only a bill of materials, with part composition and mass data, and market data for recycled materials. No knowledge of recycling systems or separation techniques is necessary.

Product	$\Sigma m_i k_i$ ($)	H (bits)	Recycling Rate
automobile battery	$ 10.95	1.30	96%
automobile	$ 358.61	2.22	95%
catalytic converter	$ 107.54	.699	95%
refrigerator	$ 34.69	1.67	90%
newspaper	$ .028	.095	70%
automobile tire	$ 1.85	.575	66%
steel can	$ .004	.060	63%
aluminum can	$ .019	.001	45%
HDPE bottle (#2)	$ .012	.163	27%
PET bottle (#1)	$ .008	.476	23%
paper bag	$ .009	.001	21%
glass bottle	$ .002	.003	20%
desktop computer	$ 17.69	2.36	11%
television	$ 7.05	2.09	11%
laptop computer	$ 2.79	2.89	11%
aseptic container	$ .005	1.10	6%
plastic bag	$ .001	.001	5%
cell phone	$ .908	2.91	1%
work chair	$ 12.19	2.27	0%
fax machine	$ 6.43	2.09	0%
coffee maker	$ .535	1.93	0%
cordless screwdriver	$ .130	1.80	0%
Styrofoam™ cup	$ .0002	.000	0%

Table 2: Product data used in Figure 8. Bills of materials and recycling rates for the products examined here come from various sources, as noted in the "Product References" section. Market price data for recycled materials, k_i, reflects market prices on March 19, 2007 (Recycler's World 2007, Kitco 2007).[11] Recycling rates are for the US.[12]

While the calculations behind Figure 8 are relatively straightforward, the real issue is whether or not such an approach has the ability to differentiate between products that are economically worthwhile to recycle and those that are not. In general, products that are economically worthwhile to recycle would have high recycled material value and low material mixing. Such products would tend to fall in the upper-left of Figure 8. Products that are not economically worthwhile to recycle would have low recycled material value and high material mixing. Such products would tend to fall in the lower-right of Figure 8. Re-plotting Figure 8, such that the recycling rate in the US is represented by the area of the circle surrounding each data point, shows that this simple method based on recycled material value and material mixing has a strong ability to distinguish between those products that are economically worthwhile to recycle and those that are not. From Figure 9, it is clear that products with higher recycling rates in the US, meaning that they are generally economically worthwhile to recycle, tend to fall in the upper-left, having both higher recycled material value and lower material mixing. Products with lower recycling rates in the US, meaning that they are generally not economically worthwhile to recycle, tend to fall in the lower-right, having both lower recycled material value and higher material mixing. Between these two categories of products, an apparent recycling boundary can be drawn. In the region in which *H* is greater than 0.5, this apparent recycling boundary divides products with recycling rates between 0 and 11% from products with recycling rates between 66 and 96%.[13]

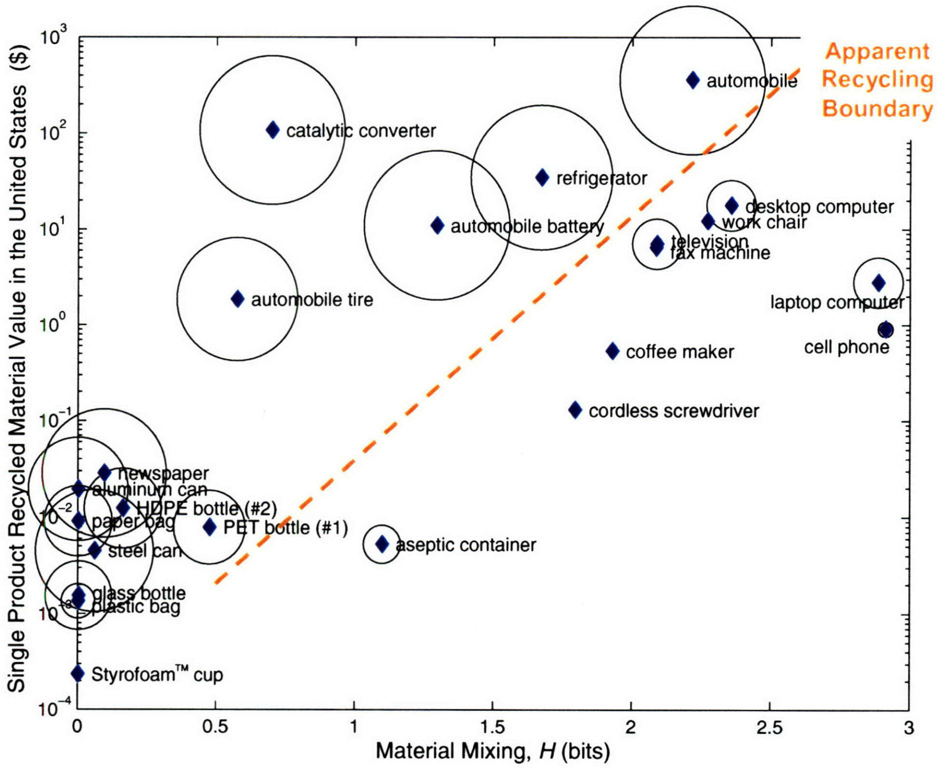


Figure 9: Single product recycled material value in the US ($\Sigma m_i k_i$) versus material mixing (*H*) for 23 products. The area of the circle surrounding each data point represents the recycling rate in the US for that product.

The ability to differentiate between products that are economically attractive to recycle and those that are not, is perhaps more clearly seen in Figure 10. Plotting Figure 8 on a three-dimensional plot, where recycling rate in the US is represented on the third axis, again shows the ability of two simple measures, namely recycled material value and material mixing, to differentiate between products. This plot also clearly shows the discontinuity in recycling rates across the apparent recycling boundary, particularly for products with values of *H* greater than 0.5. The category of products with *H* less than 0.5, will be discussed in greater detail later.

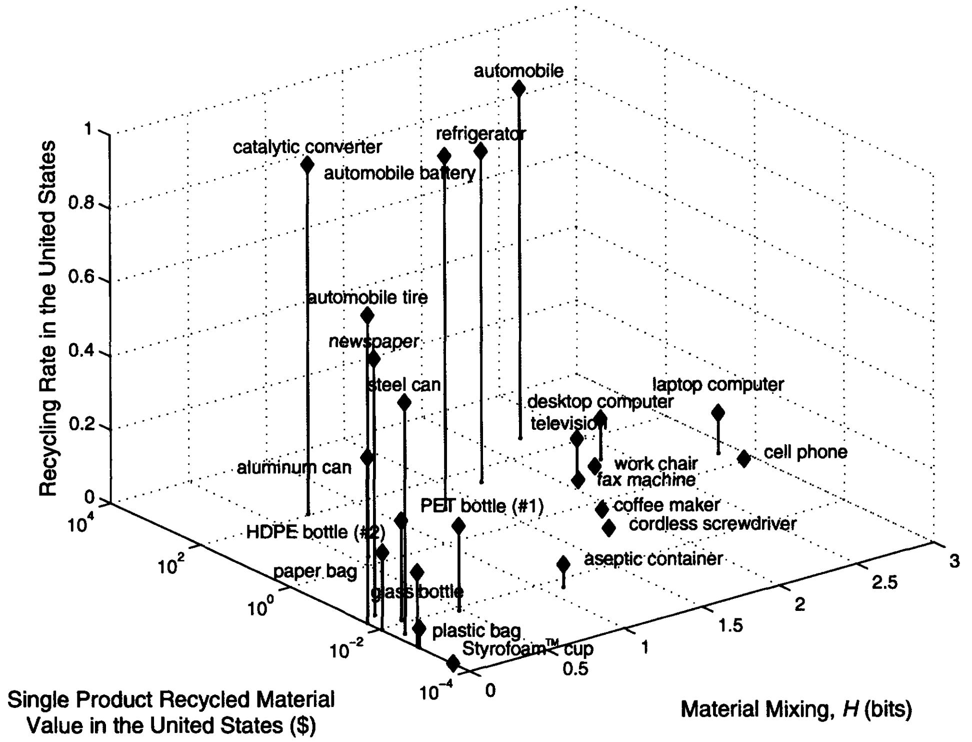


Figure 10: Single product recycled material value in the US ($\Sigma m_i k_i$) versus material mixing (H) versus recycling rate in the US for 23 products.

Material Counting

In the calculation of both the value of the recycled materials and the measure of material mixing, it is important that the material counting scheme remains consistent. The 25 materials considered (24 materials and one "other"), shown in Table 3, were chosen both because of the fact that they can be separated from one another, and because of the fact that if they are separated, markets for such recycled materials exist. Thus, material counting is dependent on both the physics of separation processes as well as the economics of secondary material markets. The material categories are intentionally broad, again due to the limitations of the separation process, which, while capable of separating steel from aluminum, would have a more difficult time separating one alloy of aluminum from another. The list of materials shown in Table 3 is also quite extensive, including many of the materials commonly found in products. In fact, as can be seen in Table 4, the concentration of valuable materials in the products analyzed here, where valuable materials are considered to be all materials besides the "other" category, are all above 70% and, in many cases, above 95%.

Non-Precious Metals	**Precious Metals**	**Plastics**	**Non-Metal, Non-Plastic**
aluminum	gold	acrylonitrile/butadiene/styrene (ABS)	glass
copper	palladium	polyamide (PA)	paper
iron	platinum	polycarbonate (PC)	rubber
lead	rhodium	polyethylene (PE)	other
nickel	silver	polyethylene terephthalate (PETE)	
steel		polypropylene (PP)	
tin		polystyrene (PS)	
zinc		polyvinyl chloride (PVC)	

Table 3: Material counting scheme used to generate data in Table 2 and in Figures 8, 9, and 10.

Each material that is identified in Table 3, is separated out in a material recycling system. Thus, in a branching tree diagram for material separation, as seen in Figures 2 and 3, each material listed in Table 3 would constitute a separate terminal branch on the tree. Any materials that are not specifically listed in Table 3 are considered to be "other". This "other" category generally includes materials for which no secondary markets exist, meaning that separation of such a material would be unlikely. In some cases, materials that are a part of this "other" category represent a cost, as disposal is required.

Product [illegible]	**c_v**
aluminum can	100%
aseptic container	100%
glass bottle	100%
HDPE bottle (#2)	100%
paper bag	100%
PET bottle (#1)	100%
plastic bag	100%
steel can	100%
Styrofoam™ cup	100%
newspaper	99%
automobile tire	98%
desktop computer	98%
cordless screwdriver	97%
coffee maker	95%
work chair	94%
laptop computer	88%
refrigerator	88%
automobile	86%
television	84%
catalytic converter	82%
fax machine	78%
cell phone	73%
automobile battery	70%

Table 4: Products and their concentration of valuable materials, c_v.

While the material list shown in Table 3 is critical to the results presented in Table 2 and in Figures 8, 9, and 10, other material lists, either more detailed or less detailed, could have instead been used, with limited changes to the values for material mixing, *H*. Figure 11 illustrates this concept by calculating material mixing values for four different products using four different material counting schemes. The material counting schemes used, which include a low-level material decomposition (four materials), a mid-level material decomposition (ten materials), a high-level material decomposition (25 materials), and an ultra high-level material decomposition (40 materials), are presented in Table 5. From Figure 11, it appears that once approximately ten materials are counted, the relative results, in terms of material mixing, remain unchanged. Also, at higher levels of material decomposition, it appears that material mixing values for a given product may in fact converge.

Low-level	Mid-level	High-level	Ultra High-level
ferrous metals	aluminum	aluminum	aluminum
non-ferrous metals	copper	copper	antimony
plastics	iron	gold	beryllium
other	lead	iron	brass
	nickel	lead	cadmium
	steel	nickel	chromium
	tin	palladium	cobalt
	zinc	platinum	copper
	plastics	rhodium	gold
	other	silver	iron
		steel	lead
		tin	magnesium
		zinc	mercury
		acrylonitrile/butadiene/styrene (ABS)	nickel
		polyamide (PA)	palladium
		polycarbonate (PC)	platinum
		polyethylene (PE)	rhodium
		polyethylene terephthalate (PETE)	silver
		polypropylene (PP)	stainless steel
		polystyrene (PS)	steel
		polyvinyl chloride (PVC)	tin
		paper	zinc
		glass	acetal
		rubber	acrylic resin
		other	acrylonitrile/butadiene/styrene (ABS)
			epoxy resin
			phenolic resin
			polyamide (PA)
			polycarbonate (PC)
			polyethylene (PE)
			polyethylene terephthalate (PETE)
			polymethyl methacrylate (PMMA)
			polyoxymethylene (POM)
			polypropylene (PP)
			polystyrene (PS)
			polyvinyl chloride (PVC)
			paper
			glass
			rubber
			other

Table 5: Four different material counting schemes used to generate Figure 11.

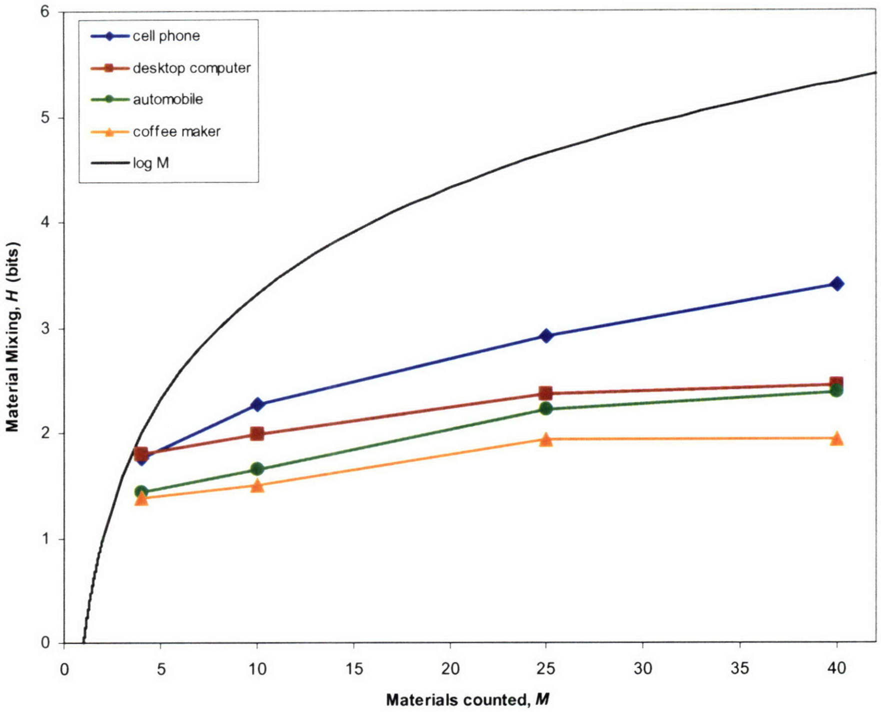


Figure 11: Material mixing, *H*, versus materials counted, *M*, for four different material counting schemes. The upper line, log *M*, represents the case in which all materials occur in equal concentrations, and thus provides an upper limit on material mixing values.

While material mixing values may be relatively unaffected by the material counting scheme used, single product recycled material value calculations may change more noticeably. In particular, the inclusion of precious metals such as gold and platinum, can have important effects on the material value calculation. For example, in the case of the desktop computer, under the high-level material counting scheme, the material value is $17.69. However, excluding precious metals, namely gold and silver, from the material counting scheme, results in a material value of only $6.29, a 64% drop in value. At the same time, including or excluding these small fractions of precious metals have little effect on *H*. In the scenario with precious metals, *H* for the desktop computer is 2.357, while in the scenario without precious metals, *H* is 2.355.

In selecting an appropriate material counting scheme, it is important to consider actual recycling processes and actual markets for secondary materials. In general, the level of material decomposition should correspond to both the separation capabilities of the recycling system and the marketability of the recycled material streams.

Product Variability

It is also important to note that while the product data shown in earlier figures and tables presents exact values for H and single product recycled material value, there is typically a range of designs for any given product, and thus a range of values. As an example, consider again the desktop computer. Based on one bill of materials, H for a desktop computer is 2.36 and the single product material value is \$17.69.[14] These values are used in Table 2. However, using a different bill of materials, H for a desktop computer is 2.56 and the single product material value is \$19.11.[15] While these values are clearly comparable, a third bill of materials for a desktop computer lists over three grams of gold.[16] With gold values around \$15 per gram, the single product recycled material value for this desktop computer is upwards of \$50, clearly moving it closer to the apparent recycling boundary. These large variations in bills of materials may be due to a variety of reasons, including differences between manufacturers and between models. Such variations could also be attributed to different manufacturing dates of the products, an issue that will be addressed in greater detail later. The main point, however, is that the precise product values listed in Table 2, while accurately showing representative products, do not show the range of values that exist for any given product type.

Special Material Categories

The issue of special material categories, including resalable components, independently-processed subassemblies, and hazardous materials, is also important to address. The products analyzed above are assumed to go through a manual presorting operation prior to shredding and separation. In this presorting operation, resalable components and independently-processed subassemblies may be removed from certain products. For example, in the recycling of laptop computers, cell phones, and cordless screwdrivers, batteries would typically be removed in the presorting step. Thus, batteries are not included in the bills of materials for these products. While some of the batteries that are removed during presorting may find their way to secondary markets, others will be processed in material recovery facilities specifically designed to process batteries. In the case of automobile processing, batteries, tires, and catalytic converters are typically removed prior to shredding. Thus, these components are not included in the bill of materials for the automobile, but are instead analyzed on their own. In this case, as in the case of batteries, these components or subassemblies can be sold into secondary markets or, more likely, processed for material recovery. It is also important to point out that these automobile components, particularly batteries and tires, are often purchased and retired independently from the automobile.[17]

For some products, the presence of hazardous materials can be an important issue in end-of-life material recycling. For example, some materials in batteries, including lead and nickel, are considered hazardous (US EPA 2006a). At the same time, these materials, if they can be safely separated, have considerable value on the secondary material market. There are of course other examples, such as refrigerants in refrigerators and electrolytes in automobile batteries, for which secondary material market values are low or, in some cases, negative, meaning that money must be paid to properly dispose of such materials. In these cases, the cost of both separating out and disposing of hazardous materials could clearly make recycling less economically attractive. For the purposes of the analysis conducted here, hazardous materials that are not part of the 24 materials listed in Table 3, are considered to be part of the "other" category of materials. While this does have the potential effect of grouping together hazardous and non-hazardous materials, it does provide a simple material counting scheme. Alternatively, a more-detailed analysis, splitting the "other" material category into "other-hazardous" and "other-non-hazardous", could have been used. Using such a material counting scheme, H values for refrigerators would increase from 1.67 to 1.72, while H values for batteries would increase from 1.30 to 1.31. Clearly, the effect of this change on material mixing values is small.[18]

Simple Products

Figures 9 and 10 show the strong ability of two simple measures, namely material mixing and material value, to differentiate between products that are economically attractive to recycle and those that are not. While an apparent recycling boundary can be clearly drawn for more materially complex products, namely products with higher material mixing values, there appears to be less differentiation for more materially simple products. These simple products cluster in the lower left of Figures 8 and 9, having both low recycled material value and low material mixing. Most of these products, many of which are containers for products, are primarily composed of a single material, and thus have relatively low material mixing values, generally less than 0.5.[19] These single-material products stray from the general assumptions set forth earlier. In particular, the assumption that total processing costs scale with material mixing is brought into question, as other costs, including collection costs, begin to play a more important role. The assumption that products have multiple target materials is also no longer valid, as these simple products generally have only a single target material. While the separation of a single target material does fall within the realm of the Sherwood plot, in the case of these simple products, the concentration of this single target material is quite high. In the Sherwood plot, the concentration of target material is generally significantly lower.

Clear parallels can be drawn between the behavior of the Sherwood plot at high concentrations, and the behavior of the model presented here at low material mixing. In the case of the Sherwood plot, processing costs scale with concentration, except at higher concentrations, where other costs begin to come into play. In the case of the model developed here, processing costs scale with material mixing, except at lower mixing values, where other costs begin to come into play. These limitations on the various models will be discussed in greater detail in the next section.

Sherwood-Shannon Continuum

The measure of material mixing developed here addresses material mixtures that are both concentrated, in terms of valuable material, and materially complex, conditions that generally apply to products. The Sherwood plot, on the other hand, addresses material mixtures that are dilute, in terms of valuable materials, and materially simple, conditions that generally apply to ores, among other materials. At the intersection of these two scenarios, lie material mixtures that are concentrated and materially simple, such as single-material products, as described earlier, and high-grade ores, such as iron and aluminum. Figure 12 plots material mixing, H, versus the concentration of valuable material, c_v, for both products and ore deposits. For products, values for H and c_v come from Tables 2 and 4, respectively. For ore deposits, H is calculated as it would be for products, where each ore type is counted as a separate material, and the gangue is counted as a single material. For c_v, the mass of valuable ore is divided by the total mass of material processed. In calculating H and c_v for ore deposits, data from mineral deposit models are used (Cox and Singer 1986).[20]

The regions in which each method is effective are indicated on Figure 12. The designation of "Shannon" refers to the method developed here to address material mixing in products. This approach can be applied to complex material mixtures that have high concentrations of valuable material. The designation of "Sherwood" refers to ores and other dilute material mixtures, as addressed in Figure 1. This approach can be applied to simple material mixtures that have low concentrations of valuable materials. The third region, labeled "Concentrated and Materially

Simple", refers to a category that is neither Shannon nor Sherwood, and represents an area that challenges the limits of both approaches. This region features H values less than 0.5 which, as mentioned earlier, are less predictive than higher H values; thus, this region falls outside the domain of the Shannon model. This region also features c_v values greater than 1 to 10% which, as can be seen in Figure 1, are less predictive than lower c_v values; thus, this region also falls outside the domain of the Sherwood model. This region of "Concentrated and Materially Simple" mixtures represents an area of future research.

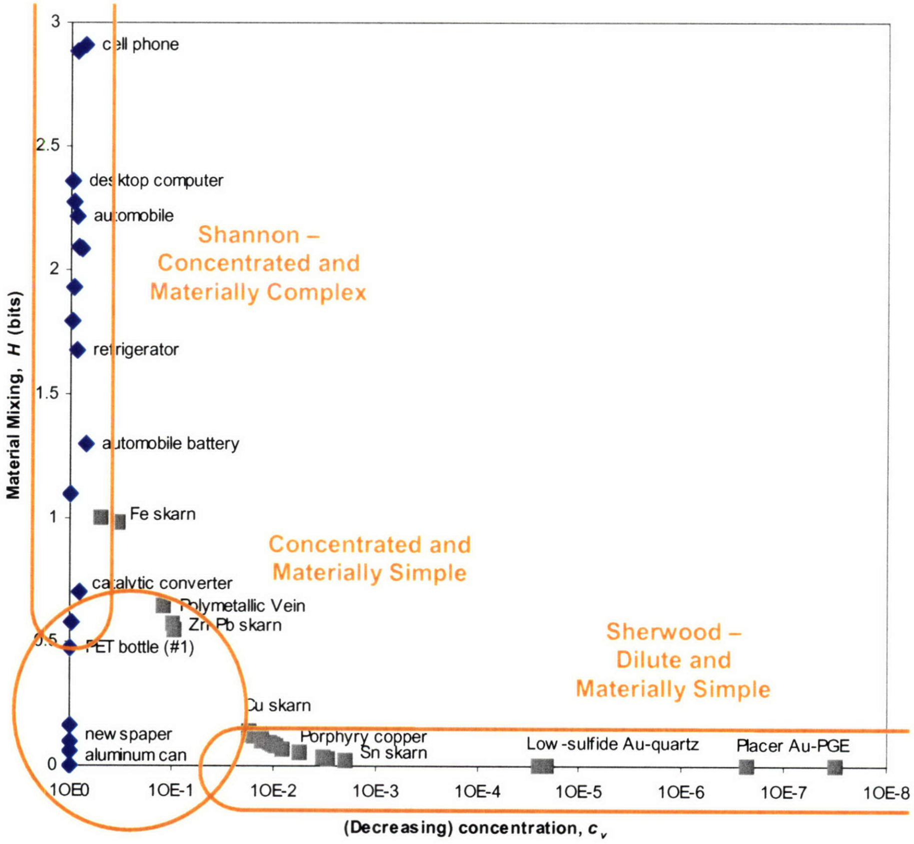


Figure 12: Material mixing, H, versus the concentration of valuable materials, c_v. Data points shown as blue diamonds represent product data, while data points shown as grey squares represent ore deposit data. Select data points are labeled with the names of products, as in previous figures, or names of mineral deposit models, as per Cox and Singer (Cox and Singer 1986).

It is important to point out that some products, given a limited material counting scheme, can fall in the Sherwood region of Figure 12, making them more directly comparable to ores. For example, consider a very simple material counting scheme that consists of only two materials, precious metals and not precious metals. Using this binary material counting scheme on a product such as a cell phone, which has a small but valuable concentration of precious metals, results in an H of 0.048 and a c_v of around 5 x 10^{-3}. These values put cell phones, given a two-material counting scheme, in the Sherwood region. Other products, including catalytic converters, also fall into the Sherwood region when a two-material counting scheme is used. In the case of catalytic converters, counting only precious metals and not precious metals results in an H of 0.0080 and a c_v of around 7 x 10^{-4}. For both of these products, precious metals account for over 75% of the total recycled material value.

While the assumption behind the measure of material mixing for products is that all materials are of interest, there are scenarios, as described above, in which only a few materials may be of interest. Such situations can occur in products that contain a small concentration of highly valuable materials. In general, however, many products have a number of materials that have value, and are thus of interest to recyclers. Also, in scenarios in which only a single low-concentration material is targeted, the amount of non-target material that must be disposed of can be considerable.

Design and Recycling Trends

The results shown in Figure 9 and 10, suggest that there is an apparent recycling boundary between those products which are economically worthwhile to recycle and those that are not. This boundary clearly shows that society recycles products with high value and low mixing, and ignores products with low value and high mixing. These parameters, material value and material mixing, are both specified in design. Thus, the recycling potential for products is a function of design, and can be varied through design activities such as material selection.

It is important to note that just as the recycling potential for products can change depending on material choices, the apparent recycling boundary can also change, depending on recycling technology. As recycling technologies improve, k_b, the processing cost per bit, decreases. Reductions in cost could help to drive the apparent recycling boundary towards the lower right, thus making the recycling of additional product types economically viable. In fact, some of the products close to the apparent recycling boundary, in particular desktop computers, are increasingly discussed as potential candidates for wider-scale recycling. However, while recycling technologies may be improving, design trends seem to be pushing products towards lower material value and greater material mixing. Designers are constantly motivated to reduce material costs in products, either by using less material or by using less-expensive materials. At the same time, materials are being used in new and different applications, presenting designers with an increasingly wider selection of potential materials.

These trends in product design can be seen in Figure 13. Historical data for refrigerators and automobiles show general trends towards greater material mixing. It is interesting to note that in the case of automobiles, sport utility vehicles (SUVs) seem to move against this general trend. This is due in part to the fact that SUVs have higher concentrations of certain materials, namely steel and aluminum, than do typical automobiles, thus resulting in lower material mixing. SUVs also have considerably more material than automobiles, 1500 kg for a 2000 automobile versus almost 2000 kg for a 2000s SUV, and thus greater material value. Figure 13 also shows differences in electronic products, comparing desktop computers to laptop computers. As consumer electronics continue to get smaller, there seems to be little chance that an effect similar to the SUV effect seen in automobiles, will occur.

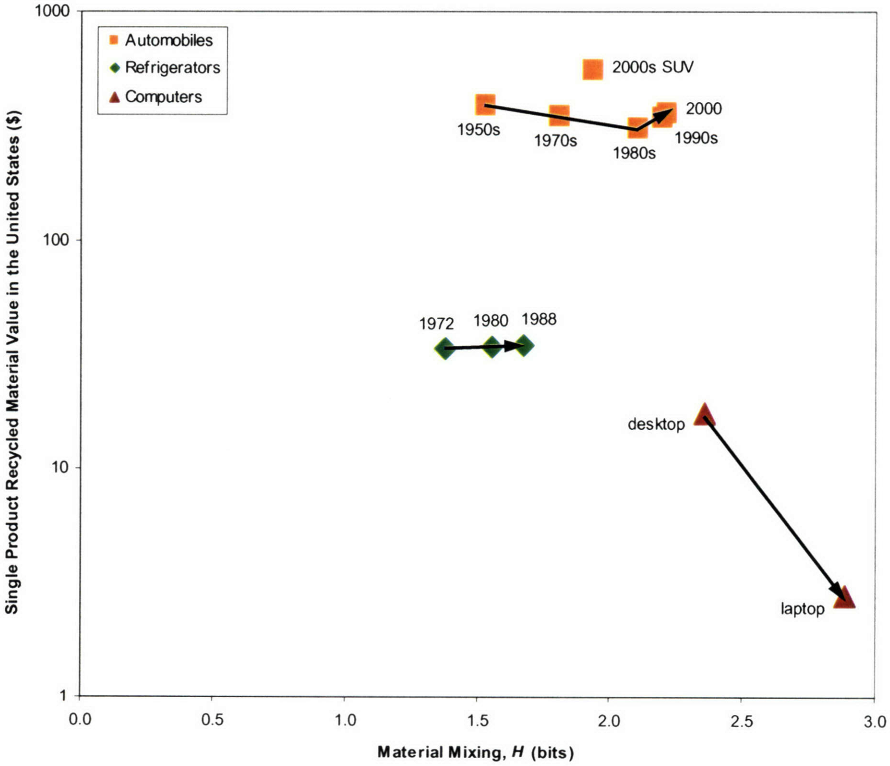


Figure 13: Design trends in refrigerators, automobiles, and computers.

In short, while recycling technologies are moving the apparent recycling boundary towards the lower right in Figure 9, design engineers are also moving products in the same direction. These competing trends are alarming, particularly when one compares the significant resources spent on design to the more modest resources spent on recycling.

In terms of recycling policy, the work presented here does provide some insights into possible policy approaches. Having identified an apparent recycling boundary between those products that are economically worthwhile to recycle and those that are not, different policy options may exist to either move the boundary or move products across the existing boundary. One potential approach would be to move the recycling boundary towards the lower right, perhaps through funding more research and development in the area of recycling technologies. Such work would hopefully serve to lower k_b, the processing cost per bit, thus making more products economically worthwhile to recycle. Another potential approach involves attempting to reduce material mixing in products, thereby moving products to the left. While attempting to legislate the mix of materials in a product would be unreasonable, legislating extended producer responsibility, in which product manufacturers are responsible for their products at end-of-life, could serve to increase the importance of recycling and material separation issues during initial product design. Such an emphasis could lead to reductions in material mixing, among other changes. A final approach would be to put incentives in place to encourage the recycling of products that, on a material value basis, are not economically worthwhile to recycle. For example, for products falling below the apparent recycling boundary, subsidies could be offered such that the total revenue potential, composed of material value and subsidy, would make the product worthwhile to recycle. Theoretically, if the apparent recycling boundary could be definitively plotted, the exact subsidy amount necessary to make recycling economically worthwhile could be calculated for each product. It is important to point out that these approaches focus on improving the economics of recycling, which, while critical to a viable recycling system, is concerned only with the private benefits of recycling, ignoring possible environmental and social benefits (Porter 2002).

Conclusion

This work presents a compact means by which the material recycling potential of products at end-of-life can be evaluated. This method is based on two measures: the value of the materials used in a product and the mixture of materials used in a product. The insights provided by this approach can be applied to help guide design and policy decisions related to recycling.

Notes

1. This explanation assumes that the market price is directly proportional to cost, an assumption that is used throughout this explanation of the Sherwood plot.

2. The abscissa in the Sherwood plot shown in Figure 1, is in fact c_v, not $1/c_v$. However, using c_v, along with a graph containing numbers less than one, and using $1/c_v$, along with a graph containing numbers greater than one, are equivalent. For example, for a concentration of one part in 1000, c_v is 1/1000 or 10^{-3}, while $1/c_v$ is 1000 or 10^3. Thus, the abscissa in Figure 1 could have instead used $1/c_v$, which would make the exponents in the axis labels positive, but would otherwise leave the plot unchanged

3. Other metals, for example titanium, also deviate for the same reason as does aluminum, namely high smelting costs (Holland and Petersen 1995).

4. On the version of the Sherwood plot shown in Figure 1, there are other metals that, despite being co-mined, do not appear to be outliers. In particular, cobalt, which is a by-product of nickel refining, and silver, which is often co-mined with copper, zinc, and lead, fall squarely on the regression line (Phillips and Edwards 1976, Holland and Petersen 1995). Figure 1, by Grübler, adapted the metal data from Holland and Petersen, who in turn gathered their metal data from Cox and Singer (Cox and Singer 1970, Grübler 1998, Holland and Petersen 1995). Following this chain of references, it appears that the ore grades for cobalt and silver, as identified by Holland and Petersen, are generally at the higher end of the range of values presented by Cox and Singer (Cox and Singer 1970, Holland and Petersen 1995). Perhaps this optimistic take is meant to reflect scenarios in which cobalt and silver are the primary target metals, as opposed to scenarios in which they are by-product metals. Whatever the reason, the result is that the range of ore grades shown for cobalt and silver in Figure 1, tend to be slightly high. Lower ranges of ore grades, which would move cobalt and silver to the right in Figure 1, would result in market values less than what their respective ore grades would suggest. Such deviations are typical for co-mined metals.

5. A branching tree of part of the metal recovery module from the DEER2 project is shown in Figure N1. The materials that are separated include printed wiring boards, ferrous metals, non-ferrous metals, and plastics. Many of these separated material categories go on to further separation steps, and thus on to further branching trees. For example, the stream of plastics exiting the branching tree in Figure N1 serves as the input stream for the branching tree shown in Figure 2.

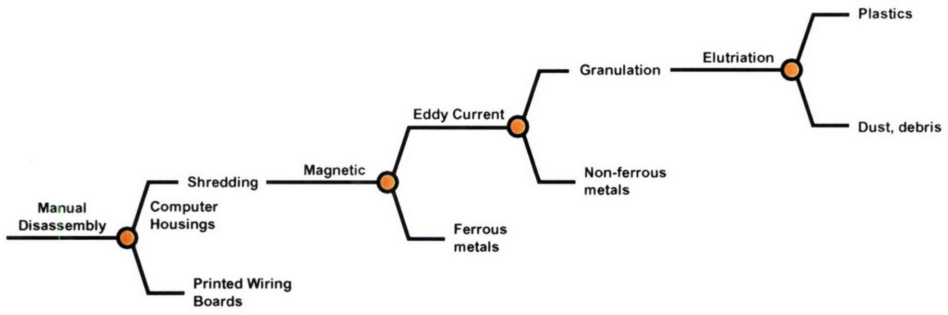


Figure N1: Part of the metal recovery module from the DEER2 project. Circles indicate separation steps.

Alternative material separation trees for end-of-life consumer electronics can also be drawn. For example, the processing of electronics at a Hewlett-Packard recycling facility is shown in Figure N2. In this branching tree, the materials that are separated include ferrous metals, aluminum, and plastics.

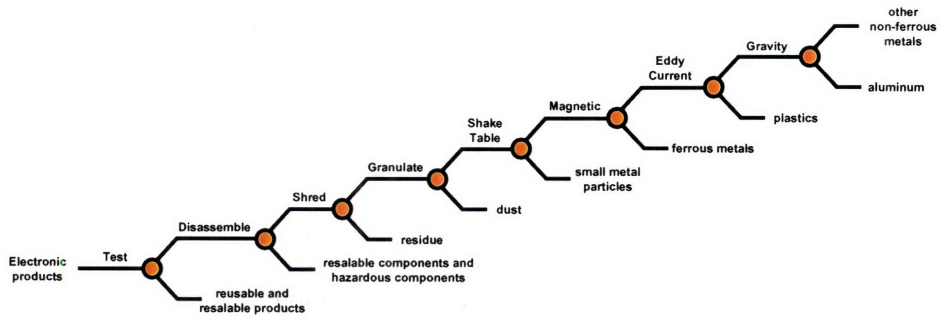


Figure N2: Material recovery at a Hewlett-Packard recycling facility. Circles indicate separation steps.

Such branching trees are not limited to electronics. For example, a material separation system for end-of-life automobile recycling is shown in Figure N3. In this branching tree, separated materials include ferrous metals and non-ferrous metals.

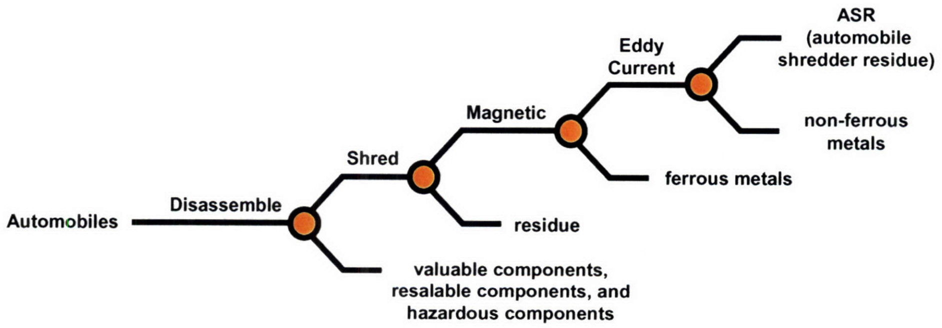


Figure N3: Material recovery at an automobile recycling facility. Circles indicate separation steps.

6. This means that a small change in probability, p_i, should result in a small change in uncertainty, H.

7. This means that with messages of equal probability, when there are more messages, there exists greater uncertainty.

8. This means that if a message is in fact composed of two successive messages, the total measure of uncertainty should be the weighted sum of the individual values of uncertainty. Thus, the two decompositions shown in Figure N4, have the same uncertainty.

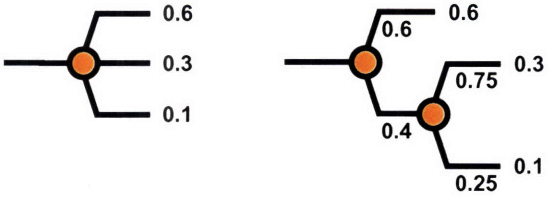


Figure N4: Two possible decompositions of three outcomes.

Mathematically,

$$H(0.6,0.3,0.1) = H(0.6,0.4) + 0.4H(0.75,0.25)\,.$$

9. Many of the material categories counted in this analysis can be separated from one another using mechanical separation processes, including magnetic separation, eddy current separation, electrostatic separation, sink/float separation, and hydrocyclone separation, among others. However, one class of materials listed in Table 3, namely precious metals, generally require chemical separation methods to isolate individual metals (Kang and Schoenung 2004).

10. Using a bill of materials from the manufacture of a product to estimate the materials available at the end-of-life of a product, assumes that the mass of a product and the mixture of materials in a product do not change considerably during the use phase. This is generally true for the products presented here, the most noticeable exception being automobile tires, which can lose around 20% of their initial mass during use (Yamaguchi 2000). Catalytic converters can also experience material losses during the use phase (Lloyd et al. 2005).

    It is also important to note that the method of calculating single product recycled material value used here, assumes that the materials in a product can be fully separated and recovered. In reality, separation processes can have significant material losses due to inefficiencies in the system (Verhoef et al. 2004). Thus, the single product recycled material value calculated here represents an upper bound.

11. The Recycler's World web site provides market price data for recycled materials. For materials that are not listed on Recycler's World, namely precious metals, market price data was provided by the Kitco web site. The prices provided by Recycler's World for recycled

materials were, on average, roughly 25% less than virgin material prices. Thus, prices provided by Kitco for virgin materials were reduced by 25% for the purposes of this analysis. Since material value for the products examined is plotted on a log axis, changing this price reduction of 25% for precious metals does not have a significant effect on the results.

In considering prices for recycled materials, it is interesting to note recent market trends. In particular, over the past couple years, prices for recycled materials have increased considerably, in large part because of surging demand in countries such as China and India. This trend has led to an increase in the recycled material value for products at end-of-life, and may lead to an increased interest in recycling.

12. Recycling rates are measured differently for various products. In general, the recycling rate tries to capture the number of products recycled in a given time period divided by the total number of such products retired in that same time period. For some products with short lifecycles, such as bottles and cans, recycling rates are often determined by dividing the number of products recycled in a given time period by the total number of such products produced in that same time period (ACC 2007).

    In general, recycling refers to material recovery. Thermal recycling, in which the product is incinerated for energy recovery, is generally not considered to be recycling. However, in the case of automobile tires, the recycling rate of 66% includes both material recovery and thermal recycling. Without thermal recycling, the recycling rate for automobile tires drops to 24% (Blumenthal 2001). The reason that thermal recycling is included in the recycling rate in the case of automobile tires is because of the fact that after incineration, the steel in the tires is often recovered for material recycling (Ibid.). Thus, thermal recycling in the case of automobile tires involves both thermal recycling and material recovery.

13. For comparison, a similar plot can be drawn for the single product recycled material value in the US, $\Sigma m_i k_i$, versus material mixing, as measured by the number of materials in a product, M. Such a plot, as shown below, does not differentiate well between products that are economically worthwhile to recycle and those that are not.

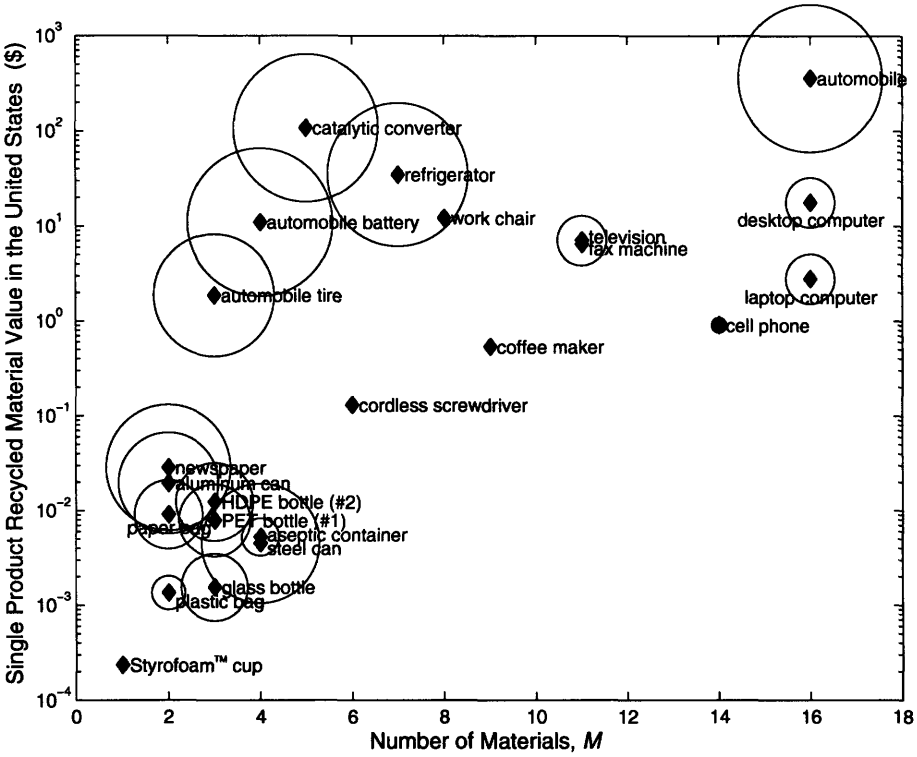


Figure N5: Single product recycled material value in the US ($\Sigma m_i k_i$) versus the number of materials in a product (M) for 23 products. The area of the circle surrounding each data point represents the recycling rate in the US for that product.

From this plot, it is also clear that a closely related measure of material mixing, namely a simple count of the number of separation steps necessary to separate the materials in a product, M-1, would also prove ineffective in differentiating between products that are economically worthwhile to recycle and those that are not.

Other measures for material value are also possible, including measuring the total recycled material value in the US. This measure multiplies the single product recycled material value in the US, $\Sigma m_i k_i$, by the number of such products retired annually in the US, N_p, to capture the entire revenue potential for such products. In this formulation, (11) becomes

$$N_p \sum_{i=1}^{M} m_i k_i > H k_b .$$

This plot, shown below, does show some ability to differentiate between products that are economically worthwhile to recycle and those that are not. A more complete description of this plot, and an explanation of the equations behind this plot, are provided in an earlier work (Dahmus and Gutowski 2006).

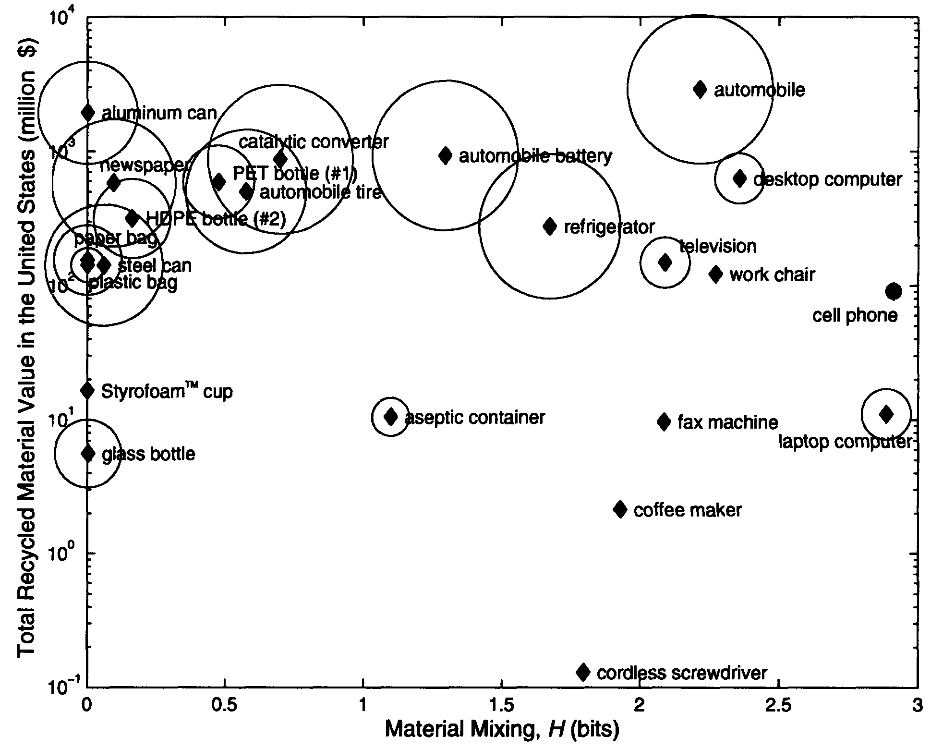


Figure N6: Total recycled material value in the US ($N_p\Sigma m_ik_i$) versus material mixing (H) for 23 products. The area of the circle surrounding each data point represents the recycling rate in the US for that product.

Another possible measure for material value is the per unit mass recycled material value in the US. This measure divides the single product recycled material value, Σm_ik_i, by the mass of the product, Σm_i, to capture the per unit mass revenue potential. In this formulation, (11) becomes

$$\frac{\sum_{i=1}^{M} m_i k_i}{\sum_{i=1}^{M} m_i} > Hk_b \; .$$

This plot, shown below, does not appear to be able to differentiate between products that are economically worthwhile to recycle and those that are not.

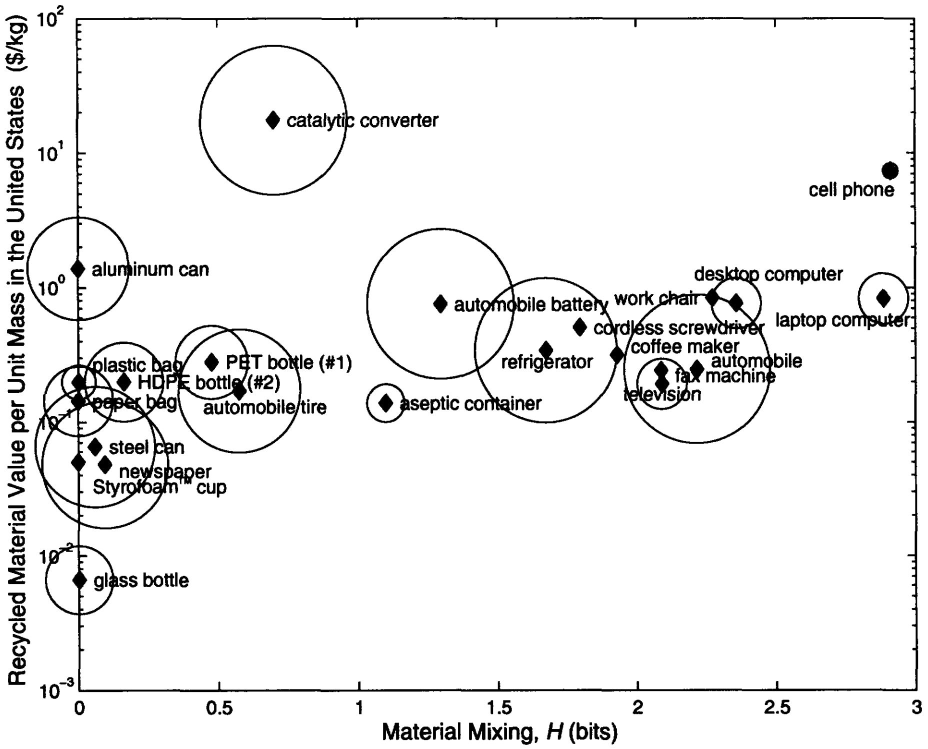


Figure N7: Per unit mass recycled material value in the US ($\Sigma m_i k_i / \Sigma m_i$) versus material mixing (H) for 23 products. The area of the circle surrounding each data point represents the recycling rate in the US for that product.

A complete set of product data, including the product data used in Figures N5, N6, and N7, is provided in Table N1.

Product	$\Sigma m_i k_i$ ($)	H (bits)	Recycling Rate	Σm_i (kg)	M (materials)	c_v (%)	N_p (million products)
automobile battery	$ 10.95	1.30	96%	14.50	4	70%	84.9
automobile	$ 358.61	2.22	95%	1451.50	16	86%	8.09
catalytic converter	$ 107.54	.699	95%	6.12	5	82%	8.09
refrigerator	$ 34.69	1.67	90%	101.59	7	88%	7.95
newspaper	$ .028	.095	70%	.595	2	99%	20314.74
automobile tire	$ 1.85	.575	66%	10.88	3	98%	270.0
steel can	$ .004	.060	63%	.069	4	100%	31434.7
aluminum can	$ .019	.001	45%	.014	2	100%	99800.0
HDPE bottle (#2)	$ .012	.163	27%	.062	3	100%	25536.68
PET bottle (#1)	$ .008	.476	23%	.028	3	100%	75240.85
paper bag	$ .009	.001	21%	.063	2	100%	17000.0
glass bottle	$ .002	.003	20%	.233	3	100%	3637.46
desktop computer	$ 17.69	2.36	11%	23.12	16	98%	35.44
television	$ 7.05	2.09	11%	36.74	11	84%	21.0
laptop computer	$ 2.79	2.89	11%	3.36	16	88%	3.94
aseptic container	$ .005	1.10	6%	.038	4	100%	2000.0
plastic bag	$ .001	.001	5%	.007	2	100%	105333.33
cell phone	$ .908	2.91	1%	.124	14	73%	100.0
work chair	$ 12.19	2.27	0%	14.54	8	94%	10.0
fax machine	$ 6.43	2.09	0%	26.57	11	78%	1.5
coffee maker	$ .535	1.93	0%	1.69	9	95%	4.0
cordless screwdriver	$ .130	1.80	0%	.257	6	99%	1.0
Styrofoam™ cup	$ .0002	.000	0%	.005	1	100%	70246.54

Table N1: Product data used in Figures N5 through N7.

14. Complete bills of materials for desktop computers are difficult to find. This set of results is based on data from a study by Miyamoto et al. (Miyamoto et al. 1998). However, this study ignores precious metals, due to their low masses (Inaba 2007). Thus, precious metals data from Williams is added to the bill of materials from Miyamoto et al. (Williams 2004).

15. This set of results is based on a study by Williams (Williams 2004). However, this study fails to differentiate between various types of plastics. Thus, more-detailed plastics data from Miyamoto et al. is used to sub-divide the plastics category from Williams into individual types of plastics (Miyamoto et al. 1998).

16. This set of results is based on a study by Kulkarni et al. (Kulkarni et al. 2005). This study examines only the computer tower, and does not include a CRT monitor, as do the other analyses. However, the computer tower alone has a value of $56.55, which will only increase with the addition of a monitor.

17. Of the 23 products analyzed here, only a handful of products have components removed during presorting. Those products, and the components that are removed, are listed below:

    automobile – battery, catalytic converter, tires
    cell phone – battery
    cordless screwdriver – battery
    laptop computer – battery.

    There is also the unique case of refrigerators, which sometime have their compressors removed during presorting. Compressors, which can represent over 10% of the refrigerator mass, can be treated in a few different ways at product end-of-life. Some compressors are simply left on the refrigerator and undergo shredding and material separation along with the rest of the machine (Bohr 2007). Other compressors are removed from the refrigerator, then either sold into secondary markets, or shredded and separated for material recovery (Ibid.). While different end-of-life options clearly exist, for the analysis completed here, compressors were assumed to remain with the rest of the refrigerator, and were not removed during presorting. If compressors were assumed to be removed from refrigerators during presorting, the measure of material mixing would be reduced from 1.67 to 1.57, and the single product recycled material value would be reduced from $34.69 to $20.07. While this would move refrigerators closer to the apparent recycling boundary, it would still clearly fall above the boundary, along with other commonly recycled products.

18. Besides refrigerants in refrigerators and electrolytes in automobile batteries, most of the other hazardous materials in the products examined here are related to electronics. Products such as desktop computers and laptop computers often contain small amounts of a number of hazardous materials, including cadmium, chromium, and mercury, among others (Abron and Corbitt 1999, Kulkarni et al. 2005, Shrivastava et al. 2005). Other products, including automobiles, can also contain hazardous materials from electronics, including mercury from mercury switches (US EPA 2006b).

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19. Aluminum cans, steel cans, glass bottles, PET bottles (#1), HDPE bottles (#2), and aseptic containers are perhaps more commonly thought of as containers for beverage and food products, not as products in their own right.

20. In many of the mineral deposit models presented by Cox and Singer, multiple ores can be found in any given deposit (Cox and Singer 1986). While most deposits contain only a few different ores, and are thus relatively materially simple, some ore deposits contain a larger number of ores, and thus could be considered to be materially complex. For example, the Komatiitic Ni-Cu deposit model contains ores of cobalt, nickel, copper, palladium, platinum, iridium, and gold (Ibid.). Although there are eight materials in this deposit model, the low concentrations of metal ores and high concentration of gangue results in a low value of material mixing, *H*, indicating a relatively simple mixture.

References

Abron, L.A. and R.A. Corbitt, 1999. "Air and Water Quality Standards" in Standard Handbook of Environmental Engineering, 2nd edition, ed. R.A. Corbitt. New York, New York, USA: McGraw-Hill.

American Chemistry Council and The Association of Postconsumer Plastic Recyclers (ACC), 2007. "2005 National Post-Consumer Plastics Bottle Recycling Report." The American Chemistry Council, Plastic Recycling and Beyond, Plastic Recycling, Plastic Recycling Statistics. Available online at http://www.plasticsresource.com/s_plasticsresource/docs/1900/1874.pdf. (Accessed March 22, 2007.)

Ash, R.B., 1965. Information Theory. New York, New York, USA: Dover Publications, Inc.

Blumenthal, M., 2001. "Tires," in The McGraw-Hill Recycling Handbook, 2nd edition, ed. H.F. Lund. New York, New York, USA: McGraw-Hill.

Bohr, P., 2007. PhD Student, Technische Universität Berlin. Personal communication, April 26, 2007.

Chapman, P.F. and F. Roberts, 1983. Metal Resources and Energy. London, UK: Butterworth and Co Ltd.

Cox, D.P. and D.A. Singer, 1986. Mineral Deposit Models. US Department of the Interior, US Geological Survey. Available online at http://pubs.usgs.gov/bul/b1693/html/bullfrms.htm. (Accessed March 29, 2007.)

Dahmus, J.B. and T.G. Gutowski, 2006. Material Recycling at Product End-of-Life. Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, San Francisco, California, USA. May 8-11, 2006: 206-211.

Graedel, T.E. and B.R. Allenby, 2003. Industrial Ecology, Second Edition. Upper Saddle River, New Jersey, USA: Pearson Education, Inc.

Grübler, A., 1998. Technology and Global Change. Cambridge, UK: Cambridge University Press.

Gyftopoulos, E.P. and G.P. Beretta, 2005. Thermodynamics: Foundations and Applications. Mineola, New York, USA: Dover Publications, Inc.

Holland, H.D. and U. Petersen, 1995. Living Dangerously: The Earth, Its Resources, and the Environment. Princeton, New Jersey, USA: Princeton University Press.

Inaba, A., 2007. Professor, Research into Artifacts, Center for Engineering, University of Tokyo. Personal communication, March 22, 2007.

Isaacs, J.A. and S.M. Gupta, 1997. Economic Consequences of Increasing Polymer Content for the Automobile Recycling Infrastructure. Journal of Industrial Ecology 1(4): 19-33.

Jody, B.J. and E.J. Daniels, 2006. End-of-Life Vehicle Recycling: The State of the Art of Resource Recovery from Shredder Residue. Argonne National Laboratory, Energy Systems Division, Report ANL/ESD/07-8, September 25, 2006. Available online at http://www.es.anl.gov/Energy_systems/CRADA_Team_Link/publications/Recycling_Report_(print).pdf. (Accessed March 14, 2007.)

Kang, H.Y. and J.M. Schoenung, 2004. Used Computer Electronics: A Comparative Analysis of Materials Recycling Technologies. Proceedings of the 2004 IEEE International Symposium on Electronics and the Environment, Phoenix, Arizona, USA. May 19-23, 2004: 226-230.

Kitco, 2007. Kitco, Champlain, New York, USA. Available online at http://www.kitco.com. (Accessed March 19, 2007.)

Kulkarni, R., H.C. Zhang, J. Li, and J. Sun, 2005. A Framework For Environmental Impact Assessment Tools: Comparison Validation and Application Using Case Study of Electronic Products. Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment, New Orleans, Louisiana, USA. May 16-19, 2005: 210-214.

Lloyd, S.M, L.B. Lave, and H.S. Matthews, 2005. Life Cycle Benefits of Using Nanotechnology To Stabilize Platinum-Group Metal Particles in Automotive Catalysts. *Environmental Science and Technology* 39(5): 1384-1392.

McDougall, F, P. White, M. Franke, and P. Hindle, 2001. Integrated Solid Waste Management: a Life Cycle Inventory, Second Edition. Oxford, UK: Blackwell Science.

Miyamoto, S., M. Tekawa, and A. Inaba, 1998. Life Cycle Assessment of Personal Computers for the Purpose of Design for Environment. *Energy and Resources* (Japan) 19(1): 75-80.

National Research Council (NRC), 1987. Separation and Purification: Critical Needs and Opportunities. Washington, DC, USA: National Academy Press.

Perlez, J. and K. Johnson, 2005. Behind Gold's Glitter: Torn Lands and Pointed Questions. *New York Times*, October 24, 2005.

Phillips, W.G.B. and D.P. Edwards, 1976. Metal prices as a function of ore grade. *Resources Policy* 2(3):167-178.

Porter, R.D., 2002. The Economics of Waste. Washington, D.C., USA: Resources for the Future.

Recycler's World, 2007. RecycleNet Corporation, Richfield Springs, New York, USA. Available online at http://www.recycle.net. (Accessed March 19, 2007.)

Shannon, C.E., 1948. A Mathematical Theory of Communication. *Bell System Technical Journal* 27(July and October): 379-423, 623-656. Available online at http://cm.bell-labs.com/cm/ms/what/shannonday/shannon1948.pdf. (Accessed March 14, 2007.)

Shannon, C.E. and W. Weaver, 1964. The Mathematical Theory of Communication. Urbana, Illinois, USA: University of Illinois Press.

Shent, H., R.J. Pugh, and E. Forssberg, 1999. A review of plastics waste recycling and the flotation of plastics. Resources, Conservation and Recycling 25(2): 85-109.

Sherwood, T.K., 1959. "Mass Transfer Between Phases," *Phi Lambda Upsilon*. University Park, Pennsylvania, USA: Pennsylvania State University.

Shrivastava, P., H.C. Zhang, J. Li, and A. Whitley, 2005. Evaluating Obsolete Electronic Products For Disassembly, Material Recovery and Environmental Impact Through a Decision Support System. Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment, New Orleans, Louisiana, USA. May 16-19, 2005: 221-225.

Sodhi, M.S., J. Young, and W.A. Knight, 1999. Modelling material separation processes in bulk recycling. *International Journal of Production Research* 37(10): 2239-2252.

Tchobanoglous, G., H. Theisen, and S. Vigil, 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. New York, New York, USA: McGraw-Hill, Inc.

United States Environmental Protection Agency (US EPA), 2005. Report of the Panel Session: Emerging Electronics Issues – How Can We Minimize the Health and Environmental Impacts of Electronics Recycling? Office of Research and Development, Report EPA/600/R-05/101, September 2005. Panel discussion held on May 19, 2005.

United States Environmental Protection Agency (US EPA), 2006a. Original List of Hazardous Air Pollutants. EPA Home, Technology Transfer Network, Air Toxics Website. Available online at http://www.epa.gov/ttn/atw/188polls.html. (Accessed April 26, 2007.)

United States Environmental Protection Agency (US EPA), 2006b. August 2006 Fact Sheet: National Vehicle Mercury Switch Recovery Program. EPA Home, Mercury, Laws and Regulations, National Vehicle Mercury Switch Recovery Program. Available online at http://www.epa.gov/mercury/switchfs.htm. (Accessed April 26, 2007.)

Verhoef, E.V., G.P.J. Dijkema, and M.A. Reuter, 2004. Process Knowledge, System Dynamics, and Metal Ecology. *Journal of Industrial Ecology* 8(1-2): 23-43.

Williams, E., 2004. "Environmental Impacts in the Production of PCs," in Computers and the Environment: Understanding and Managing Their Impacts, eds. R. Kuehr and E. Williams. Dordrecht, Netherlands: Springer.

Yamaguchi, E., 2000. "Waste Tire Recycling." Buffalo, New York, USA. Available online at http://p2pays.org/ref/11/10504/html/summary/sindex.htm. (Accessed March 23, 2007.)

Young, J.E., 1992. Mining the Earth, Worldwatch Paper 109. Washington, DC, USA: Worldwatch Institute.

Product References

Aluminum can

Bill of materials:

Cohen, E., 2005. What's in those cans besides beer? *Notre Dame Magazine*. Summer 2005. Available online at http://www.nd.edu/~ndmag/can1su00.htm. (Accessed March 22, 2007.)

Dahmus, J., 2005. Laboratory measurements, March 10, 2005.

Recycling rate:

Container Recycling Institute, 2006. "Aluminum Can Recycling Rates (1990-2004)." Recycling Rates, Aluminum Cans, Statistical Notes, Graph: Aluminum Can Recycling Rate: 2 Methods of Measuring (1990-2004). http://container-recycling.org/alumrate/Recrate-CRIvsAA-90-04.htm. (Accessed March 22, 2007.)

Aseptic container

Bill of materials:

Aseptic Packaging Council, 2006. "Question and Answer." Aseptic Packaging Council. Available online at http://www.aseptic.org. (Accessed March 23, 2007.)

Recycling rate:

Hurd, D., 2005. Tetra Pak Environmental Coordinator, Personal communication, April 7, 2005.

Automobile

Bill of materials:

1950s:

Graedel, T.E. and B.R. Allenby, 1998. Industrial Ecology and the Automobile. Upper Saddle River, New Jersey, USA: Prentice Hall.

1970s:

Time, 1974. Detroit Bucks a Buyer Rebellion. *Time*, December 2, 1974: 35-37.

Weber, A. 1989. "Plastics in the Automotive Industry." Plastics in the Automotive Industry, Antwerp, Belgium, May 25-26, 1989. The Royal Flemish Society of Engineers (K.VIV), Section on Plastics.

1980s:

Ward's Communications, 2004. Ward's Motor Vehicle Facts and Figures. Southfield, Michigan, USA: Ward's Communications.

Weber, A. 1989. "Plastics in the Automotive Industry" in Plastics in the Automotive Industry. Antwerp, Belgium: The Royal Flemish Society of Engineers (K.VIV), Section on Plastics.

1990s:
Sullivan, J.L., R.L. Williams, S. Yester, E. Cobas-Flores, S.T. Chubbs, S.G. Hentges, and S.D. Pomper, 1998. "Life Cycle Inventory of a Generic U.S. Family Sedan Overview of Results USCAR AMP Project." Total Life Cycle Conference and Exposition, Graz, Austria, Dec 1-3, 1998. Society of Automotive Engineers, Technical Paper 982160.

2000:
Ward's Communications, 2004. Ward's Motor Vehicle Facts and Figures. Southfield, Michigan, USA: Ward's Communications.

Graser, K., R. Hoock, and D. Urth, 2000. "Innovative Recycling Solutions for Plastic Components" in Plastics in Automotive Engineering. Düsseldorf, Germany: VDI Verlag GmbH.

2000s SUV:
Sullivan, J. L., 2005. Ford Motor Company. Personal communication. October 26, 2005.

Recycling rate:
Auto Alliance, 2006. "Automotive Recycling: Your car's afterlife." The Alliance of Automobile Manufacturers, February 13, 2006, Washington, D.C., USA. Available online at http://autoalliance.org/archives/RECYCLE_17.pdf. (Accessed March 20, 2007.)

IHS Automotive, 2004. "The Nature of Automotive Recycling." Automotive Industry Trends, March 2004, Englewood, Colorado, USA. Available online at http://auto.ihs.com/news/newsletters/auto-mar04-auto-recycling.htm. (Accessed March 21, 2007.)

Automobile battery

Bill of materials:
Adams, A.P., 2001. "Batteries," in The McGraw-Hill Recycling Handbook, 2nd edition, ed. H.F. Lund. New York, New York, USA: McGraw-Hill.

Salkind, A.J., A.G. Cannone, F.A. Trumbure, 2002. "Lead-Acid Batteries," in Handbook of Batteries, 3rd edition, eds. D. Linden and T.B. Reddy. New York, New York, USA: McGraw-Hill.

Sassmannhausen, G. and E. Nann, 2003. "Motor Vehicle Starter Batteries," in Batttery Technology Handbook, 2nd edition, ed. H.A. Kiehne. New York, New York, USA: Marcel Dekker.

Socolow, R. and V. Thomas, 1997. The Industrial Ecology of Lead and Electric Vehicles. *Journal of Industrial Ecology* 1(1): 13-36.

Recycling rate:
Battery Council International, 2006. "Battery Recycling." Battery Council International, Chicago, Illinois, USA. Available online at http://www.batterycouncil.org/recycling.html. (Accessed March 22, 2007.)

Socolow, R. and V. Thomas, 1997. The Industrial Ecology of Lead and Electric Vehicles. *Journal of Industrial Ecology* 1(1): 13-36.

Automobile tire

Bill of materials:

Amari, T., N.J. Themelis, I.K. Wernick, 1999. Resource recovery from used rubber tires. *Resources Policy* 25(3): 179-188.

Yamaguchi, E., 2000. "Waste Tire Recycling." Buffalo, New York, USA. Available online at http://p2pays.org/ref/11/10504/html/summary/sindex.htm. (Accessed March 23, 2007.)

Recycling rate:

Blumenthal, M., 2001. "Tires," in The McGraw-Hill Recycling Handbook, 2nd edition, ed. H.F. Lund. New York, New York, USA: McGraw-Hill.

Yamaguchi, E., 2000. "Waste Tire Recycling." Buffalo, New York, USA. Available online at http://p2pays.org/ref/11/10504/html/summary/sindex.htm. (Accessed March 23, 2007.)

Catalytic converter

Bill of materials:

Donovan, J., 2004. President, Panhandle Converter and Scrap Company. Personal communication, January 20, 2004.

Lloyd, S.M, L.B. Lave, and H.S. Matthews, 2005. Life Cycle Benefits of Using Nanotechnology To Stabilize Platinum-Group Metal Particles in Automotive Catalysts. *Environmental Science and Technology* 39(5): 1384-1392.

Recycling rate:

Estimated.

Cell phone

Bill of materials:

Verhoef, E.V., G.P.J. Dijkema, and M.A. Reuter, 2004. Process Knowledge, System Dynamics, and Metal Ecology. *Journal of Industrial Ecology* 8(1-2): 23-43.

Recyclewirelessphones.org, undated material. Wireless: the New Recyclable, Frequently Asked Questions. Available online at http://www.recyclewirelessphones.org/index.cfm?fuseaction=main.FAQ#Q5. (Accessed March 3, 2005.)

Recycling rate:

Most, E., 2003. "Calling All Cell Phones: Collection, Reuse, and Recycling Programs in the US." New York, New York, USA: Inform. Available online at http://www.informinc.org/media/Calling_Cellphones.pdf. (Accessed March 23, 2007.)

Hagelüken, C., 2006. Improving metal returns and eco-eficiency in electronics recycling. Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, San Francisco, California, USA. May 8-11, 2006.

Coffee maker

Bill of materials:

Glomski, P., 2004. End of Life Analysis - Mr. Coffee ADS12. Class Project, 2.83 - Environmentally Benign Manufacturing, Professor Timothy Gutowski, Massachusetts Institute of Technology, Spring 2004.

Recycling rate:

Estimated.

Cordless screwdriver

Bill of materials:

Dahmus, J.B., Y.F. Wei, and M. Yong, 1999. Master Mechanic Screwdriver. Class Project, 2.875 - Mechanical Assembly and its Role in Product Development, Professor Daniel Whitney, Massachusetts Institute of Technology, Fall 1999.

Recycling rate:

Estimated.

Desktop computer

Bill of materials:

Inaba, A., 2007. Professor, Research Into Artifacts, Center for Engineering, University of Tokyo and Director, Research Center for Life Cycle Assessment, National Institute of Advanced Industrial Science and Technology. Personal communication, March 22, 2007.

Miyamoto, S., 2007. Manger, Research Planning Division, NEC Corporation. Personal communication, May 1, 2007.

Miyamoto, S., M. Tekawa, and A. Inaba, 1998. Life Cycle Assessment of Personal Computers for the Purpose of Design for Environment. *Energy and Resources* (Japan) 19(1): 75-80.

Puckett, J., L. Byster, S. Westervelt, R. Gutierrez, S. Davis, A. Hussain, and M. Dutta, 2002. "Exporting Harm: The High-Tech Trashing of Asia." Seattle, Washington, USA and San Jose, California, USA: The Basel Action Network and Silicon Valley Toxics Coalition. Available online at http://svtc.etoxics.org/site/DocServer/technotrash.pdf?docID=123. (Accessed March 22, 2007.)

Williams, E., 2004. "Environmental Impacts in the Production of PCs," in Computers and the Environment: Understanding and Managing Their Impacts, eds. R. Kuehr and E. Williams. Dordrecht, Netherlands: Springer.

Recycling rate:

Computer Takeback Campaign, 2004. "Poison PCs and Toxic TVs." The Problem, Computer TakeBack Campaign. Available online at http://www.computertakeback.com/document.cfm?documentID=23. (Accessed March 22, 2007.)

Goldberg, C., 1998. Where do Computers Go When They Die? Into the Attic, Under the Ping-Pong Table – but Hardly Ever Into the Trash. *New York Times*, March 12, 1998.

Grossman, E., 2006. High Tech Trash: Digital Devices, Hidden Toxics, and Human Health. Washington, D.C., USA: Island Press, Shearwater Books.

Fax machine

Bill of materials:

Environmental Product Declaration, 2001. Ricoh RIFAX ML4500 FAX machine, Ricoh Company, Ltd., Tokyo, Japan. Available online at http://www.environdec.com/reg/e_epde8.pdf. (Accessed March 23, 2007.)

Recycling rate:

Estimated.

Glass bottle

Bill of materials:

Dahmus, J., 2005. Laboratory measurements, March 10, 2005.

Recycling rate:

Container Recycling Institute, 2006. "Glass Beverage Bottle Recycling Rates, (%) 1996-2006e." Recycling Rates, Glass Bottles, Graphs, Glass Recycling Rate (1996-2006). Available online at http://container-recycling.org/images/glass/graphs/recrate-percent-96-06.gif. (Accessed March 22, 2007.)

HDPE bottle (#2)

Bill of materials:

Dahmus, J., 2005. Laboratory measurements, March 11, 2005.

Recycling rate:

American Chemistry Council and The Association of Postconsumer Plastic Recyclers, 2007. "2005 National Post-Consumer Plastics Bottle Recycling Report. The American Chemistry Council, Plastic Recycling and Beyond, Plastic Recycling, Plastic Recycling Statistics. Available online at http://www.plasticsresource.com/s_plasticsresource/docs/1900/1874.pdf. (Accessed March 22, 2007.)

Laptop computer

Bill of materials:

Inaba, A., 2007. Professor, Research Into Artifacts, Center for Engineering, University of Tokyo and Director, Research Center for Life Cycle Assessment, National Institute of Advanced Industrial Science and Technology. Personal communication, March 22, 2007.

Miyamoto, S., 2007. Manger, Research Planning Division, NEC Corporation. Personal communication, May 1, 2007.

Miyamoto, S., M. Tekawa, and A. Inaba, 1998. Life Cycle Assessment of Personal Computers for the Purpose of Design for Environment. *Energy and Resources* (Japan) 19(1): 75-80.

Shrivastava, P., H.C. Zhang, J. Li, and A. Whitley, 2005. Evaluating Obsolete Electronic Products For Disassembly, Material Recovery and Environmental Impact Through a Decision Support System. Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment, New Orleans, Louisiana, USA. May 16-19, 2005: 221-225.

Recycling rate:

Computer Takeback Campaign, 2004. "Poison PCs and Toxic TVs." The Problem, Computer TakeBack Campaign. Available online at http://www.computertakeback.com/document.cfm?documentID=23. (Accessed March 22, 2007.)

Goldberg, C., 1998. Where do Computers Go When They Die? Into the Attic, Under the Ping-Pong Table – but Hardly Ever Into the Trash. *New York Times*, March 12, 1998.

Grossman, E., 2006. High Tech Trash: Digital Devices, Hidden Toxics, and Human Health. Washington, D.C., USA: Island Press, Shearwater Books.

Newspaper

Bill of materials:

American Forest and Paper Association, 2005. Recovered Paper Statistical Highlights. Washington, D.C., USA: American Forest and Paper Association. Available online at http://www.afandpa.org/Content/NavigationMenu/Environment_and_Recycling/Recycling/Statistics5/FINAL2005RPSH.pdf. (Accessed March 22, 2007.)

News Limited, undated material. "Inks and the Environment." News Limited Australia, Environmental Secretariat, Surry Hills, New South Wales, Australia. Available online at http://environment.news.com.au/html/inks.htm. (Accessed March 22, 2007.)

Newspaper Association of America, 2004. "U.S. Daily Newspaper Circulation." 2004 Information Resource Center, Facts About Newspapers. Available online at http://www.naa.org/info/facts04/circulation-daily.html. (Accessed March 22, 2007.)

Recycling rate:

Paper Industry Association Council, 2007. "Recovered Paper Statistical Highlights." 2005 Recovered Paper Annual Statistics. Available online at http://stats.paperrecycles.org/index.php?func=print&graph=recuse&sub=. (Accessed March 22, 2007.)

Paper bag

Bill of materials:

Dahmus, J., 2007. Laboratory measurements, April 21, 2007.

United States Environmental Protection Agency, 2006. "Questions About Your Community: Shopping Bags: Paper or Plastic or...?" New England Communities, Questions, Washington D.C., USA. Available online at http://www.epa.gov/region1/communities/shopbags.html. (Accessed April 21, 2007.)

Recycling rate:

United States Environmental Protection Agency, 2007. Municipal Solid Waste in the United States: 2005 Facts and Figures. Office of Solid Waste, Report EPA530-R-06-011, October 2006. Available online at http://www.epa.gov/msw/pubs/mswchar05.pdf. (Accessed April 21, 2007.)

PET bottle (#1)

Bill of materials:

Dahmus, J., 2005. Laboratory measurements, March 11, 2005.

Recycling rate:

American Chemistry Council and The Association of Postconsumer Plastic Recyclers, 2007. "2005 National Post-Consumer Plastics Bottle Recycling Report." The American Chemistry Council, Plastic Recycling and Beyond, Plastic Recycling, Plastic Recycling Statistics. Available online at http://www.plasticsresource.com/s_plasticsresource/docs/1900/1874.pdf. (Accessed March 22, 2007.)

Plastic bag

Bill of materials:

Dahmus, J., 2007. Laboratory measurements, April 20, 2007.

United States Environmental Protection Agency, 2006. "Questions About Your Community: Shopping Bags: Paper or Plastic or...?" New England Communities, Questions, Washington D.C., USA. Available online at http://www.epa.gov/region1/communities/shopbags.html. (Accessed April 21, 2007.)

Recycling rate:

United States Environmental Protection Agency, 2007. Municipal Solid Waste in the United States: 2005 Facts and Figures. Office of Solid Waste, Report EPA530-R-06-011, October 2006. Available online at http://www.epa.gov/msw/pubs/mswchar05.pdf. (Accessed April 21, 2007.)

Refrigerator

Bill of materials:

American Chemistry Council, 2007. "Composition, Properties and Economic Study of Recycled Refrigerators," based on the report "Composition, Properties and Economic Study of Recycled Refrigerators," by A.M. Zolotor, 1994. The American Chemistry Council, Reading Room, Reports. Available online at http://www.plasticsresource.com/s_plasticsresource/doc.asp?TRACKID=&CID=174&DID=381. (Accessed March 22, 2007.)

Recycling rate:

Steel Recycling Institute, undated material. "Steel Recycling Fact Sheet." Appliance Recycling Resources, Fact Sheet: Steel Recycling Fact Sheet. Available online at http://www.recycle-steel.org/PDFs/2005Graphs.pdf. (Accessed March 22, 2007.)

Steel can

Bill of materials:

Crawford, G.L., 2001. "Steel Recycling," in The McGraw-Hill Recycling Handbook, 2nd edition, ed. H.F. Lund. New York, New York, USA: McGraw-Hill.

Dahmus, J., 2005. Laboratory measurements, March 10, 2005.

Warne, D., 1988. Manual on Fish Canning, FAO Fisheries Technical Paper -285. Rome, Italy: Food and Agriculture Organization of the United Nations. Available online at http://www.fao.org/docrep/003/t0007e/T0007E00.htm#Contents. (Accessed March 22, 2007.)

Recycling rate:

Steel Recycling Institute, undated material. "Steel Recycling Fact Sheet." Steel Can Resources, Fact Sheet: Steel Recycling Fact Sheet. Available online at http://www.recycle-steel.org/PDFs/2005Graphs.pdf. (Accessed March 22, 2007.)

Styrofoam™ cup

Bill of materials:

Franklin Associates, Ltd., 2006. Life Cycle Inventory of Polystyrene Foam, Bleached Paperboard, and Corrugated Paperboard Foodservice Products, Executive Summary. Prepared for the Polystyrene Packaging Council, American Chemistry Council. Available online at http://www.factsonfoam.com.au/web/factfoam.nsf/files/Franklin2006_ES.pdf/$FILE/Franklin2006_ES.pdf. (Accessed April 21, 2007.)

Recycling rate:

United States Environmental Protection Agency, 2007. Municipal Solid Waste in the United States: 2005 Facts and Figures. Office of Solid Waste, Report EPA530-R-06-011, October 2006. Available online at http://www.epa.gov/msw/pubs/mswchar05.pdf. (Accessed April 21, 2007.)

Television

Bill of materials:

Kotera, Y. and S. Sato, 1997. An Integrated Recycling Process for Electric Home Appliances. *Mitsubishi Electric ADVANCE* September 1997: 23-26. Available online at http://global.mitsubishielectric.com/pdf/advance/vol80/80r&d.pdf. (Accessed March 23, 2007.)

Fisher, M.M., M.B. Biddle, T. Hainault, D.S. Smith, D.J. Cauchi, and D.A. Thompson, 2000. Characterization and Processing of Plastics from Minnesota's Demonstration Project for the Recovery of End-of-Life Electronics. Society of Plastics Engineers, Annual Recycling Conference, Dearborn, Michigan, USA. November 8-9, 2000. Available online at plasticsresource.com/s_plasticsresource/docs/900/849.pdf. (Accessed March 23, 2007.)

Recycling rate:

Estimated.

Work chair

Bill of materials:

Environmental Product Declaration, 2004. Think work chair, Steelcase, Grand Rapids, Michigan, USA. Available online at http://www.steelcase.com/na/files/1c8c96be2dc345b78562645262308e6f/Seating.pdf. (Accessed March 23, 2007.)

Recycling rate:

Estimated.

Efficiency, Production, and Resource Consumption

A Historical Analysis of Ten Activities

Abstract

This work explores the historical effectiveness of efficiency improvements in reducing resource consumption. Ten activities are analyzed, including pig iron production, aluminum production, nitrogen fertilizer production, electricity generation from coal, oil, and natural gas, freight rail travel, passenger air travel, motor vehicle travel, and refrigeration. The data and analyses presented here show that historically, over long time periods, improvements in efficiency have not succeeded in outpacing increases in production. The result has been sizeable increases in impact. However, there do exist shorter, decade-long time periods in which efficiency improvements were able to outpace production increases. In these cases, efficiency mandates, price pressures, and industry upheaval led to periods of reduced impact. In the future, efficiency mandates and price mechanisms, given certain conditions, could prove successful in realizing reductions in impact.

Keywords: efficiency, production, resource consumption, IPAT identity, rebound effect

Introduction

Efficiency improvements are often touted as effective and unobtrusive means of reducing mankind's impact on the earth. For many, and perhaps in particular for engineers, the idea that reductions in environmental impact can be achieved through technology-based solutions is especially attractive. As such, improving efficiency is often mentioned as a critical component of design for environment (DfE) or green engineering approaches (Graedel and Allenby 1998, Anastas and Zimmerman 2003). Such efficiency improvements have also frequently been embraced as "win-wins", in that they allow for both economic and environmental progress to occur (DeSimone and Popoff 1997, OECD 1998, WBCSD 2000).

Although improving efficiency may appear to be a promising approach to reducing environmental impact, it is important to point out that such improvements have been taking place for centuries. While these improvements have clearly helped to drive economic and social progress, where have they led us with regards to the environment? Perhaps more importantly, what do past efficiency improvements say about efficiency as a means of reducing environmental impact in the future? This paper addresses these very questions, and makes recommendations about the use of efficiency improvements as a means of reducing mankind's impact.

The IPAT Identity

One effective way to examine the relationship between efficiency improvements and environmental impact is to use the *IPAT* identity. This identity, first developed in the 1970s, is commonly used to help identify and quantify the multiple factors that contribute to mankind's impact on the earth. The *IPAT* identity equates impact (I) to the product of population (P), affluence (A), and technology (T). It can be written as

$$Impact = Population \; x \; \frac{Production}{Population} \; x \; \frac{Impact}{Production} \; , \qquad (1)$$

where affluence is represented as production over population and technology is represented as impact over production. It is this disaggregation of impact into its core constituents that helps make the *IPAT* identity a useful tool. While its simplicity allows one to more easily focus on individual aspects of sustainability, from population growth to economic growth to technological development, it is important to note that these terms are not independent. Instead, as others have pointed out, the variables in the *IPAT* identity are in fact coupled (Ehrlich and Holdren 1972).

In discussing the role of efficiency improvements in modifying mankind's impact on the earth, the technology term in (1) is of particular interest. This technology term represents environmental intensity, the inverse of which is environmental efficiency. Thus, the relationship between technology and efficiency can be written as

$$Technology = \frac{Impact}{Production} = \frac{1}{Efficiency} \quad . \tag{2}$$

The efficiency term shown in (2) is in fact an eco-efficiency, a ratio of economic value to environmental load (Ehrenfeld 2005).[1] The quantification of economic value and environmental load can range greatly, from dollar figures to production quantities in the case of economic value, and from amounts of resources consumed to amounts of emissions outputted in the case of environmental load.[2]

It is clear from (2) that those who tout efficiency improvements as a means of reducing environmental impact are in fact advocating improving the technology term in the *IPAT* identity. Graedel and Allenby affirm this focus on efficiency improvements, commenting that the technology term, "...appears to offer the greatest hope for a transition to sustainable development, especially in the short term, and it is modifying this term that is among the central tenets of industrial ecology." (Graedel and Allenby 2003).

While many variants on the *IPAT* identity exist, the variant used in this paper combines population and affluence into a single term that represents total production. Thus, (1) simplifies to

$$Impact = Production \ x \ \frac{Impact}{Production} \quad , \tag{3}$$

or, using (2),

$$Impact = Production \ x \ \frac{1}{Efficiency} \quad . \tag{4}$$

From (4) it is clear that in order for efficiency improvements to successfully reduce impact, the rate of improvement in efficiency must exceed the rate of increase in production. At the same time, in order to maintain economic growth, the rate of change in production must be positive. Thus, in order for this "win-win" scenario to occur, the inequality

$$\frac{\Delta e}{e} > \frac{\Delta P}{P} > 0, \tag{5}$$

where e represents efficiency and P now represents production, must be true.[3]

Historical Trends in Efficiency and Production

Historical efficiency and production data were compiled to examine if past improvements in efficiency have been able to outpace past increases in production. If this had indeed been the case, (5) would have been satisfied, and reductions in impact would have occurred. The data presented here covers ten activities, including pig iron production, aluminum production, nitrogen fertilizer production, electricity generation from coal, oil, and natural gas, freight rail travel, passenger air travel, motor vehicle travel, and refrigeration.

Figure 1 plots worldwide production of pig iron, measured as the mass of pig iron produced, and efficiency, measured as the mass of pig iron produced per unit of energy consumed in smelting.[4] Figure 2 plots worldwide aluminum production, measured as the mass of aluminum produced, and efficiency, measured as the mass of aluminum produced per unit of electricity consumed in the Hall-Heroult process.[5] Figure 3 plots worldwide nitrogen fertilizer production, measured as the mass of nitrogen produced, and efficiency, measured as the mass of nitrogen produced per unit of energy consumed in the Haber-Bosch process.[6] The data plotted in Figures 1 through 3 show almost continuous increases in both efficiency and production.

Figures 4, 5, and 6 show efficiency and production data for electricity generation from coal, oil, and natural gas in the US. These figures plot US production of electricity, measured in units of electricity produced, and efficiency, measured in units of electricity produced per mass or volume of fossil fuel consumed. In each of these three figures, despite significant disturbances in both efficiency and production, the general trends show both efficiency and production increasing over time.[7, 8, 9]

Figures 7 through 10 plot efficiency and production data for freight rail travel, passenger air travel, motor vehicle travel, and refrigeration. These cases differ from those presented in Figures 1 through 6 in that while the previous examples showed efficiency during the production phase, the data presented here shows efficiency during the use phase.[10]

Figure 7 plots the efficiency and production of freight rail travel by US Class I railroads.[11] Production is measured in revenue tonne-kilometers of freight rail travel, while efficiency is measured in revenue tonne-kilometers of freight rail travel per volume of fuel consumed.[12] Figure 8 plots the efficiency and production of passenger air travel by US airlines. Production is measured in available seat kilometers of passenger air travel, while efficiency is measured in available seat kilometers of passenger air travel produced per volume of fuel consumed.[13] As in Figures 1 through 6, Figures 7 and 8 again show efficiency and production increasing in parallel.

Figure 9 shows efficiency and production data for motor vehicle travel in the US.[14] Production is measured in vehicle-kilometers of motor vehicle travel produced, while efficiency is measured in vehicle-kilometers of motor vehicle travel produced per volume of fuel consumed.[15] Figure 10 shows production and efficiency data for residential refrigeration in the US.[16] Production is measured in hours of refrigeration produced, while efficiency is measured in hours of refrigeration produced per unit of electricity consumed. Figures 9 and 10 both show an earlier period of declining efficiency, followed by a more recent period of improving efficiency.[17] Throughout these changes in efficiency, production in both activities has continued to increase.

FIGURE 1: Worldwide Pig Iron Production (*P*) and the Energy Efficiency of Pig Iron Smelting (*e*)[a]

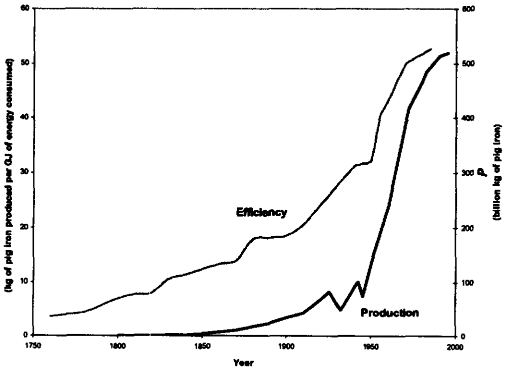


FIGURE 2: Worldwide Primary Aluminum Production (*P*) and the Energy Efficiency of the Hall-Heroult Process (*e*)[b]

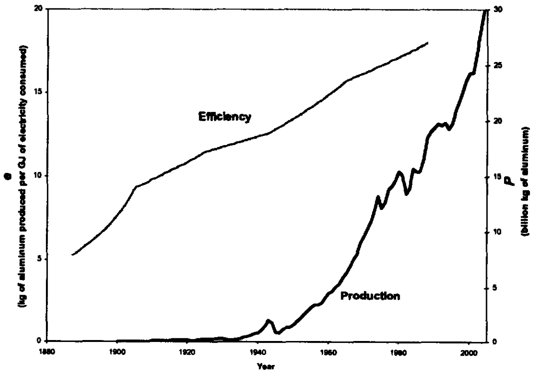


FIGURE 3: Worldwide Nitrogen Fertilizer Production (*P*) and the Energy Efficiency of the Haber-Bosch Process (e) [c]

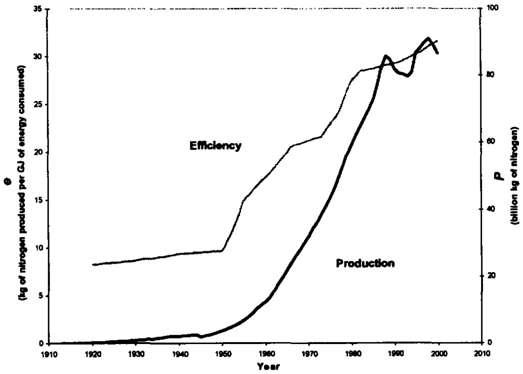


FIGURE 4: Electricity Generation from Coal (*P*) and the Efficiency of Electricity Generation from Coal (e) (US data) [d]

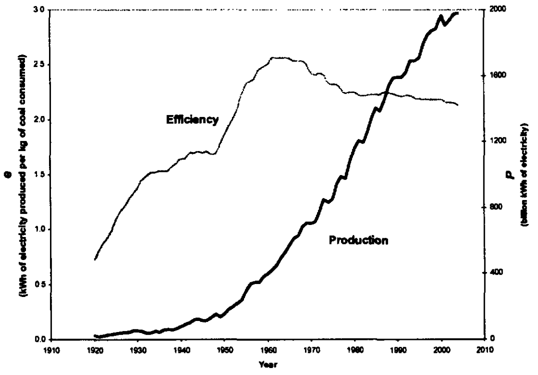


FIGURE 5: Electricity Generation from Oil (*P*) and the Efficiency of Electricity Generation from Oil (e) (US data) [d]

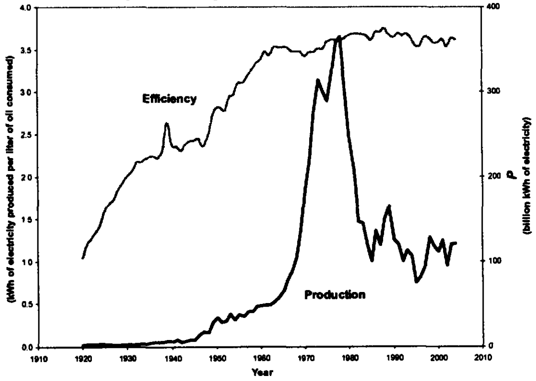


FIGURE 6: Electricity Generation from Natural Gas (*P*) and the Efficiency of Electricity Generation from Natural Gas (e) (US data) [d]

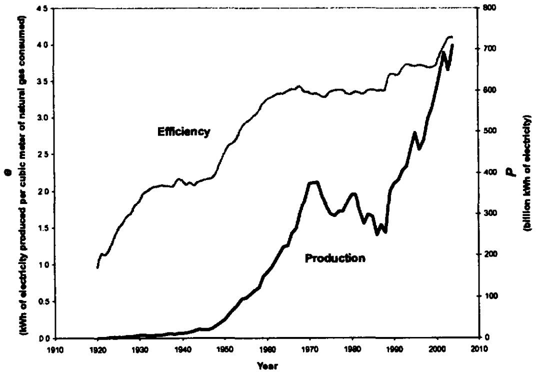


FIGURE 7: Freight Rail Travel (*P*) and the Energy Efficiency of Freight Rail Travel (e) (US Class I railroads) [e]

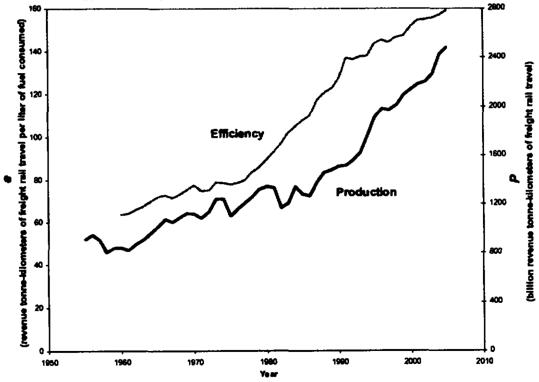


FIGURE 8: Passenger Air Travel (*P*) and the Energy Efficiency of Passenger Air Travel (e) (US airlines) [f]

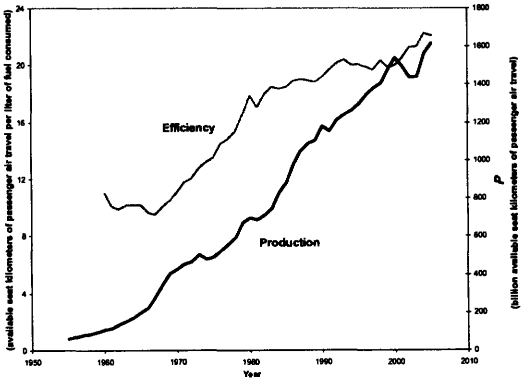


FIGURE 9: Motor Vehicle Travel Produced (*P*) and the Efficiency of Motor Vehicle Travel (*e*) (US data) [g]

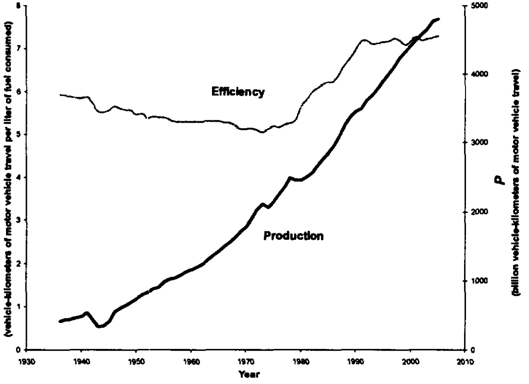


FIGURE 10: Refrigeration Produced (*P*) and the Efficiency of Refrigerators (*e*) (US data) [h]

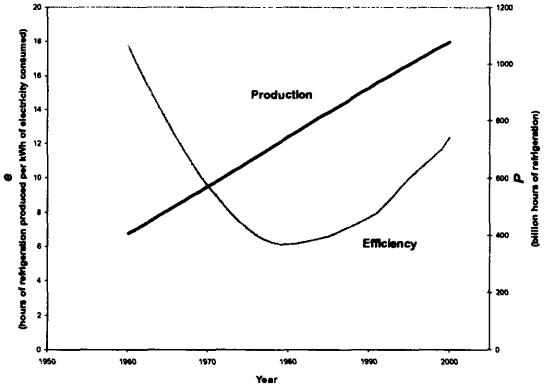


Table 1 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in production, $\Delta P/P$, for the ten activities analyzed in Figures 1 through 10. Positive values for changes in efficiency indicate efficiency improvements, while positive values for changes in production indicate production increases. The historical data clearly show that in each of these industries, the average annual $\Delta P/P$ exceeded the average annual $\Delta e/e$, meaning that, on average, (5) was not satisfied. Thus, despite significant improvements in efficiency, the impact of each of these activities, as calculated using (4), has increased. Figures in Appendix A clearly show this overall increase in impact over the time periods analyzed here.

Industrial Activity	Time Period	Average Annual $\Delta e/e$	Average Annual $\Delta P/P$	Average $\Delta P/P$ / Average $\Delta e/e$
Pig Iron	1800-1984	1.1%	4.1%	3.7
Aluminum	1900-1987	1.0%	11.1%	11.4
Nitrogen Fertilizer	1915-2000	0.9%	9.6%	10.2
Electricity				
from Coal	1920-2005	1.3%	5.8%	4.5
from Oil	1920-2005	1.5%	6.9%	4.5
from Natural Gas	1920-2005	1.8%	9.6%	5.4
Freight Rail Travel	1960-2005	2.0%	2.5%	1.2
Passenger Air Travel	1960-2005	1.3%	6.5%	4.9
Motor Vehicle Travel	1936-2005	0.3%	3.9%	13.0
Refrigeration	1960-2000	-0.9%	2.5%	---

Table 1: Average annual $\Delta e/e$, average annual $\Delta P/P$, and the ratio of the two for ten activities over different time periods. In these activities, increases in production outpace improvements in efficiency by factors ranging from 1.2 to 13.0.

The values in Table 1 can also be shown graphically by plotting the average annual change in production versus the average annual change in efficiency, as shown in Figure 11. The solid diagonal line in Figure 11 is the line of constant impact, representing the condition in which the average annual $\Delta e/e$ is equal to the average annual $\Delta P/P$. Points above this line represent periods of increasing impact, where (5) is not satisfied, while points below this line represent periods of decreasing impact, where (5) is satisfied. From Figure 11, it is clear that in each of the ten cases examined above, (5) is not satisfied.

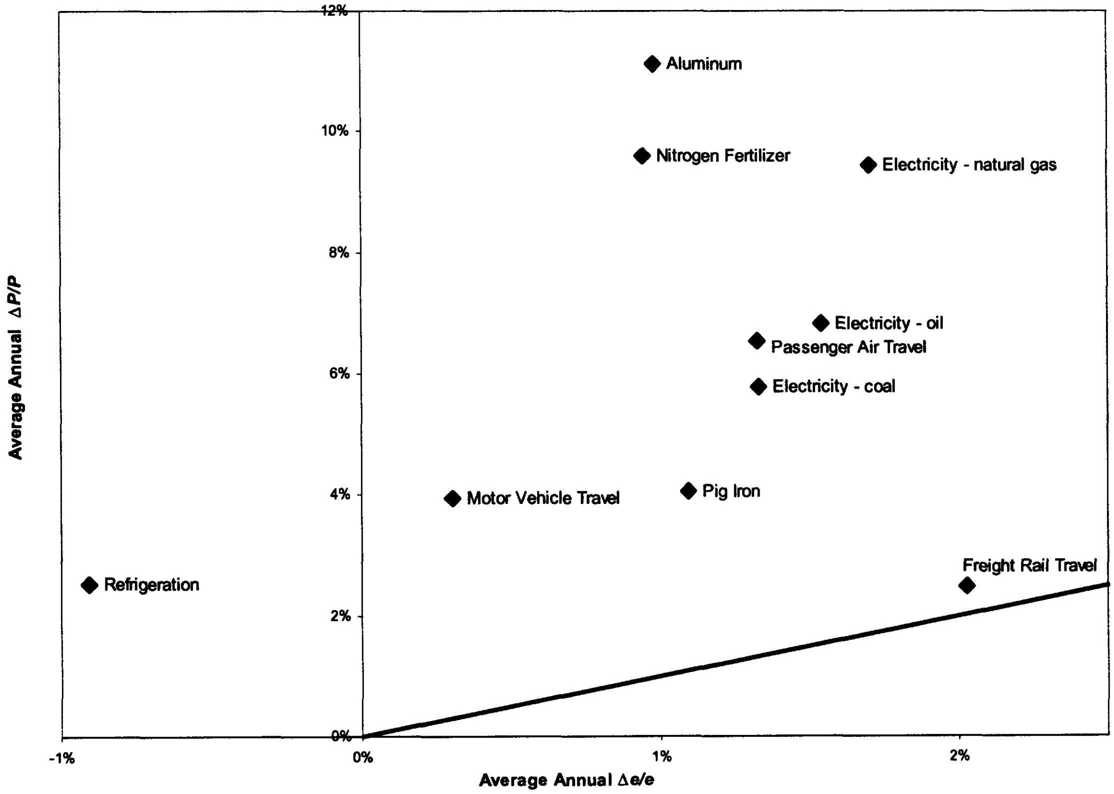


Figure 11: Average annual $\Delta P/P$ versus average annual $\Delta e/e$ for ten activities.

The fact that improvements in efficiency have not been able to outpace increases in production over the long term is perhaps not surprising, particularly given mankind's increasing impact on the earth. However, this inability of past efficiency improvements to reduce impact does bring into question the effectiveness of efficiency improvements as a means of reducing impact in the future.

Decade-by-Decade Analysis

While the long time periods presented above may appear to show little hope for efficiency improvements, a decade-by-decade analysis of these activities reveals a few time periods in which improvements in efficiency did outpace increases in production, resulting in periods of decreasing impact. Two such examples occur in the cases of freight rail travel and passenger air travel. Table 2 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in production, $\Delta P/P$, for freight rail travel and passenger air travel, both overall and on a decade-by-decade basis. As before, positive values for changes in efficiency indicate efficiency improvements, while positive values for changes in production indicate production increases.

Industrial Activity	Time Period	Average Annual $\Delta e/e$	Average Annual $\Delta P/P$
Freight Rail Travel	1960-2000	2.0%	2.5%
	1960-1969	1.7%	3.0%
	1970-1979	1.3%	1.8%
	1980-1989	3.7%	1.4%
	1990-1999	1.9%	3.6%
	2000-2005	1.2%	2.9%
Passenger Air Travel	1960-2005	1.3%	6.5%
	1960-1969	-1.6%	15.6%
	1970-1979	4.7%	5.3%
	1980-1989	1.4%	5.2%
	1990-1999	0.6%	3.0%
	2000-2005	1.8%	1.6%

Table 2: Average annual $\Delta e/e$ and average annual $\Delta P/P$ for freight rail travel and passenger air travel over different decades. The time periods in which average annual $\Delta e/e$ outpaced average annual $\Delta P/P$ are highlighted.

Figures 12 and 13 provide graphical displays of the data in Table 2. As in Figure 11, the dark diagonal lines in Figures 12 and 13 represent lines of constant impact, where the average annual $\Delta e/e$ is equal to the average annual $\Delta P/P$. Points above this line represent periods of increasing impact, where (5) is not satisfied, while points below this line represent periods of decreasing impact, where (5) is satisfied.

FIGURE 12: Average Annual ΔP/P versus Average Annual Δe/e for Freight Rail Travel (US Class I railroads)*

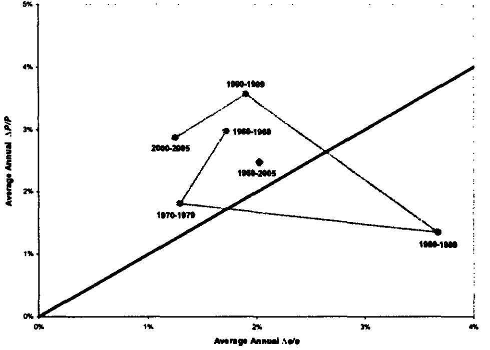
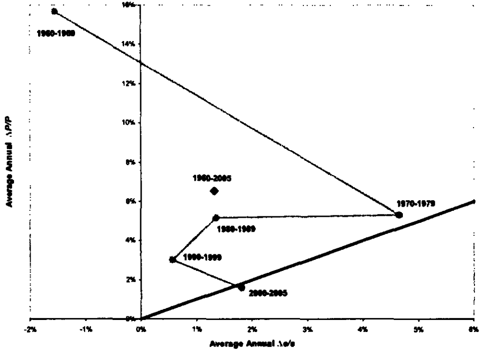


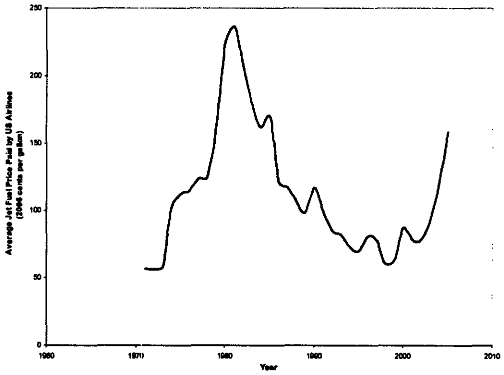
FIGURE 13: Average Annual ΔP/P versus Average Annual Δe/e for Passenger Air Travel (US airlines)[1]



As can be seen in Table 2 and in Figures 12 and 13, both freight rail travel and passenger air travel did have periods in which improvements in efficiency outpaced increases in production. In the case of US freight rail travel, the 1980s marked the only period in which (5) was satisfied. This period featured relatively slower growth in production, and relatively faster improvements in efficiency. In general, the 1980s marked a renaissance in US freight rail travel, as the financial health of the industry improved considerably (Pauly et al. 1980, Duke et al. 1992, Braeutigam 1993). This industry revitalization was driven by various factors, the most important of which was government legislation that deregulated the rail industry. In particular, the Staggers Rail Act of 1980, which, among other things, gave rail companies the freedom to set their own rates and to shut down unprofitable rail lines, helped the rail industry to both increase revenue and reduce costs (Duke et al. 1992, Braeutigam 1993).[18] These actions also had important impacts on fuel efficiency, as fewer lines, now carrying more freight, proved to be more efficient (Business Week 1984, Flint 1986).[19]

In the case of passenger air travel, a shorter, more-recent time period, namely 2000-2005, featured average annual $\Delta e/e$ values that exceeded average annual $\Delta P/P$ values. This period of declining impact can be attributed to both increased improvement in efficiency and decreased growth in production. In the case of efficiency, the increase in average annual improvement was driven in large part by increasing jet fuel prices, as seen in Figure 14. In an industry where fuel costs can at times represent over a quarter of operating costs, increases in jet fuel prices often lead to both operational changes, which improve efficiency in the short-term, and technological changes, which improve efficiency in the long-term (ATA 2007).[20] In the case of production, the decrease in average annual growth was due to a two to three year decline in passenger air travel, as seen in Figure 8, which was driven by numerous factors, including the economic slowdown in the early 2000s, the events of September 11th, 2001, the start of military action in Iraq, and the outbreak of severe acute respiratory syndrome (SARS) in Asia. This decrease in average annual production growth also followed a general trend of declining growth, as seen in Table 2. Whether or not this recent reduction in impact for passenger air travel will continue throughout the rest of this decade, remains to be seen.

FIGURE 14: Historical Jet Fuel Prices[f]



It is also interesting to note the time period from 1970 to 1979, during which the average annual $\Delta e/e$ values for passenger air travel nearly exceeded the average annual $\Delta P/P$ values, as seen in Figure 13. Although (5) was not satisfied, this was a period of relatively stable impact in the industry, as measured by the volume of fuel consumed. This period was marked by both a slower rate of production growth and an increased rate of efficiency improvement, as compared to the previous decade. This increase in the rate of efficiency improvement was again driven in large part by increasing jet fuel prices (Morrison 1984). Although there are of course other influences on fuel efficiency besides fuel prices, in the case of passenger air travel, the two periods of increased efficiency improvement, namely the 1970s and the early 2000s, directly correspond to the two time periods in which real jet fuel prices were increasing.

Another case in which improvements in efficiency did outpace increases in production on a decade-by-decade basis, is refrigeration. For comparison, a related case, but one in which (5) was not met, namely motor vehicle travel, is also examined. Table 3 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in production, $\Delta P/P$, for refrigeration and motor vehicle travel, both overall and on a decade-by-decade basis.

Industrial Activity	Time Period	Average Annual Δe/e	Average Annual ΔP/P
Refrigeration	1960-2000	-0.9%	2.5%
	1960-1969	-5.9%	3.6%
	1970-1979	-4.9%	2.8%
	1980-1989	1.9%	2.2%
	1990-1999	4.6%	1.7%
Motor Vehicle Travel	1936-2005	0.3%	3.9%
	1940-1949	-0.5%	5.3%
	1950-1959	-0.5%	5.2%
	1960-1969	-0.3%	4.3%
	1970-1979	0.4%	3.8%
	1980-1989	2.4%	3.2%
	1990-1999	0.5%	2.5%
	2000-2005	0.5%	1.8%

Table 3: Average annual Δ*e*/*e* and average annual Δ*P*/*P* for refrigeration and motor vehicle travel over different decades. The time period in which average annual Δ*e*/*e* outpaced average annual Δ*P*/*P* is highlighted.

Figures 15 and 16 provide a graphical display of the data in Table 3. The dark diagonal lines in these figures again represent lines of constant impact, where the average annual Δ*e*/*e* is equal to the average annual Δ*P*/*P*.

FIGURE 15: Average Annual Δ*P*/*P* versus Average Annual Δe/e for Refrigeration (US data) [h]

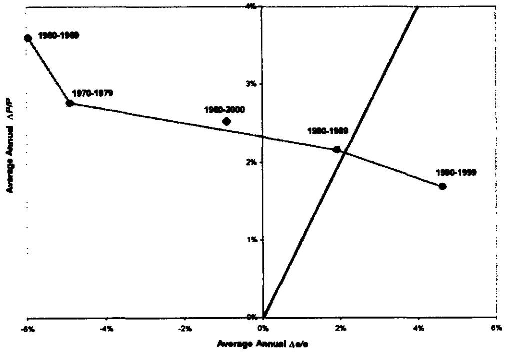
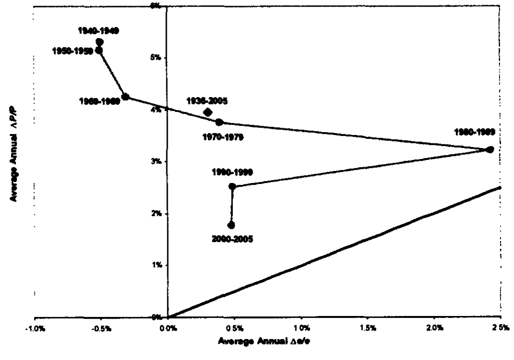


FIGURE 16: Average Annual Δ*P*/*P* versus Average Annual Δe/e for Motor Vehicle Travel (US data) [g]



From Figure 15, it is clear that refrigeration did succeed in crossing below the line of constant impact. The efficiency trends show that prior to the 1980s, refrigerator efficiency decreased.[21] However, after this period, efficiency improved considerably, driven primarily by a series of state and federal efficiency mandates on appliances.[22] Throughout these periods of changing efficiency, production of refrigeration hours increased, albeit at a progressively slower rate, as both the number of American households and the hours of refrigeration used per household increased.[23]

Unlike in the case of refrigeration, motor vehicle travel has never crossed below the line of constant impact, meaning that (5) has never been satisfied. The efficiency data shows an extended period of declining efficiency from the 1940s through the 1960s, as motor vehicles became larger and more powerful.[24] In the 1970s, consumer concerns about gasoline supplies, along with government legislation in the form of Corporate Average Fuel Economy (CAFE) standards, marked the beginning of an extended period of improving efficiency.[25] In the 1980s, when the average annual efficiency improvement peaked, motor vehicle travel did move closer to the line of constant impact, as shown in Figure 16. However, more recently, consumer demand and the lack of updated legislation have allowed the average annual efficiency improvements to decline considerably in magnitude.[26] Meanwhile, throughout these periods of changing efficiency, the number of vehicle-miles of motor vehicle travel produced has increased considerably, as both the number of motor vehicles and the miles traveled per motor vehicle have increased. As in the cases of passenger air travel and refrigeration, the rate of increase in vehicle-miles produced has decreased in each decade, which, if the trend continues, could possibly make future impact stabilization or reduction easier to achieve.

These decade-by-decade analyses show that in the cases of freight rail travel, passenger air travel, and refrigeration, there did exist periods in which efficiency improvements successfully outpaced production increases, meaning that (5) was satisfied and a reduction in impact occurred. Looking forward, it is critical to understand the circumstances that enabled efficiency improvements to outpace production increases in these three cases. If these conditions can be identified and recreated, there exists the possibility that future efficiency improvements could also lead to successful reductions in impact.

Behind Changes in Efficiency and Production

Before examining the circumstances behind these cases in greater detail, the means by which changes in efficiency and production come about, will first be explored. Understanding how these changes are realized helps to explain the complexity of actually satisfying (5).

Efficiency

Improvements in efficiency can be attributed to a number of different factors, from technological innovations to learning effects to market effects.

Technological Innovation

Technological innovation is frequently behind both evolutionary and revolutionary improvements in performance. Often, such performance improvements, when plotted over time, are said to follow an S-shaped technology curve (Ulrich and Eppinger 2000). Such curves typically show limited performance improvement at the start of a new technology, as companies and industries first become aware of an innovation and begin working on it (Otto and Wood 2001). As the technology becomes more widely disseminated and more resources are applied to the problem, a period of rapid improvement ensues (Ibid.). Finally, there is a plateau in performance, as technologies mature and reach their practical and/or thermodynamic limits (Ibid.). In the mature region of the S-curve, further efficiency improvements can sometimes occur by switching to a new technology, which corresponds to jumping to a new S-curve (Foster 1986, Grübler 1998).

For example, consider the case of nitrogen fertilizer production. The invention of the Haber-Bosch process for ammonia synthesis, developed and commercialized in the early 1900s, represented a revolution in nitrogen production, and a jump to a new S-curve.[27] While other industrial methods of nitrogen production did already exist, the Haber-Bosch process was significantly more energy efficient (Tamaru 1991). By the mid-1920s, it had become the most common means of producing nitrogen (Smil 2001).

Following its invention, efficiency improvements in the Haber-Bosch process have roughly followed an S-shaped technology curve, as can be seen in Figure 3. These efficiency improvements have been realized through a broad range of technological innovations, including the use of natural gas instead of coal as a feedstock, the design of improved reactors, the recovery of waste heat, the use of centrifugal compressors instead of reciprocating compressors, and the development of improved catalysts, among others (Dybkjaer 1995, Smil 1999, Smil 2001). As the Haber-Bosch process nears its 100th anniversary, efficiency improvements may be reaching a plateau. Such leveling would not be surprising, as the process is nearing its stoichiometric efficiency limit of 39.4 kg of nitrogen produced per GJ of energy consumed (Smil 2001).

Learning Effect

Efficiency improvements can also come about through improvements in the application of existing technologies. This type of efficiency improvement can be attributed to learning and/or experience, and is often referred to as "learning by doing" or "learning by using" (Grübler 1998, Ruttan 2001). Learning is typically said to occur when the unit cost of production decreases as cumulative experience, often measured as cumulative output, increases (Argote and Epple 1990). Originally identified in the aircraft industry, learning effects have been seen in many different activities, from shipbuilding to power plant construction (Searle 1945, Joskow and Rose 1985). The improvements in efficiency resulting from learning can be quite impressive. For example, in the case of Liberty ships built for the US and its allies for use in World War II, between December 1941, the delivery date of the first Liberty ship, and December 1942, the average number of man-hours per ship decreased 45% and the average days per ship decreased 76% (Searle 1945). Overall, across ten different shipyards, the average number of labor hours required to build a Liberty ship decreased by around 20% for each doubling of output (Ibid.).

In the case of learning effects, production drives efficiency. Thus, while (5) shows that in order to reduce impact, the rate of efficiency improvements must exceed the rate of production increases, the existence of learning effects means that these two measures are often in fact positively correlated.

Market Effect

While longer-term efficiency improvements are largely driven by technological innovation and learning effects, shorter-term efficiency changes can come about through market dynamics, such as through dips or surges in demand. In some cases, short-term efforts to scale-back production, can lead to an improvement in efficiency, as operations are streamlined and less-efficient equipment is shelved. Conversely, short-term efforts to scale-up production, can lead to a decline in efficiency, as all available equipment, including less-efficient equipment, is brought into use. In general, this negative correlation between production and efficiency appears to be brought about by dynamic markets, and is most commonly seen in industries with high capital costs and/or long lead-times for capital equipment.

As an example, consider the case of passenger air travel in the early 2000s. With the precipitous decline in passenger air travel during this time, airlines, facing a surplus of capacity, scaled-back operations by removing excess aircraft from service (Perez et al. 2003, Setaishi 2003, Wong 2003). In general, the planes that were the most costly to operate, which often corresponded to the planes that were the least fuel efficient, were parked, thereby increasing overall fuel efficiency in the short-term.[28] Thus, in this situation, sharp decreases in production drove short-term efficiency gains, as airlines adapted to changing market conditions (McCartney and Carey 2003).

While in the recent case of passenger air travel, efficiency improved as production decreased, the opposite can also occur. Consider the case of freight rail travel in the late 1980s and early 1990s, a period marked by increases in the production of revenue tonne-kilometers of freight rail travel. This increase in production led to an increase in demand for locomotives, which was in turn met by increasing the production of new, more-efficient locomotives, as well as by increasing the repair and refurbishment of older, less-efficient locomotives, some of which had previously been idled (Holusha 1989, Kruglinski 1993). Thus, this surge in production pushed older, less-efficient machines back into use, contributing to a decrease in average annual efficiency gains. Over longer time periods, more new locomotives were brought into use to meet the surging demand. However, in the short term, production and efficiency were negatively correlated.

Production

Much like changes in efficiency, changes in production can also be attributed to many different factors, including consumers, consumer demand, and efficiency.

Consumers and Consumer Demand

It is clear that consumers have a large impact on production. As the population of consumers increases, and/or as the affluence of consumers increases, production typically increases to meet this surging demand.[29] In fact, in this work, production is defined as the product of population and affluence, where affluence is represented as production over population. Using this definition, it is not surprising that increases in population and affluence have, over time, driven increases in production.

Changing consumer taste can also play an important role in production. For example, in the case of passenger air travel, the number of available seat kilometers produced has been affected by changes in consumer preferences, as consumers have increasingly chosen air travel over other transportation options, including bus, train, and boat travel. Of course, these changing consumer attitudes have themselves been driven by various factors, including technological innovations that have led to improvements in the safety, cost, and convenience of air travel. Had air travel not improved, it is likely that consumer preferences, and production increases to keep pace with consumer preferences, would not have changed as dramatically.[30]

Rebound Effect

Another mechanism by which efficiency drives production is through the rebound effect. As early as 1865, W. Stanley Jevons observed that improvements in efficiency can in fact lead to increases in production. Observing coal mining in the United Kingdom, Jevons wrote,

> "It is wholly a confusion of ideas to suppose that the economical use of a fuel is equivalent to a diminished consumption. The very contrary is the truth." (Jevons 1865).

This idea, alternately known as "Jevons' Paradox," the "rebound effect," and the "take back effect," has been the subject of much debate in the economics and energy policy literature (Herring 1998, Hertwich 2005, Herring 2006). At its root however, is the idea that efficiency improvements lead to a decrease in the effective price of a good or service. This price reduction, given a sufficient price elasticity of demand, leads to increased demand.

The mechanisms behind the rebound effect can be explained at both the microeconomic and macroeconomic level. At the microeconomic level, the decrease in the effective price of a good or service resulting from an improvement in efficiency leads to both a substitution effect and an income effect. In the case of the substitution effect, in which the level of utility remains constant, more of the now less-expensive good or service is consumed instead of other goods and services (Pindyck and Rubinfeld 2001, Lovell 2004). In the case of the income effect, in which the level of utility increases, more of all goods and services are consumed, reflecting an increase in real purchasing power (Ibid.). In both cases, exactly how much more is consumed depends on the price elasticity of demand for these goods and services. While the substitution effect always leads to greater consumption, the income effect can lead to either an increase or a decrease in consumption, depending on the type of good.[31] In most cases however, there is an overall increase in consumption, as the substitution effect is typically larger in magnitude than the income effect (Pindyck and Rubinfeld 2001). At the macroeconomic level, efficiency improvements lead to broader effects, including economy-wide changes in the price of other goods and services and factor substitution in economic growth (Brookes 1990, Brookes 2000, Greening et al. 2000). Efficiency improvements can in fact drive economic growth, which in turn can lead to an increase in overall production (Brooks 1990, Saunders 1992, Saunders 2000, Stern 2004).

In large part, the debate about the rebound effect comes down to a debate about the size of the rebound. Some argue that the size of the rebound is insignificant, meaning that efficiency improvements of a given amount will lead to impact reductions of approximately the same amount (Lovins 1988, Grubb 1990, Grubb 1992). Others argue that the size of the rebound is sufficiently large to be of significance and that in some cases, an improvement in efficiency can in fact lead to an increase in impact (Khazzoom 1980, Khazzoom 1982, Khazzoom 1987, Khazzoom 1989, Brookes 1990, Brookes 1992). While efforts have been made to quantify the rebound effect, these measurements only take into account the microeconomic effects, also known as the direct rebound effect, not the macroeconomic or indirect rebound effects.

The size of the direct rebound effect can vary greatly, depending on the price elasticity of demand, which in turn depends on many factors, including the economic actors involved, the goods or services in question, and the length of time since the efficiency improvement. In a survey of measured direct rebound effects in the US, some categories, such as appliances or "white goods", showed essentially no rebound, while other categories, including automobile transport, showed noticeably larger rebound (Greening et al. 2000). In the case of automobile transport, the rebound effect, expressed as the percentage increase in consumption resulting from a 100% improvement in efficiency, was estimated to be between 10 and 30% (Ibid.). Research into the magnitude of the direct rebound for other goods and services has, in some cases, shown larger rebounds, particularly among lower-income populations (Milne and Boardman 2000, Roy 2000). While many of the measurements of direct rebound, including the ones mentioned above, have focused on rebound in the residential and transportation sectors, there have also been some attempts to measure rebound in industry. Estimates of direct rebound in industry resulting from improvements in energy efficiency vary, depending on country, energy prices, and measurement approach, but generally range from 0 to 25% (Berkhout et al. 2000, Greening et al. 2000, Bentzen 2004). Accurate measurements of the size of the complete rebound effect, including direct and indirect effects, are difficult given the many factors involved and the broad range of macroeconomic consequences of efficiency improvements (Smil 2003).

Discussion

There are clearly many factors that contribute to changes in efficiency and production. It is also clear that efficiency and production are coupled, meaning that the terms in (5) are not independent. Thus, in order to reduce impact, one cannot simply focus on a single term in (4), but must instead approach this as a system problem.

Looking at the periods of impact reduction in the cases of freight rail travel, passenger air travel, and refrigeration, it is apparent that different circumstances drove each case. For freight rail travel, the period of impact reduction in the 1980s was attributable to a major upheaval in the industry, driven by deregulation. For passenger air travel, price pressures, namely increases in jet fuel prices, led to a period of declining impact in the early 2000s. For refrigeration, government efficiency mandates led to impact reduction in the 1990s. Of these different circumstances, it appears that two of them, namely price mechanisms and efficiency mandates, are reproducible, and thus represent potential approaches for future impact reduction. The third, industrial transformation, is harder to recreate.

Efficiency Mandates

In attempting to use efficiency mandates to realize impact reductions, the size of the rebound effect can be critical to success. With little or no rebound, both direct and indirect, efficiency mandates can lead to a case in which (5) is satisfied. However, with more considerable rebound, efficiency mandates may, at best, lead to impact reductions that are smaller in magnitude than expected; at worst, efficiency mandates may lead to larger overall impact. In fact, efficiency mandates could lead to larger impacts more quickly than without efficiency mandates.

Residential refrigeration is an ideal candidate for efficiency mandates, as appliances exhibit essentially no direct rebound (Greening et al. 2000). As the efficiency of refrigerators improves, the effective price of refrigeration decreases. In response, consumers can increase their utilization of refrigerators and/or increase their ownership of refrigerators (Khazzoom 1982). However, since refrigerators typically run constantly, increasing utilization is difficult. Increasing ownership is possible through the use of additional refrigerators, but over 80% of US households still find one refrigerator to be sufficient (US DOE 2001). With low price elasticities of demand in both utilization and ownership, there is little rebound. Thus, efficiency mandates have worked very well in the case of refrigeration.[32]

Efficiency mandates for other goods and services with little rebound may also prove successful. For example, efficiency mandates on other appliances may lead to impact reductions, as the direct rebound on "white goods" is essentially zero (Greening et al. 2000). Motor vehicle travel, with a direct rebound effect between 10 and 30%, may also represent a case in which efficiency mandates can lead to impact reduction (Ibid.). While the existence of rebound effects may erode some of the overall impact reduction, efficiency mandates on motor vehicles may still prove to be successful. Indeed, past efficiency mandates on motor vehicles did play a role in helping to move motor vehicle travel closer to impact reduction in the 1970s and 1980s, as can be seen in Figure 16. In general, applying efficiency mandates to activities with little to no rebound seems to be an attractive approach to satisfying (5), and thus reducing impact.

Price Pressures

Price pressures also appear to be a promising approach to realizing impact reductions, although the exact effect depends largely on the short-run and long-run price elasticities of demand. In the case of durable goods, which have high short-run price elasticities of demand and lower long-run price elasticities of demand, price increases can lead to sizeable decreases in demand in the short term, but a recovery in demand in the long term. For non-durable goods, which have low short-run price elasticities of demand and higher long-run elasticities of demand, price increases can lead to limited decreases in demand in the short term, and efficiency improvements in the long term. While these efficiency improvements resulting from price increases can eventually lead to increases in demand through the rebound effect, the short-term decrease in demand that price pressures induce may serve to balance out this later increase in demand. In this regard, efficiency improvements that come about through price mechanisms may have an advantage over efficiency improvements that come about through efficiency mandates.

In the case of passenger air travel, price pressures, in the form of increased jet fuel prices, did help lead to a period of impact reduction. With no real substitutes for jet fuel, passenger airlines were forced to find other means by which to compensate for rising fuel prices, from passing on higher costs to consumers through measures such as fuel surcharges, to improving fuel efficiency through measures such as reducing aircraft weight (Pindyck and Rubinfeld 2001, Sharkey 2004, Heimlich 2007). Thus, in this case, the low short-run price elasticity of demand for jet fuel did help to spur efficiency improvements in the longer term (Pindyck and Rubinfeld 2001).

Using price pressures to reduce the impact of other goods and services may also prove successful. For example, in the case of automobile travel, the price elasticity of demand for motor fuel follows that of most non-durable goods. Thus, increases in the price of motor fuel could lead to a small drop in demand in the short term, and efficiency improvements in the long term (Pindyck and Rubinfeld 2001). Interestingly, the real price of motor fuel in the US has been on the rise recently, increasing by about 66% over the five-year span from early 2001 to early 2006 (Krauss et al. 2007). However, despite this increase, there has been little change in demand for fuel, and only a slow shift towards more fuel-efficient motor vehicles (Hughes et al. 2006, Krauss et al. 2007). While these price increases have not yet decreased demand and/or spurred efficiency enough to satisfy (5), it remains to be seen whether or not these market-driven price pressures will continue in the future, and whether or not they will someday be sufficient to bring about an overall reduction in impact.

While the price pressures in the cases of airline passenger travel and motor vehicle travel came from market forces, other price pressures may need to be legislated, perhaps through taxation. Although introducing new taxes is politically difficult, it may prove to be an effective approach to reducing impact. Of course, the size of the price increase does play an important role, both in terms of political feasibility and in terms of effect. Thus, much care must be taken to apply appropriate price pressures to allow for impact reduction without hindering economic growth. For cases in which considerable price increases may be necessary, efficiency mandates may prove to be the more politically-feasible approach (Hughes et al. 2006).

Updates

In order to continue to realize impact reductions over the long term, it appears that both efficiency mandates and price pressures should be updated regularly. Without constant updating, the rate of efficiency gains will revert back to previous levels, and old dynamics may return. For example, in the case of motor vehicle travel, the failure to update past efficiency mandates, among other factors, reversed a trend towards increasing rates of efficiency improvement. Instead, the old dynamics returned, with average annual production growth outpacing average annual efficiency improvements by a sizeable margin. On the other hand, in the case of refrigeration, continually-updated efficiency mandates eventually led to impact reduction. In the case of price mechanisms, the increases in the rate of efficiency improvement in passenger air travel during periods of increasing fuel prices, and the decreases in the rate of efficiency improvement during periods of decreasing fuel prices, also seem to suggest the importance of continually applying price pressures.

Conclusion

Historically, past efficiency improvements have not proven to be successful in reducing mankind's impact on the earth. Of the over 75 decades examined across ten activities, only three decades had rates of efficiency improvement that outpaced rates of production increase. In these three cases, efficiency mandates, price pressures, and industry upheaval contributed to these periods of decreasing impact. Based upon this evidence, it does appear that efficiency mandates and price pressures, given certain conditions, may prove effective in reducing impact. However, efficiency improvements without external pressures or mandates, do not appear to lead to impact reductions.

It seems that much of the debate over the effectiveness of efficiency improvements in reducing impact comes down to a matter of system boundaries. To engineers, who generally draw their system boundaries at the level of an individual product or process, the beneficial effects of efficiency improvements on the environment seem clear. However, to economists, who generally draw their system boundaries at the level of the society or the economy as a whole, the beneficial effects of efficiency improvements on the environment is much less clear. Khazzom captures this issue of system boundaries with the succinct comment,

> "For the laboratory engineer, a 3-percent improvement in efficiency will always mean, as it should, a 3-percent reduction in energy, since the engineers's (sic) basic assumption is that the appliance will be used to derive the same amount of service as before. But this result cannot be extended mechanically from the laboratory to society. Consumers cannot be assumed to be oblivious to the economic consequences of changing efficiency." (Khazzom 1980).

As engineers, it is critical to understand how product- and process-level efficiency improvements play out in the larger system. While working on such efficiency improvements is worthwhile from an economic and social perspective, it is not necessarily worthwhile from an environmental perspective. Instead, as the many links between efficiency and production have shown, improvements in efficiency can in some cases simply lead to more production and greater impact.

While engineers should continue to pursue efficiency improvements, such improvements may need to be combined with appropriate conditions or policies in order to realize impact reduction.

The true message for engineers and others who encourage efficiency-based solutions to our environmental problems, is that product- and process-level efficiency improvements, in the absence of external pressures or mandates, do not equate to system-level impact reductions. Thus, improving efficiency should not be thought of as a goal by itself. Instead, the true goal must be to reduce environmental impact.

Appendix A

Figures A1 through A10 show increasing impact for the activities shown in Figures 1 through 10.

FIGURE A1: Impact (*I*) of Worldwide Pig Iron Production [a]

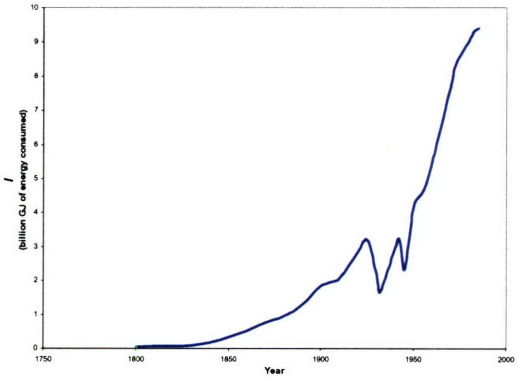


FIGURE A2: Impact (*I*) of Worldwide Primary Aluminum Production [b]

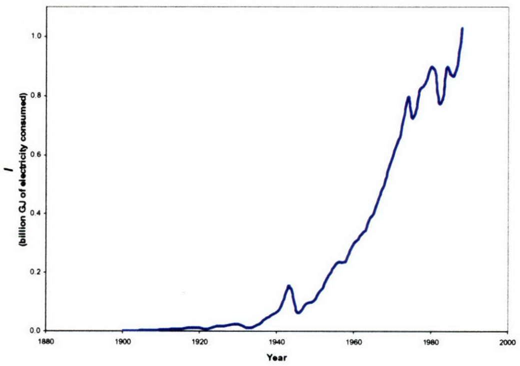


FIGURE A3: Impact (*I*) of Worldwide Nitrogen Fertilizer Production [c]

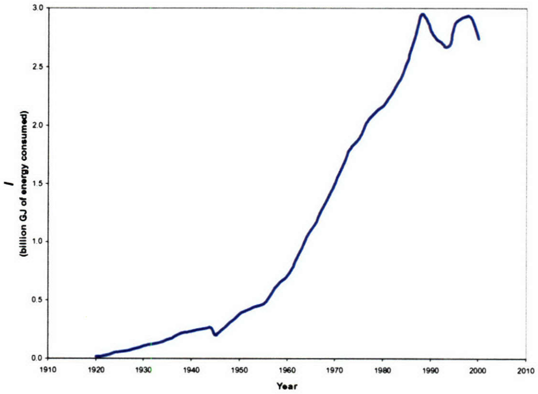


FIGURE A4: Impact (*I*) of Electricity Generation from Coal (US data) [d]

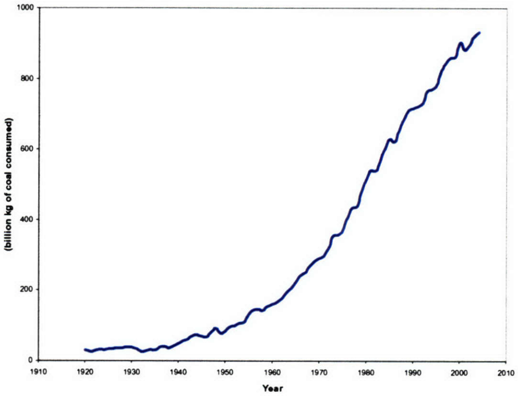


FIGURE A5: Impact (*I*) of Electricity Generation from Oil (US data) [d]

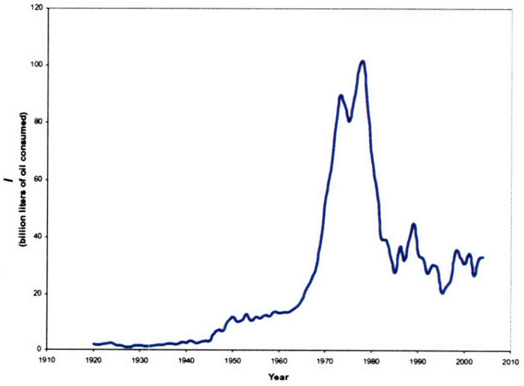


FIGURE A6: Impact (*I*) of Electricity Generation from Natural Gas (US data) [d]

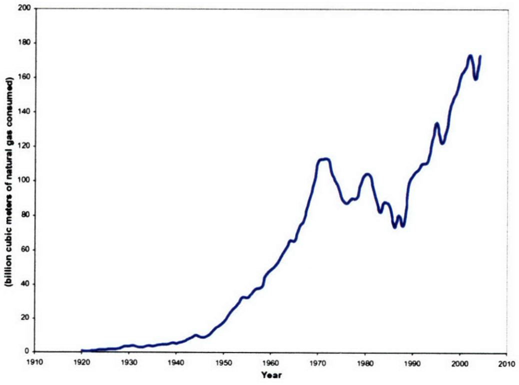


FIGURE A7: Impact (*I*) of Freight Rail Travel (US Class I railroads) [e]

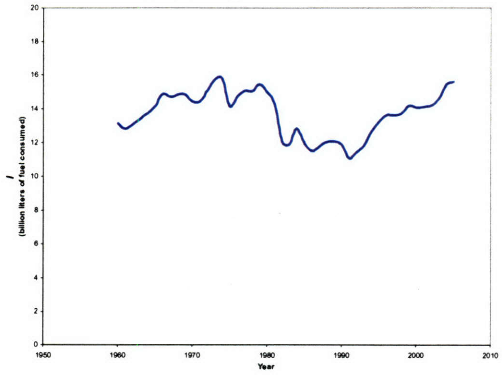


FIGURE A8: Impact (*I*) of Passenger Air Travel (US airlines) [f]

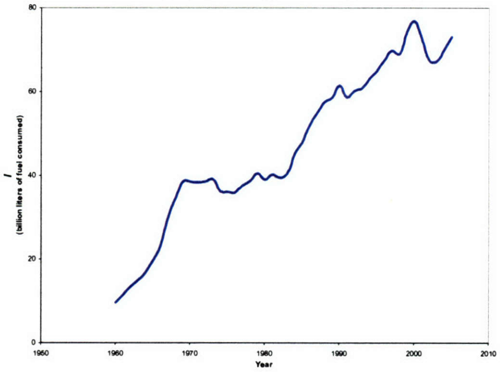


FIGURE A9: Impact (*I*) of Motor Vehicle Travel (US data) [g]

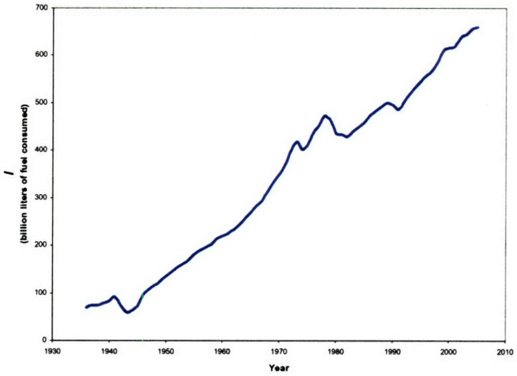
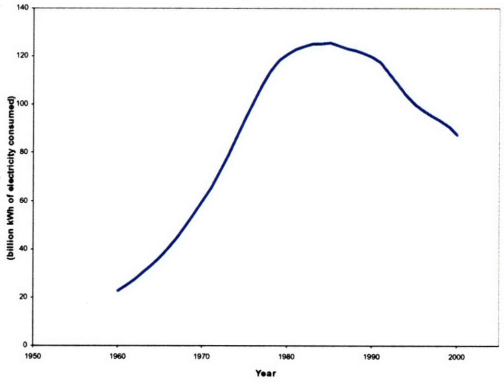


FIGURE A10: Impact (*I*) of Refrigerator Use [h]



Notes

1. The efficiency described here is different from the typical engineering efficiency. While engineering efficiency is often defined as output over input for a single variable, for example energy output over energy input, eco-efficiency is typically a ratio of two variables, for example production output over energy input. In this paper, "efficiency" refers to eco-efficiency.

2. Since efficiency is simply production over impact, this characterization of efficiency also provides a characterization of production and impact. Production is thus measured in terms of dollar figures or production quantities, while impact is measured in terms of resource consumption or emissions output. While this measure for production is quite typical, this measure for impact may not be. In this work, the use of the term "impact" to measure resource consumption is different from the use of this term in life cycle assessment, where "impact" is used to measure environmental effects, such as global warming potential or ozone depletion potential. In the vernacular of life cycle assessment, the "impacts" measured here would typically be considered "inventories".

3. For the remainder of this paper, P will represent total production, not population.

4. The efficiency data used in the pig iron analysis comes from the UK (1760-1910), the US (1910-1940), and Japan (1940-1985), and thus represents some of the most efficient technology available for pig iron smelting at a given time. The actual global average efficiency would be lower, given the technologies in use in less technologically-advanced countries.

5. The Hall-Heroult process, independently invented in 1886 by Charles Hall in the US and Paul Heroult in France, is the process by which aluminum oxide, produced from bauxite, is reduced, producing aluminum. The Hall-Heroult process is the primary method of aluminum production.

6. The Haber-Bosch process, invented by Fritz Haber and commercialized by Carl Bosch in the early 1900s, is the process by which ammonia is synthesized from nitrogen and hydrogen. The Haber-Bosch process is the primary method of nitrogen fertilizer production. The efficiency data used in the nitrogen fertilizer analysis represents the most efficient technology available at a given time. Thus, the actual global average efficiency would be lower, given the technologies in use in less technologically-advanced plants.

   The noticeable drop in nitrogen fertilizer production in the late 1980s and early 1990s can be attributed primarily to the decline of the Soviet Union. In 1988, the Soviet Union was the world's largest producer of ammonia, with over 15 billion kilograms of nitrogen produced (Smil 2001). However, by 1996, the former Soviet states combined for only about half of the production quantity of 1988 (Ibid.).

7. In the case of electricity generation from coal, shown in Figure 4, the efficiency trends demonstrate an extended period of improving efficiency followed by an extended period of

slowly declining efficiency. This long downward trend in efficiency is attributable to various factors, including fuel substitution and power plant efficiencies.

The increased use of low-sulfur bituminous coal provides one likely explanation for the decline in the efficiency of electricity generation from coal. As part of the 1970 Clean Air Act, controls on certain emissions from power plants, including sulfur dioxide, nitrogen oxides, and particulates, were established. Such legislation led to the implementation of various emission reduction strategies at coal-fired power plants, from implementing flue-gas desulfurization units to switching to low-sulfur coal (Ellerman et al. 2000). This low-sulfur coal, which is primarily found in the Western US, also has lower heating values. Thus, the use of Western low-sulfur coal resulted in lower overall electricity generation efficiencies, as measured in units of electricity produced per mass of coal consumed. It should be noted that efficiency could have been measured with respect to an environmental load other than resource consumption. For example, efficiency could have been measured in units of electricity produced per mass of sulfur dioxide emitted. In this case, efficiency may have increased, not decreased, as a result of the Clean Air Act.

Another possible explanation for this downturn in efficiency is the plateauing of power plant efficiencies. The 1970 Clean Air Act, as described above, established stricter pollution controls on power plants. However, existing power plants were exempt from these new regulations. This resulted in many companies choosing to maintain old power plants that were exempt from these regulations, instead of building new power plants that would be subject to these regulations. This had the effect of locking-in existing equipment and efficiencies. It is also interesting to note that around this same time, the thermal efficiency of steam turbines, a critical component of power plants, was beginning to plateau, after almost a century of improvement (Smil 1999).

8. Figure 5, which plots efficiency and production data for electricity generation from oil, shows large fluctuations in production but relatively steady improvements in efficiency. This variation in production is due to both price and supply volatility for oil, as well as to various policy interventions.

   In the late 1960s, electricity generation from oil increased dramatically, primarily because of low oil prices, but also due to environmental reasons, as oil burns more cleanly than coal. With the oil embargo of 1973, oil prices increased dramatically. However, due to severe shortages in other fuels used for electricity generation, namely natural gas, the use of oil for electricity generation continued well into the 1970s. In 1978, the Powerplant and Industrial Fuel Use Act was passed, restricting the construction of power plants that used oil or natural gas. This, along with the Iranian oil shock of 1979, led to a rapid decline in the production of electricity from oil. Since then, electricity generation from oil has fluctuated considerably, but the general trend has been to move away from the use of oil for this purpose.

9. In the case of electricity generation from natural gas, shown in Figure 6, there are significant fluctuations in production but relatively steady improvements in efficiency. As in the case of electricity generation from oil, this variation in electricity production from natural gas is due to both price and supply volatility for natural gas, as well as to various policy interventions.

In the 1950s and 1960s, government price regulation of natural gas led to declines in production and increases in demand (Tugwell 1988). This combination brought about severe natural gas shortages in the 1970s. During these times of limited supply, homes and businesses were given priority over electricity generation facilities. Thus, electricity generation from natural gas during the 1970s and into the 1980s was quite volatile. This uncertainty of supply, along with the 1978 Powerplant and Industrial Fuel Use Act, which, as discussed previously, restricted the construction of power plants that used oil or natural gas, brought about an overall decline in electricity generation from natural gas during the 1970s and 1980s. The repeal of parts of the Powerplant and Industrial Fuel Use Act in 1987, combined with falling natural gas prices, helped to bring about a resurgence in the use of natural gas for electricity generation that has continued to this day.

10. When looking at products during the use phase, it is perhaps more common to look at the amount of goods or services consumed by the customer, not the amount of goods or services produced by the product. For example, in the case of refrigerators, it is perhaps more common to consider the hours of refrigeration consumed, not the hours of refrigeration produced. However, if one assumes that supply meets demand, the number of hours of refrigeration consumed is equal to the number of hours of refrigeration produced. Referring to the output of the use phase as goods and services produced, instead of as goods and services consumed, does not change the results. In fact, if the affluence term in (1) were to be represented as consumption per population instead of production per population, and if the technology term in (1) were to be represented as impact per consumption instead of impact per production, (4) could correctly be written as

$$Impact\ = Consumption\ x\ \frac{1}{Efficiency}.$$

In order to reduce impact while maintaining economic growth, (5) would then become,

$$\frac{\Delta e}{e} > \frac{\Delta C}{C} > 0,$$

where e represents efficiency and C represents consumption.

11. In the US, freight railroads are categorized using a system designated by the Surface Transportation Board. This classification system has three categories, Class I, Class II, and Class III, which are based on operating revenue. In 2005, Class I railroads had operating revenues of $319.3 million or more, Class II railroads had operating revenues between $25.5 million and $319.2 million, and Class III railroads had operating revenues less than $25.5 million (AAR 2006). These monetary cut-offs are adjusted annually for inflation.

In 2005, there were only seven Class I railroads in the US, including railroads such as Norfolk Southern, Union Pacific, and CSX Transportation. Although limited in number, Class I railroads accounted for 68% of all US freight rail mileage and 93% of all US freight rail revenue in 2005 (Ibid.).

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12. Revenue tonne-kilometer (RTK) is a measure of production for freight railroads. RTK values can be obtained by multiplying the number of revenue-generating tonnes of freight by the distance, in kilometers, that each paid tonne of freight travels. One RTK represents one revenue-generating tonne of freight traveling one kilometer.

    Efficiency of freight rail travel is measured in RTKs of freight rail travel per volume of fuel consumed, where the fuel consumed is diesel. While other types of fuel have been used for freight rail travel, by 1960, over 97% of the locomotives used by Class I railroads in the US were diesel (AAR 1965). Since then, diesel has remained the most popular fuel for freight rail.

13. Available seat kilometer (ASK) is a measure of production or capacity for airlines. ASK values can be obtained by multiplying the number of seats available for passengers by the distance, in kilometers, that each of those seats is flown (Bazargan 2004). One ASK represents one seat traveling one kilometer.

14. The term "motor vehicle", refers to virtually all vehicles on the road, including passenger cars, motorcycles, buses, and trucks.

15. Vehicle-kilometer is a measure of production for motor vehicles. Vehicle kilometer values can be obtained by multiplying the number of motor vehicles by the distance, in kilometers, that each vehicle travels. One vehicle-kilometer represents one vehicle traveling one kilometer.

16. The noticeable smoothing of the data in the case of refrigeration is due to both limited data, in the case of production data, and fleet averaging, in the case of efficiency data. For annual production data, values between limited data points were obtained using a third order polynomial with an r-squared value of approximately 0.99996. The annual efficiency data for refrigeration is a measure of the average efficiency of the refrigerators in service in a given year. This value is obtained by using both the efficiency data for new refrigerators in a given year and data about the age distribution of the refrigerator fleet in a given year (Rosenfeld 1999, US DOE 1993, US DOE 1997, US DOE 2001).

17. In the cases of motor vehicle travel and refrigeration, earlier trends of declining efficiency were reversed in large part due to government efficiency mandates. While the efficiency of other activities, including electricity generation, freight rail travel, and passenger air travel, were clearly also affected by legislation, motor vehicle travel and refrigeration were unique in that in these cases, efficiency itself was explicitly legislated. These cases, and the efficiency mandates that contributed to these cases, will be discussed later in greater detail.

18. Giving rail companies the ability to set their own rates and to shut down unprofitable rail lines had a number of important ramifications. First, the ability to set their own rates made the rail industry much more competitive with trucking, as rail was now able to negotiate individual contracts for each customer (Williams 1985, Flint 1986). This ability to set rates also allowed rail companies to fill trains will low-rate cargo in order to avoid empty mileage, which in some years could account for 40% of total miles (Flint 1986). This reduction in empty mileage helped to improve both profitability and fuel efficiency. The fact that rail

companies could now close down unprofitable sections of track allowed for a reduction in operating costs, which also improved profitability.

Another factor driving the revitalization of the industry was the increase in oil prices in the 1970s, which had two important effects. The high oil prices made transport by freight rail, which is more fuel efficient per tonne-kilometer than transport by truck, more attractive, thus helping rail to gain market share (Pauly et al. 1982, Williams 1985, Railway Age 1990, Duke et al. 1992). The high oil prices also helped to increase demand for domestic coal. Railroads, which provided the most effective means of transporting coal from Western mines to US factories and utilities, thus benefited greatly (Pauly et al. 1980).

19. The deregulation of the rail industry led to many other efficiency improvements. The ability to set rates allowed rail companies to fill trains that may have previously run empty on return trips with low-rate cargo, thus improving efficiency (Flint 1986). The ability to close unprofitable rail lines allowed companies to discontinue service on less-traveled sections of track, sections that had in some cases deteriorated to the point that trains were forced to travel as slowly as 10 miles per hour (Pauly et al. 1980). The closing of rail lines, along with a recession-related equipment surplus in the early 1980s, allowed some older, less-efficient equipment to be removed from service (AAR 1983).

Other operational and technological changes also led to further efficiency improvements. For example, operational changes by train engineers, including reducing unnecessary braking and reducing acceleration rates, led to noticeable improvements (Railway Age 1990, Shedd 1984). Changes in train dispatching, including the increased use of computers in scheduling and routing trains, also led to efficiency improvements (Shedd 1984, Omaha World-Herald 1984, Houston Chronicle 1986). In equipment, new innovations in cargo haulers, including the use of piggyback trains, in which containers and trailers, and sometimes double-stacked containers and trailers, are carried on flat rail cars, increased the type and amount of freight that could be transported by a single train (Williams 1985, Flint 1986, Duke et al. 1992). Other changes in equipment, including the introduction of high-efficiency, microprocessor-controlled locomotives, and the use of advanced wheel slip-control systems, also improved fuel efficiency, although such improvements generally took longer to manifest themselves at the fleet level (Shedd 1984, Houston Chronicle 1986).

20. There are many different approaches to improving fuel efficiency in passenger air travel, from improvements in aircraft and engine technology to operational changes. While each of these approaches can improve fuel efficiency, the time scales over which these improvements are realized can differ greatly. In the case of changes to aircrafts and engines, the long lifespan of aircraft, typically around 25 years, results in a considerable lag in technology (IPCC 1999, Lee at al. 2001). In general, it takes about 10 to 15 years for the US aircraft fleet to reach the efficiency levels of a new aircraft (Lee at al. 2001). This lag, along with considerable time spent in development, certification, and production, means that an increased interest in fuel efficiency by the air travel industry may not manifest itself in the aerodynamic and engine efficiency of the aircraft fleet for quite some time. Some have estimated this time delay between initial development and actual impact at the fleet level to be as much as 25 years (Ibid.).

While improvements to aircraft and engines take some time to manifest themselves, there are operational changes that can yield more immediate results. Improvements in air traffic management, including reducing air and ground delays, improving flight routing, and, more recently, reducing vertical separation minimums, can lead to considerable increases in fuel efficiency (IPCC 1999, Lee et al. 2001, ICF 2005, McCartney 2006). Other common operational approaches to improve fuel efficiency include reducing aircraft weight, by removing unnecessary equipment such as magazines and seat-back phones, and reducing aircraft drag, by lowering cruising speeds and implementing stricter repair and maintenance programs (McCartney 2006, Heimlich 2007). Together, these various operational changes can lead to immediate improvements in fuel efficiency. It is important to point out that increasing passenger load factors, a technique that has been employed frequently by airlines in recent years, improves efficiency on a revenue passenger kilometer (RPK) basis, but not on the available seat kilometer (ASK) basis used here. The number of ASKs, multiplied by the passenger load factor, yields the number of RPKs.

21. This decrease in efficiency was due to various factors, including additional refrigerator features and increased refrigerator size.

22. Starting in the 1970s, states, in particular California, began mandating minimum efficiency requirements on new household appliances (Gellar 1995). These requirements were updated over time, ensuring that efficiency improvements would continue. In 1987, with a patchwork of state requirements already in place, the National Appliance Energy Conservation Act created federal minimum efficiency requirements for residential appliances, including refrigerators (US DOE 2004). Since then, the efficiency standards for refrigerators have been updated multiple times, ensuring that efficiency improvements continued (IEA/OECD 2003).

23. While the number of hours of refrigeration an individual refrigerator provides is generally limited by the number of hours in a year, American households have increasingly added second refrigerators, thereby increasing the total hours of refrigeration used each year by a single household.

24. This period of declining efficiency was due in large part to market demand, as an increasingly affluent post-World War II public demanded larger, more powerful motor vehicles with more accessories (Hirsh 1999).

25. The period of improving efficiency, which began in the mid-1970s, was brought about by both market and legislative drivers. The oil crises of the 1970s introduced gasoline availability concerns and higher gasoline prices to drivers in the US, thereby stimulating consumer interest in improved motor vehicle fuel efficiency. Legislatively, Corporate Average Fuel Economy (CAFE) standards, which, beginning in 1978, mandated a minimum average fuel economy for a manufacturer's fleet of vehicles, also drove automakers to improve fuel efficiency. Combined, these factors had a noticeable effect on the efficiency of motor vehicle travel in the US.

26. The recent stabilization of automobile efficiency is due in part to the fact that CAFE standards have not been updated for over a decade. Consumer demand for larger vehicles and better performance has also contributed to this plateau in fuel efficiency (Wald 2006).

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27. Prior to the development of the Haber-Bosch process, the industrial methods available for producing nitrogen included the fixation of atmospheric nitrogen using calcium carbide at high temperatures to produce calcium cyanamide ($CaC_2 + N_2 \rightarrow CaCN_2 + C$), and the fixation of atmospheric nitrogen by electrical discharge to produce nitric oxide ($N_2 + O_2 \leftrightarrow 2NO$) (Tamaru 1991, Smil 2001).

28. It is true that in some cases, the planes that are the most costly to operate are not those with the worst fuel efficiency, but instead the planes that are of a different make or model from the majority of other planes in an airline's fleet (Wong 2003). In general, large cost savings can be realized, both in operation and in maintenance, by having a limited variety of planes.

29. Increases in affluence leading to increases in demand, and thus increases in production, applies in the case of normal goods. In the case of inferior goods, for which consumption decreases as income increases, increases in affluence lead to decreases in demand, and thus decreases in production.

30. Vaclav Smil offered his own humorous insights into the benefits of improvements in air travel and, more specifically, improvements in the efficiency of aircraft engines. In a 2007 lecture entitled "Transforming Energy Techniques", Smil commented,

    > "These new big gas turbines, these, you know, GE and Rolls Royce things, they are marvels of engineering – much more efficient, much lighter, much more durable. The single most durable machine on this planet. You notice the plane goes, two hours they refuel it, goes back, and keeps doing it for seven months before they even look at the bloody engine. They don't even look at it! The most marvelous machine ever. But what is happening? These old inefficient turbojets. In 1960, who was flying? If somebody was flying, 'Oh, he *flew* somewhere! Amazing! First person in our family who flew somewhere,' right? Now? There is (sic) 78 discount airlines in Western Europe alone really. And people are flying – where is the number one destination in the continent? 45 million people fly to Las Vegas for what, you know, to spend money which they don't have really. This is what the efficient engine has brought us. People frivolously flying into the middle of the desert without any water to spend money which they don't have, really, right. So that's the benefit of efficient engines, ok." (Smil 2007).

31. In the case of normal goods, the income effect increases demand. However, in the case of inferior goods, for which consumption decreases as income increases, the income effect decreases demand.

32. Although data is difficult to find, it would be interesting to examine overall trends in refrigeration, not just trends in residential refrigeration, as are analyzed here. Given the increase in the US of dining and food service outside the home, the overall production of refrigeration, including both the service sector and the residential sector, may have grown at a faster rate than for the residential sector alone (Herring 2007). Significantly faster growth rates in the overall production of refrigeration could eclipse the rate of efficiency improvement, thus leading to an overall increase in impact.

References

Air Transport Association (ATA), 2007. Economics & Energy, Finance, Quarterly Cost Index: U.S. Passenger Airlines. Available online at http://www.airlines.org/economics/finance/Cost+Index.htm. (Accessed February 27, 2007.)

Anastas, P.T. and J.B. Zimmerman, 2003. Design Through the 12 Principles of Green Engineering. *Environmental Science and Technology* 37(5): 94A-101A.

Association of American Railroads (AAR), 1965. Railroad Transportation, A Statistical Record, 1921-1963. Washington, D.C., April 1965.

Association of American Railroads (AAR), 1983. Railroad Facts, 1983 Edition. Washington, D.C., September 1983.

Association of American Railroads (AAR), 2006. Railroad Facts, 2006 Edition. Washington, D.C., November 2006.

Argote, L. and D. Epple, 1990. Learning Curves in Manufacturing. *Science* 247: 920-924.

Bazargan, M., 2004. Airline Operations and Scheduling. Aldershot, Hampshire, UK: Ashgate Publishing, Limited.

Bentzen, J., 2004. Estimating the rebound effect in the US manufacturing energy consumption. *Energy Economics* 26(1): 123-134.

Berkhout, P.H.G., J.C. Muskens, and J.W. Velthuijsen, 2000. Defining the rebound effect. *Energy Policy* 28(6-7): 425-432.

Braeutigan, R.R., 1993. Consequences of Regulatory Reform in the American Railroad Industry. *Southern Economic Journal* 59(3): 468-480.

Brooks, L., 1990. The greenhouse effect: the fallacies in the energy efficiency solution. *Energy Policy* 18(2):199-201.

Brooks, L., 1992. Energy efficiency and economic fallacies: a reply. *Energy Policy* 20(5): 390-392.

Brooks, L., 2000. Energy efficiency fallacies revisited. *Energy Policy* 28(6-7): 355-366.

Business Week, 1984. Can the Rails Stay Lean and Profitable? *Business Week*, May 7, 1984, pp. 72.

DeSimone, L.D. and F. Popoff, 1997. Eco-Efficiency: The Business Link to Sustainable Development. Cambridge, Massachusetts, USA: The MIT Press.

Duke, J., D. Litz, and L. Usher, 1992. Multifactor productivity in railroad transportation. *Monthly Labor Review* 115(8): 49-58.

Dybkjaer, I., 1995. "Ammonia Production Processes" in Ammonia: Catalysis and Manufacture, ed. A. Nielsen. Berlin, Germany: Springer-Verlag.

Ehrenfeld, J.R., 2005. Eco-efficiency: Philosophy, Theory, and Tools. *Journal of Industrial Ecology* 9(4): 6-8.

Ehrlich, P.R. and J.P. Holdren, 1972. Critique: One Dimensional Ecology. *Bulletin of the Atomic Scientists* 28(5): 16, 18-27.

Ellerman, A.D., P.L. Joskow, R. Schmalensee, J.P. Montero, and E.M. Bailey, 2000. Markets for Clean Air: The U.S. Acid Rain Program. Cambridge, UK: Cambridge University Press.

Flint, J., 1986. Here Come the Truckbusters: Railroads Come Back into Favor. *Forbes*, June 30, 1986: 86.

Foster, R.N., 1986. Innovation: The Attacker's Advantage. New York, New York, USA: Summit Books.

Gellar, H., 1995. "National Appliance Efficiency Standards: Cost-Effective Federal Regulations," American Council for an Energy-Efficient Economy. Available online at http://www.aceee.org/pubs/a951.htm. (Accessed February 2, 2007.)

Graedel, T. E. and B.R. Allenby, 1998. Design for Environment. Upper Saddle River, New Jersey, USA: Prentice-Hall, Inc.

Graedel, T.E. and B.R. Allenby, 2003. Industrial Ecology, Second Edition. Upper Saddle River, New Jersey, USA: Pearson Education, Inc.

Greening, L.A., D.L. Greene, and C. Difiglio, 2000. Energy efficiency and consumption – the rebound effect – a survey. *Energy Policy* 28(6-7): 389-401.

Grubb, M.J., 1990. Energy Efficiency and Economic Fallacies. *Energy Policy* 18(8): 783-785.

Grubb, M.J., 1992. Reply to Brookes. *Energy Policy* 20(5): 392-393.

Grübler, A., 1998. Technology and Global Change. Cambridge, UK: Cambridge University Press.

Heimlich, J., 2007. "U.S. Airline: Operating in an Era of High Jet Fuel Prices." Presentation by John Heimlich, Vice President and Chief Economist, Air Transport Association of America, Inc. January 24, 2007. Available online at http://www.airlines.org/NR/rdonlyres/73AADEC2-D5A2-4169-B590-1EE83A747CDA/0/Airlines_Fuel.pdf. (Accessed February 27, 2007.)

Herring, H., 1998. Does Energy Efficiency Save Energy: The Economists Debate. Energy and Environment Research Unit Report No. 074, July 1998. Available online at http://technology.open.ac.uk/eeru/staff/horace/hh3.htm. (Accessed February 2, 2007.)

Herring, H., 2006. Energy Efficiency – a critical view. *Energy* 31(1): 10-20.

Herring, H., 2007. Visiting Research Fellow, Energy and Environment Research Unit, The Open University, Milton Keynes, UK. Personal communication, April 30, 2007.

Hertwich, E.G., 2005. Consumption and the Rebound Effect: An Industrial Ecology Perspective. *Journal of Industrial Ecology* 9(1-2): 85-98.

Hirsh, R.F., 1999. Power Loss: The Origins of Deregulation and Restructuring in the American Electric Utility System. Cambridge, Massachusetts, USA: The MIT Press.

Holusha, J., 1989. Locomotives in High Gear Again. *New York Times*, April 5, 1989.

Houston Chronicle, 1986. Computerized Locomotive Continue Picking Up Steam. *Houston Chronicle*, June 29, 1986.

Hughes, J.E., C.R. Knittel, D. Sperling, 2006. Evidence of a Shift in the Short-Run Price Elasticity of Gasoline Demand. National Bureau of Economic Research Working Paper No. 12530, September 2006. Available online at http://www.nber.org/papers/w12530. (Accessed April 12, 2007.)

ICF Consulting (ICF), 2005. Assessing the Effects of Freight Movement on Air Quality at the National and Regional Level, Final Report. Prepared for the U.S. Federal Highway Administration, April 2005. Available online at http://www.oregon.gov/ODOT/TD/FREIGHT/docs/publications/federal/FHWAFrtAirQualRep1.pdf. (Accessed February 27, 2007.)

Intergovernmental Panel on Climate Change (IPCC), 1999. Aviation and the Global Atmosphere. Special report, eds. J.E. Penner, D.H. Lister, D.J. Griggs, D.J. Dokken, and M. McFarland. Available online at http://www.grida.no/climate/ipcc/aviation/index.htm. (Accessed May 13, 2007.)

International Energy Agency/Organisation for Economic Co-Operation and Development (IEA/OECD), 2003. Cool Appliances: Policy Strategies for Energy-Efficient Homes. Paris, France: IEA Publications.

Jevons, W.S., 1865. The Coal Question. Reprints of Economic Classics, ed. A.W. Flux, 1965. New York, New York, USA: Augustus M. Kelley.

Joskow, P.L. and N.L. Rose, 1985. The effects of technological change, experience, and environmental regulation on the construction cost of coal-burning generating units. *Rand Journal of Economics* 16(1):1-27

Khazzoom, J.D., 1980. Economic Implications of Mandated Efficiency Standards for Household Appliances. *Energy Journal* 1(4): 21-40.

Khazzoom, J.D., 1982. Response to Besen and Johnson's Comment on "Economic Implications of Mandated Efficiency Standards for Household Appliances". *Energy Journal* 3(1): 117-124.

Khazzoom, J.D., 1987. Energy Savings Resulting from the Adoption of More Efficient Appliances. *Energy Journal* 8(4): 85-89.

Khazzoom, J.D., 1989. Energy Savings Resulting from the Adoption of More Efficient Appliances: A Rejoinder. *Energy Journal* 10(1): 157-166.

Krauss, C., L. Munoz, and N. Schweber, 2007. Drivers Offer a Collective Ho-Hum as Gasoline Prices Soar. *New York Times*, March 30, 2007.

Kruglinski, A., 1993. A thin locomotive lease market is stretched. *Railway Age*, 194(9): 10.

Lee, J.J., S.P. Lukachko, I.A. Waitz, and A. Schafer, 2001. Historical and Future Trends in Aircraft Performance, Cost and Emissions. *Annual Review of Energy and the Environment* 26:167-200.

Lovell, M.C., 2004. Economics with Calculus. Hackensack, New Jersey, USA: World Scientific Publishing Co.

Lovins, A.B., 1988. Energy Savings Resulting from the Adoption of More Efficient Appliances: Another View. *Energy Journal* 9(2): 155-162.

McCartney, S. and S. Carey, 2003. Flight Plans: Shifts at Big Airlines Promise to Change the Industry's Course – Cuts at United and American Will Increase the Pressure on Their Smaller Rivals – 'Delicate and Difficult Period'. *Wall Street Journal*, April 17, 2003.

McCartney, S., 2006. The Middle Seat: Sparing Fliers Even Higher Airfares; Oil Hedges, Slower Speeds, Weight Reductions Help Carriers Cut Fuel Costs. *Wall Street Journal*, June 6, 2006.

Milne, G. and B. Boardman, 2000. Making cold homes warmer: the effect of energy efficiency improvements in low-income homes. *Energy Policy* 28(6-7): 411-424.

Morrison, S. A., 1984. An Economic Analysis of Aircraft Design. *Journal of Transport Economics and Policy* 18(2): 123-143.

Omaha World-Herald, 1984. Modern Railroads Embrace Computers. *The Omaha World-Herald*, October 11, 1984.

Organisation for Economic Co-Operation and Development (OECD), 1998. Eco-Efficiency. Paris, France: OECD Publications.

Otto, K.N. and K.L. Wood, 2001. Product Design: Techniques in Reverse Engineering and New Product Development. Upper Saddle River, New Jersey, USA: Prentice-Hall, Inc.

Pauly, D., W.J. Cook, and P.E. Simmons, 1980. Green Light on the Rails. *Newsweek*, February 25, 1980: 63.

Pauly, D., R. Thomas, E. Ipsen, and F. Maier, 1982. The Railroads Roll Again. *Newsweek*, May 10, 1982: 69.

Perez, E., S. Carey, and S. McCartney, 2003. Large Airlines Swing Profits With Help – Delta, Northwest, Continental Receive Government Aid Amid War-Related Travel Slump. *Wall Street Journal*, July 18, 2003.

Pindyck, R.S. and D.L. Rubinfeld, 2001. Microeconomics, Fifth Edition. Upper Saddle River, New Jersey, USA: Prentice-Hall, Inc.

Railway Age, 1990. Fuel Savers: The Payoff. *Railway Age* 191(10): 31-35.

Rosenfeld, A.H., 1999. The Art of Energy Efficiency: Protecting the Environment with Better Technology. *Annual Review of Energy and the Environment* 24:33-82.

Roy, J., 2000. The rebound effect: some empirical evidence from India. *Energy Policy* 28(6-7): 433-438.

Ruttan, V.W., 2001. Technology, Growth, and Development: An Induced Innovation Perspective. New York, New York, USA: Oxford University Press, Inc.

Saunders, H.D., 1992. The Khazzoom-Brookes Postualte and Neoclassical Growth. *Energy Journal* 13(4): 131-148.

Saunders, H.D., 2000. A view from the macro side: rebound, backfire, and Khazzoom-Brookes. *Energy Policy* 28(6-7): 439-449.

Searle, A.D., 1945. Productivity Changes in Selected Wartime Shipbuilding Programs. *Monthly Labor Review* 61: 1132-1147.

Setaishi, S., 2003. Turbulence in Airline Industry Could Hurt Its Supplier Network. *Wall Street Journal*, April 2, 2003.

Sharkey, J., 2004. Sunday Money: Spending; The Air Travel Forecast: Brisk, With Frequent Squalls. *New York Times*, May 30, 2004.

Shedd, T., 1984. The Little Engine That Does. *Technology Review* 87(2): 60-69.

Smil, V., 1999. Energies: An Illustrated Guide to the Biosphere and Civilization. Cambridge, Massachusetts, USA: The MIT Press.

Smil, V., 2001. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. Cambridge, Massachusetts, USA: The MIT Press.

Smil, V., 2003. Energy at the Crossroads: Global Perspectives and Uncertainties. Cambridge, Massachusetts, USA: The MIT Press.

Smil, V., 2007. "Transforming Energy Techniques." Public lecture at Harvard University, April 12, 2007. The Future of Energy Speaker Series 2006-2007, Harvard University Center for the Environment. Available online at http://environment.harvard.edu/video/future_of_energy/smil/presentation.html. (Accessed May 6, 2007.)

Stern, D.I., 2004. "Economic Growth and Energy" in Encyclopedia of Energy, Volume 2, ed. C.J. Cleveland. Amsterdam, The Netherlands: Elsevier.

Tamaru, K., 1991. "History of Development of Ammonia Synthesis" in Catalytic Ammonia Synthesis: Fundamentals and Practice, ed. J.R. Jennings. New York, New York, USA: Plenum Press.

Tugwell, F., 1988. The Energy Crisis and the American Political Economy: Politics and Markets in the Management of Natural Resources. Stanford, California, USA: Stanford University Press.

Ulrich, K.T. and S.D. Eppinger, 2000. Product Design and Development, Second Edition. Boston, Massachusetts, USA: McGraw Hill.

United States Department of Energy (US DOE), 1993. Residential Energy Consumption Survey (RECS) 1993, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy (US DOE), 1997. Residential Energy Consumption Survey (RECS) 1997, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy (US DOE), 2001. Residential Energy Consumption Survey (RECS) 2001, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy (US DOE), 2004. "History of Federal Appliance Standards," Energy Efficiency and Renewable Energy, Building Technologies Program, Appliances and Commercial Equipment Standards. Available online at http://www.eere.energy.gov/buildings/appliance_standards/history.html. (Accessed February 2, 2007.)

Wald, M.L., 2006. Automakers Use New Technology to Beef Up Muscle, Not Mileage. *New York Times*, March 30, 2006.

Williams, W., 1985. Turning a Railroad Around. *New York Times*, January 13, 1985.

Wong, E., 2003. Airlines' Unwanted Fleet Grows in the Desert. *New York Times*, June 7, 2003.

World Business Council for Sustainable Development (WBCSD), 2000. Eco-Efficiency: Creating More Value With Less Impact. Available online at http://www.wbcsd.org/web/publications/eco_efficiency_creating_more_value.pdf. (Accessed February 2, 2007.)

Figure References

[a] Pig iron production

Efficiency and Production data:

Smil, V., 1999. Energies: An Illustrated Guide to the Biosphere and Civilization. Cambridge, Massachusetts, USA: The MIT Press.

[b] Aluminum production

Efficiency data:

Atkins, P.R., H.J. Hittner, D. Willoughby, 1990. "Some Energy and Environmental Impacts of Aluminum Usage," from Energy and the Environment in the 21st Century, Conference Proceedings, March 26-28, 1990, eds. J.W. Tester, D.O. Wood, and N.A. Ferrari. Cambridge, Massachusetts, USA: The MIT Press.

Chapman, P.F. and F. Roberts, 1983. Metal Resources and Energy. London, UK: Butterworth and Co Ltd.

Production data:

United States Geological Survey, 2006. “Aluminum statistics,” from Historical Statistics for Mineral and Material Commodities in the United States: U.S. Geological Survey Data Series 140, comps. T.D. Kelly and G.R. Matos. Available online at http://minerals.usgs.gov/ds/2005/140/. (Accessed January 22, 2007.)

[c] Nitrogen fertilizer production

Efficiency and Production data:

Smil, V., 2001. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. Cambridge, Massachusetts, USA: The MIT Press.

[d] Electricity generation

Efficiency and Production data:

1920-1948 data: United States Bureau of the Census, 1997. Historical Statistics of the United States, Colonial Times to 1970, Electronic edition, eds. S.B. Carter, et al. [machine-readable data file]. Cambridge, UK: Cambridge University Press.

1949-2005 data: United States Department of Energy, 2006. Annual Energy Review 2005: DOE/EIA-0384(2005), Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/aer/contents.html. (Accessed January 23, 2007.)

[e] Freight rail travel

Production data:

1962-1964: Association of American Railroads, 1973. Yearbook of Railroad Facts, 1973 Edition. Washington, D.C., 1973.

1965-1978: Association of American Railroads, 1980. Yearbook of Railroad Facts, 1980 Edition. Washington, D.C., June 1980.

1979-1988: Association of American Railroads, 1989. Railroad Facts, 1989 Edition. Washington, D.C., November 1989.

1989: Association of American Railroads, 1999. Railroad Facts, 1999 Edition. Washington, D.C., October 1999.

1990-2005: Association of American Railroads, 2006. Railroad Facts, 2006 Edition. Washington, D.C., November 2006.

Impact data:

1962-1971: Association of American Railroads, 1977. Yearbook of Railroad Facts, 1977 Edition. Washington, D.C., 1977.

1972-1978: Association of American Railroads, 1980. Yearbook of Railroad Facts, 1980 Edition. Washington, D.C., June 1980.

1979-1988: Association of American Railroads, 1989. Railroad Facts, 1989 Edition. Washington, D.C., November 1989.

1989: Association of American Railroads, 1999. Railroad Facts, 1999 Edition. Washington, D.C., October 1999.

1990-2005: Association of American Railroads, 2006. Railroad Facts, 2006 Edition. Washington, D.C., November 2006.

[f] Passenger air travel

Efficiency data:

1960, 1965, 1970, 1975, 1980, 1985, 1990-2005: United States Department of Transportation, 2006. National Transportation Statistics, 2006. Bureau of Transportation Statistics, Washington, D.C., USA. Available online at http://www.bts.gov/publications/national_transportation_statistics/pdf/entire.pdf. (Accessed February 10, 2007.)

Production data:

1937-2005: Air Transport Association, 2007. Economics & Energy, Traffic, Annual Traffic and Ops: U.S. Airlines. Available online at http://www.airlines.org/economics/traffic/Annual+US+Traffic.htm. (Accessed January 24, 2007.)

Impact data:

1961-1964, 1966-1969, 1971-1974, 1976: United States Department of Transportation, 2007. Reference Services, National Transportation Library, Bureau of Transportation Statistics, Research and Innovative Technology Administration. Personal communication, February 13, 2007.

1977-1979, 1981-1984, 1986-1989: United States Department of Transportation, 2006. Bureau of Transportation Statistics, Programs, Airline Data and Statistics, Airline Fuel Cost and Consumption. Available online at http://www.bts.gov/xml/fuel/report/src/tableversion.xml. (Accessed February 10, 2007.)

Fuel price data:

1971-2005: Air Transport Association, 2007. Economics & Energy, Finance, Quarterly Cost Index: US Passenger Airlines. Available online at http://www.airlines.org/economics/finance/Cost+Index.htm. (Accessed March 12, 2007.)

Consumer Price Index: Federal Reserve Bank of Minneapolis, 2007. Economic Research and Data, Data, US Data, CPI Calculator, Consumer Price Index 1913 - . Available online at http://www.minneapolisfed.org/research/data/us/calc/hist1913.cfm. (Accessed March 12, 2007.)

[g] Motor vehicle travel

Efficiency and Production data:

1936-1994: United States Department of Transportation, 1997. Highway Statistics Summary to 1995. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Aavailable online at http://isddc.dot.gov/OLPFiles/FHWA/006654.pdf. (Accessed February 12, 2007.)

1995: United States Department of Transportation, 1997. Highway Statistics 1996. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/1996/index.html. (Accessed February 12, 2007.)

1996: United States Department of Transportation, 1998. Highway Statistics 1997. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs97/hs97page.htm. (Accessed February 12, 2007.)

1997: United States Department of Transportation, 1999. Highway Statistics 1998. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs98/hs98page.htm. (Accessed February 12, 2007.)

1998: United States Department of Transportation, 2000. Highway Statistics 1999. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs99/index.htm. (Accessed February 12, 2007.)

1999: United States Department of Transportation, 2001. Highway Statistics 2000. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs00/index.htm. (Accessed February 12, 2007.)

2000: United States Department of Transportation, 2002. Highway Statistics 2001. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs01/index.htm. (Accessed February 12, 2007.)

2001: United States Department of Transportation, 2003. Highway Statistics 2002. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/policy/ohim/hs02/index.htm. (Accessed February 12, 2007.)

2002: United States Department of Transportation, 2004. Highway Statistics 2003. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/policy/ohim/hs03/index.htm. (Accessed February 12, 2007.)

2003: United States Department of Transportation, 2005. Highway Statistics 2004. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/policy/ohim/hs04/index.htm. (Accessed February 12, 2007.)

2004-2005: United States Department of Transportation, 2006. Highway Statistics 2005. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/policy/ohim/hs05/index.htm. (Accessed February 12, 2007.)

[h] Refrigeration

Efficiency data:

Rosenfeld, A.H., 1999. The Art of Energy Efficiency: Protecting the Environment with Better Technology. *Annual Review of Energy and the Environment* 24:33-82.

Production data:

1940: United States Bureau of the Census, United States Census. University of Virginia Library, GeoStat Center: Collections, Historical Census Browser. Available online at http://fisher.lib.virginia.edu/collections/stats/histcensus/. (Accessed February 3, 2007.)

1993: United States Department of Energy, 1993. Residential Energy Consumption Survey (RECS) 1993, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

1997: United States Department of Energy, 1997. Residential Energy Consumption Survey (RECS) 1997, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

2001: United States Department of Energy, 2001. Residential Energy Consumption Survey (RECS) 2001, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

Fleet age distribution data:

United States Department of Energy, 1993. Residential Energy Consumption Survey (RECS) 1993, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy, 1997. Residential Energy Consumption Survey (RECS) 1997, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy, 2001. Residential Energy Consumption Survey (RECS) 2001, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

Appendix: Bayesian Material Separation

This appendix presents a modified and expanded version of the conference paper, "Bayesian Material Separation Model with Applications to Recycling," by T. Gutowski, J. Dahmus, D. Albino, and M. Branham, presented at the 2007 IEEE International Symposium on Electronics and the Environment in Orlando, Florida, USA.

Bayesian Material Separation

A Probabilistic Model for Material Separation and Purification

Abstract

This work presents a mathematical model of binary separation that can be applied to a wide range of processes, including material separation and purification processes. The model, based on Bayes' Theorem, requires data about both the input material stream and about the probabilistic characteristics of the separation process. With this information, the simple model developed here allows the output steams from a separation process to be completely characterized, in terms of both mass and concentration. Applications of this model to separation processes, including those used in material recycling, are demonstrated.

Keywords: material separation, material purification, recycling, Bayes' Theorem

Introduction

Material separation and purification processes are critical to many industries, from recycling to electronics. For example, in the case of material recycling, material separation is an important value-adding step, providing the difference between streams of mixed materials, which often have no value, and purified material streams, which typically have good value in the market. In the case of electronics, material purification is critical at the beginning of the electronics life-cycle, as electronics-grade silicon must be purified from less-pure silicon material. Material separation can also play a role at the end of the electronics lifecycle, again as an important step in the material recycling process.

In this work, a mathematical model for the isolation and concentration of a target material from a mixture of materials is developed. This model can be applied to any separation process that results in two output streams, and can thus be applied to a wide range of different separation and purification processes, including material recycling and material beneficiation. The work presented here addresses some of the same issues as earlier work by Murphy et al. on plastics recycling (Murphy et al. 2001).

The approach used here is based on Bayes' Theorem and requires an estimate of two probabilities: the probability of correctly identifying the target material in a mixed input stream, and the probability of correctly identifying the non-target material in a mixed input stream. From these, the probabilities for a false negative and a false positive can be obtained. With these four probabilities, Bayes' Theorem, and the conservation of mass, a complete set of equations to rigorously describe a material separation process can be derived. This mathematical model, along with information about the input material stream, can be used to fully characterize both the concentrated stream, the stream with the higher concentration of target material, and the dilute stream, the stream with the lower concentration of target material, from any material separation process.[1]

This paper presents the development of this model and its application to various areas, including material recycling systems. This application, as well as others, point to the practical utility of this mathematical model.

Development of the Model

The development of this model is based, in large part, on simple concepts from probability. First, consider a mixture of a target material, A, with mass m_A, and everything else, called non-target material, A^c, with mass $m_A{}^c$. The concentration of the target material A is just the probability of A, and is represented as c.[2] The concentration of A^c is simply $1 - c$.[3] These concentrations can be written as probabilities, as follows:

$$P(A) = c \tag{1}$$

$$P(A^c) = 1 - c \ . \tag{2}$$

Now consider a test that returns B when it has identified A, and returns the compliment, B^c, when it has identified A^c. These conditional probabilities can be defined as follows:

$$P(B/A) = r \tag{3}$$

$$P(B^c/A) = 1 - r \tag{4}$$

$$P(B^c/A^c) = q \tag{5}$$

$$P(B/A^c) = 1 - q \ . \tag{6}$$

Equation (3) is the probability that the test, when given material A, correctly returns B. It represents a correct positive. Equation (4) is the probability that the test, when given material A, incorrectly returns B^c. It represents a false negative. Equation (5) is the probability that the test, when given material A^c, correctly returns B^c. It represents the a correct negative. Equation (6) is the probability that the test, when given material A^c, incorrectly returns B. It represents a false positive. In order for this to be a viable separation process, meaning that the process is capable of purifying materials, it is assumed that $0.5 < r \leq 1.0$ and $0.5 < q \leq 1.0$.[4]

The various outcomes from a separation process are perhaps more easily understood graphically. Figure 1 shows the separation of a target material, A, from a non-target material, A^c, through the use of a separation test, B. A mixture of target and non-target materials enters the system in the upper left, passes through a separation process, B, then leaves the system either in the concentrated stream or in the dilute stream. For example, the separation process shown in

Figure 1 could represent the separation of ferrous material, A, from non-ferrous material, A^c, using an electromagnetic separation process, B. Ferrous materials would be attracted to the electromagnet, shown as a circle, and would thus tend be deposited in the concentrated stream. Non-ferrous materials would not be attracted to the electromagnet, and would thus tend to be deposited in the dilute stream. The four possible outcomes of the separation test, namely a correct positive, a false positive, a correct negative, and a false negative, are shown.

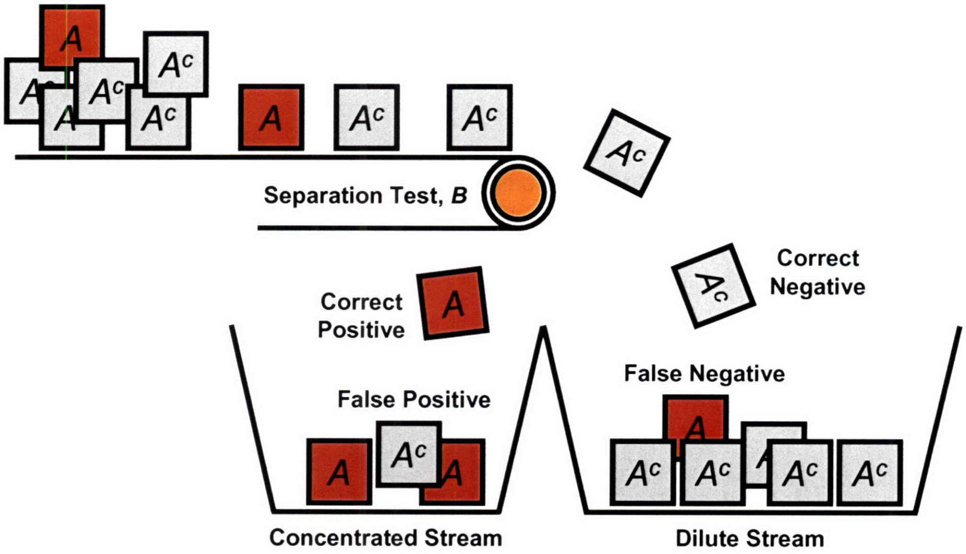

Figure 1: A general material separation system with target material, A, non-target material, A^c, and separation test, B.

The possible outcomes from a separation process can also be represented as a branching tree, as shown in Figure 2. Such a branching tree representation is common in the description of material separation and purification processes, and will be seen again later in this work.

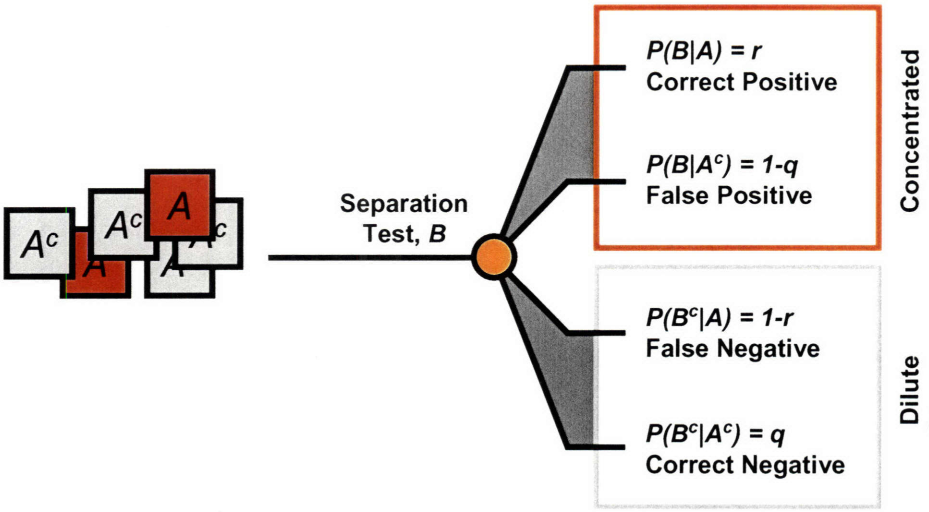

Figure 2: A branching tree representing the four possible outcomes from a separation test, *B*. The incoming stream of mixed materials is separated into two output streams, a concentrated stream, containing concentrations of target material higher than in the incoming stream, and a dilute stream, containing concentrations of target material lower than in the incoming stream.

With probabilities (1) and (2), which are associated with the incoming material stream, and with probabilities (3) through (6), which are associated with the characteristics of the separation process, Bayes' theorem can be used. Bayes' theorem, developed by Thomas Bayes in the 1700s, provides a means of updating a known probability as more data or test results become available (Ang and Tang 1975). Thus, the use of Bayes' theorem in modeling material separation processes is quite clear, as the known concentrations of the incoming material stream can be updated using the results from the material separation test. Bayes' theorem can be written as

$$P(A/B) = \frac{P(B/A)P(A)}{P(B/A)P(A) + P(B/A^c)P(A^c)}, \tag{7}$$

where *A* represents the known probability and *B* represents the test results. The left-hand side of (7) represents the conditional probability of *A* given *B*.

In terms of material separation, the left-hand side of (7) represents the probability that the material is *A*, given that the material separation test returns *B*. Thus, this conditional probability is simply the concentration of target material *A* in the concentrated output stream. Writing this concentration as c_{j+1}, renaming c from (1) as c_j, and substituting terms, Bayes' Theorem can then be rewritten as

$$c_{j+1} = \frac{rc_j}{rc_j + (1-q)(1-c_j)} \quad . \tag{8}$$

The designations used here for the various inputs to and outputs from a separation test are shown in Figure 3.

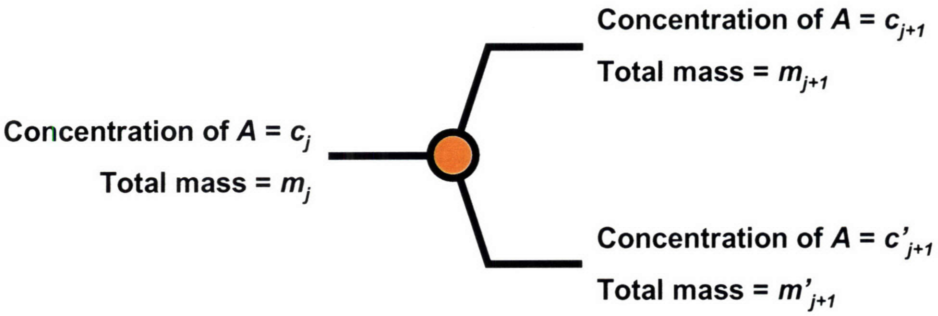

Figure 3: A binary material separation step that takes an incoming stream of mass m_j and target material concentration c_j, and outputs two streams: a concentrated stream of mass m_{j+1} and target material concentration c_{j+1}, and a dilute stream of mass m'_{j+1} and target material concentration c'_{j+1}.

The concentration of target material in the dilute stream, c'_{j+1}, can also be derived using Bayes' Theorem. Again substituting terms in (7), the concentration of target material in the dilute stream can be written as

$$c'_{j+1} = \frac{(1-r)c_j}{(1-r)c_j + q(1-c_j)} \quad . \tag{9}$$

Note that for the conditions given earlier, namely that $0.5 < r \leq 1.0$ and $0.5 < q \leq 1.0$, and given that $c_j < 1$, $c_{j+1} > c_j > c'_{j+1}$.

With equations for the concentrations c_{j+1} and c'_{j+1}, the masses of the output streams, m_{j+1} and m'_{j+1}, can now be written. The overall mass balance, using the notation from Figure 3, can be written as

$$m_j = m_{j+1} + m'_{j+1} \tag{10}$$

and the mass balance for the target material can be written as

$$c_j m_j = c_{j+1} m_{j+1} + c'_{j+1} m'_{j+1} \ . \tag{11}$$

Solving equations (10) and (11) for the output masses from the material separation step yields

$$m_{j+1} = m_j \frac{c_j - c'_{j+1}}{c_{j+1} - c'_{j+1}} \tag{12}$$

as the mass of the concentrated output stream, and

$$m'_{j+1} = m_j \frac{c_{j+1} - c_j}{c_{j+1} - c'_{j+1}} \tag{13}$$

as the mass of the dilute output stream.

The amount of target material captured in the concentrated output stream and the amount of target material remaining in the dilute output stream are also of interest. The ratio of the mass of target material A in the concentrated output stream divided by the mass of target material A in the input stream can be written as

$$\frac{c_{j+1} m_{j+1}}{c_j m_j} = r \ . \tag{14}$$

From this, the mass of target material captured in the concentrated output stream can be calculated. Equation (14) can also be rewritten, using (12), to yield

$$\frac{c_{j+1}}{c_j}\left[\frac{c_j - c'_{j+1}}{c_{j+1} - c'_{j+1}}\right] = r \quad , \tag{15}$$

where r is now a function of only the concentrations of target material in the incoming stream and in the outgoing streams. Thus, the properties of a separation process can be obtained by simply studying the properties of the incoming and outgoing material streams.

The ratio of the mass of target material A in the dilute output stream divided by the mass of target material A in the input stream can be written as

$$\frac{c'_{j+1} m'_{j+1}}{c_j m_j} = 1 - r \quad . \tag{16}$$

From this, the mass of target material left in the dilute output stream can be calculated. Similar equations can be written for the non-target material, A^c. The ratio of the mass of non-target material A^c in the concentrated output stream, divided by the mass of non-target material A^c in the input stream, can be written as

$$\frac{(1 - c_{j+1}) m_{j+1}}{(1 - c_j) m_j} = 1 - q \quad . \tag{17}$$

The ratio of the mass of non-target material A^c in the dilute output stream, divided by the mass of non-target material A^c in the input stream, can be written as

$$\frac{(1 - c'_{j+1}) m'_{j+1}}{(1 - c_j) m_j} = q \quad . \tag{18}$$

With the equations developed here, the outputs of a separation process can be completely characterized using only information about the input material stream and about the probabilistic characteristics of a separation process.

Application of the Model

The model developed here can be broadly applied to a range of different material separation and purification processes, including those used in material recycling. Various applications of this model are described here, and the results are compared to some existing results in the material separation and material recycling literature.

It is useful to first illustrate the range of results that can be obtained from the probabilistic model developed here. For this purpose, it is convenient to combine the parameters r and q into a single new parameter β, where

$$\frac{1-q}{r} = 1-\beta \quad . \tag{19}$$

Given the limits on r and q, β is confined to the range of $0 < \beta \leq 1$. When $\beta = 0$, corresponding to the case when $r = 0.5$ and $q = 0.5$, there would be no purifying effect from the separation process; when $\beta = 1$, corresponding to the case when $r = 0.5$ and $q = 1.0$, the output streams from the separation process would be pure. The range of concentrations of target material in the concentrated output stream, c_{j+1}, as a function of concentration of target material in the input stream, c_j, for different values of β, is shown in Figure 4. Note that for higher values of β, the improvement between the concentration of target material in the input stream, c_j, and the concentration of target material in the output stream, c_{j+1}, is significant at low input concentrations. However, at higher input concentrations, the improvement between the concentration of target material in the input stream and the concentration of target material in the output stream decreases dramatically. In short, as the concentration of target material in the input stream goes up, it becomes increasingly more difficult to obtain higher purity levels. This phenomenon is illustrated by the change in slope for the curves shown in Figure 4.

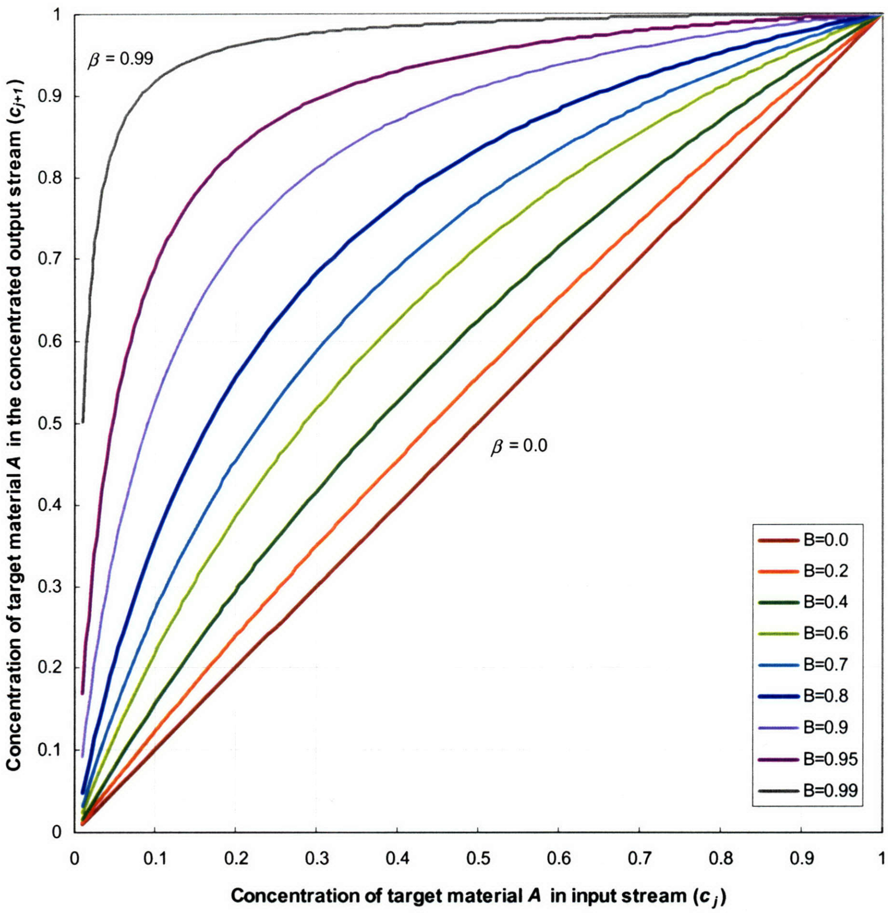

Figure 4: The performance of a separation process for various values of β.

To illustrate the effect of β on a system level, two systems with the same input concentration of target material, $c_j = 0.10$, the same total input mass, m_j = 100 kg, and the same desired output concentration of target material, $c_t \geq 0.99$, are analyzed for different values of β. The desired output target concentration is achieved through repeated separation of the concentrated output stream. The results are illustrated as tree diagrams in Figures 5 and 6.

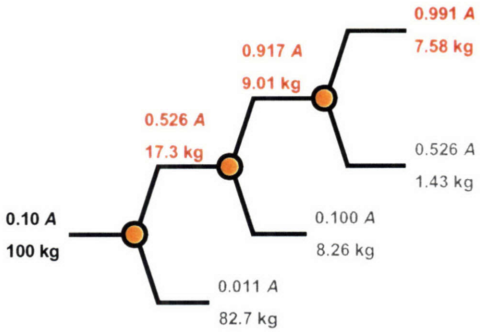

Figure 5: A material separation scheme with $r = q = 0.909$ and $\beta = 0.9$. The upper number of each two-number set represents the concentration of target material A in that stream. The lower number represents the total mass of material in that stream. Note that the desired output concentration of target material is reached in three steps.

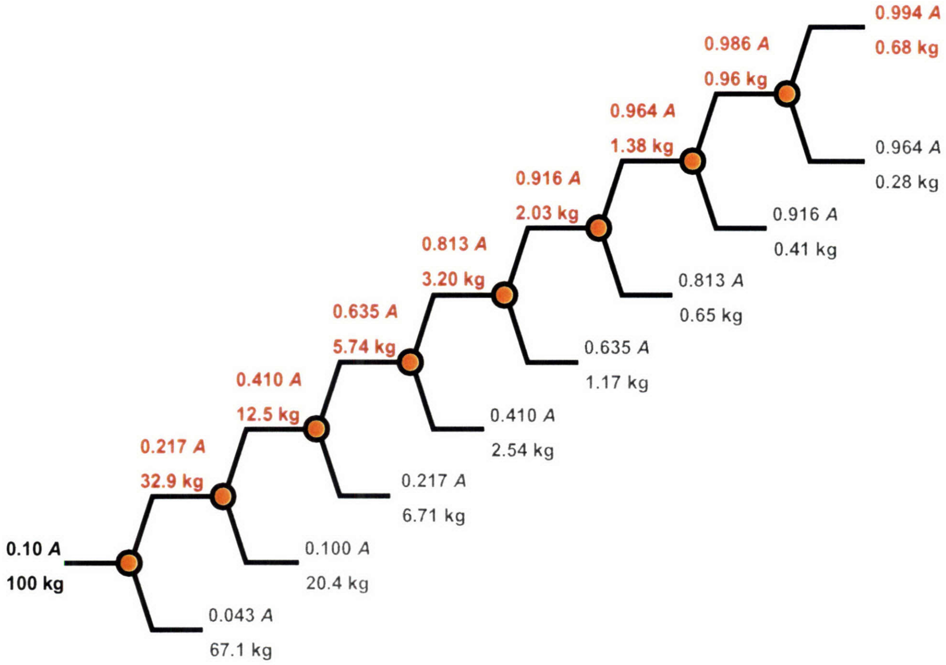

Figure 6: A material separation scheme with $r = q = 0.714$ and $\beta = 0.6$. The upper number of each two-number set represents the concentration of target material A in that stream. The lower number represents the total mass of material in that stream. Note that the desired output concentration of target material is reached in eight steps.

Figures 5 and 6 show not only the concentrating effects of separation processes, but also the amounts of target material that can be recovered. In Figure 5, the target material is concentrated from 0.10 to 0.991 in three steps. Of the 10 kg of target material A that enter, 7.51 kg

(0.991 x 7.58 kg) are captured. In Figure 6 the target material is concentrated from 0.10 to 0.994 in 8 steps. Of the 10 kg of target material *A* that enter, only 0.67 kg (0.994 x 0.68 kg) are captured. Note that as the materials proceed through the separation steps, the waste streams become highly concentrated in *A*, and could potentially re-enter the system at an earlier step.[5] Expansion of this model to include re-entrant flows is addressed by Albino (Albino 2007).

The series of separation steps shown in Figures 5 and 6 can also be examined by plotting the concentration of target material in the concentrated output stream after each separation step, c_{j+n}, as a function of the recovery rate of the target material after each separation step, r^n, where n is the number of separation steps completed. Such plots are shown in Figure 7, which corresponds to the branching tree in Figure 5, and Figure 8, which corresponds to the branching tree in Figure 6.

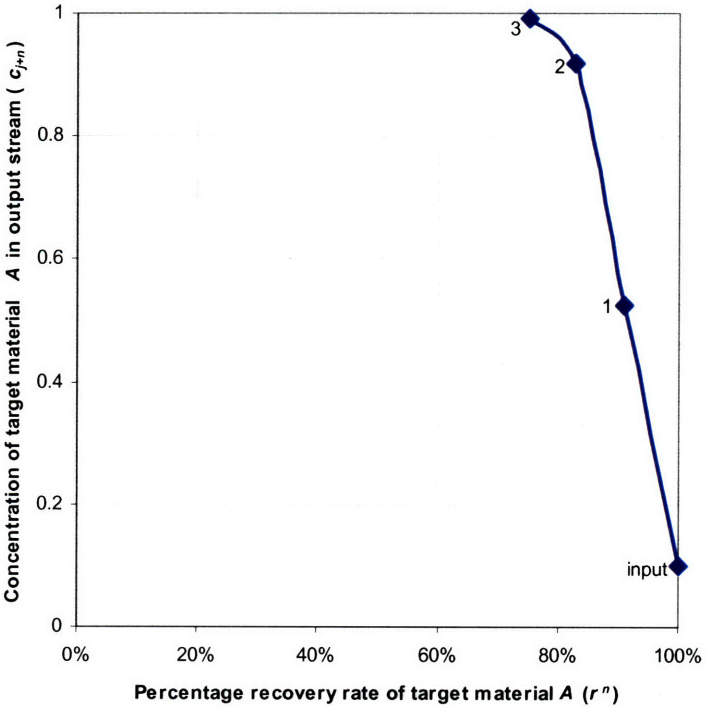

Figure 7: A plot of output concentration, c_{j+n}, as a function of the recovery rate of target material, r^n, where n is the number of separation steps already completed, for a separation process with $\beta = 0.9$. Values for n are shown next to the points on the plot.

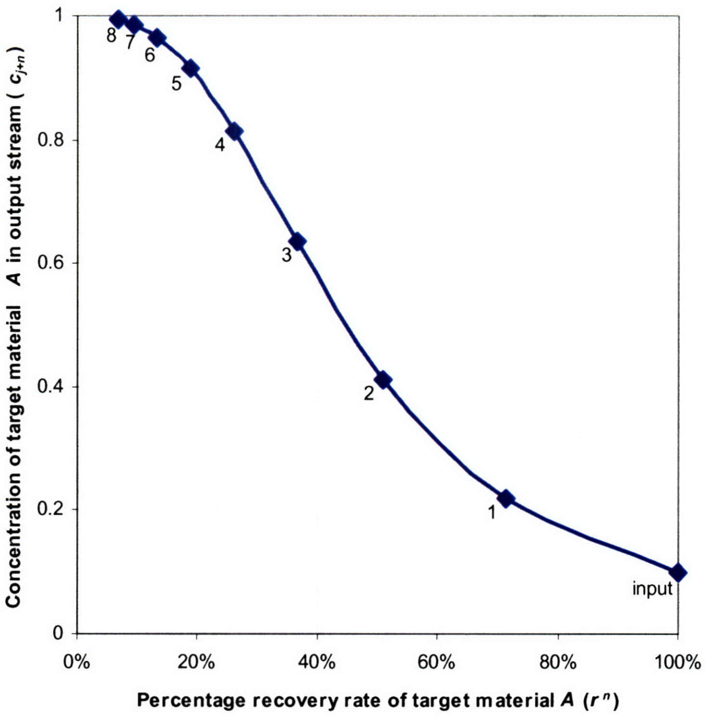

Figure 8: A plot of output concentration, c_{j+n}, as a function of the recovery rate of target material, r^n, where n is the number of separation steps already completed, for a separation process with $\beta = 0.6$. Values for n are shown next to the points on the plot.

Figures 7 and 8 show a phenomenon known as the "concentration dilemma", as illustrated in Figure 9, where the amount of material recovered decreases as final output concentrations increase (Hagelüken 2005, Hagelüken 2006). In short, there is a trade-off between yield and purity. Figures 7 and 8 also demonstrate the phenomenon, mentioned previously, in which as the concentration of target material in the incoming stream goes up, obtaining higher purity levels becomes increasingly more difficult.

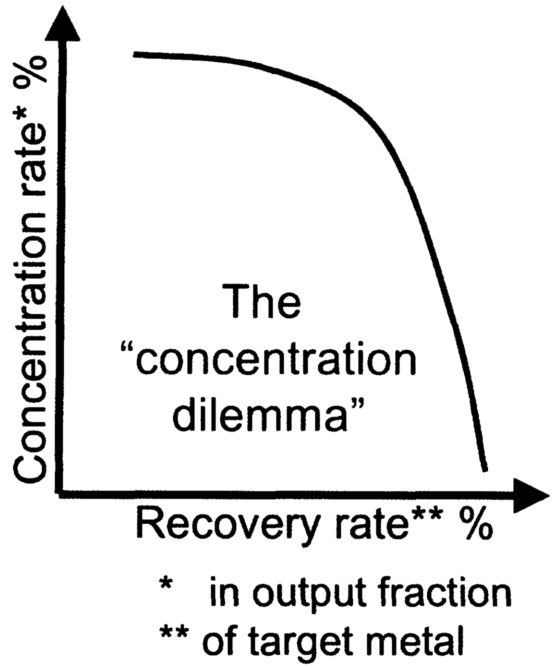

Figure 9: A plot of the "concentration dilemma", a trade-off between yield, indicated as "recovery rate", and purity, indicated as "concentration rate". Figure from Hagelüken (Hagelüken 2006).

A More General Solution

The result shown in (8), which allows for the characterization of the concentrated output stream given the properties of the input stream and separation process, can be generalized to allow for the calculation of the concentrated output stream after any arbitrary number of separations. For example, the concentration of the target material in the concentrated output stream after *n* separations is simply,

$$c_{j+n} = \frac{r^n c_j}{r^n c_j + (1-q)^n (1-c_j)} \quad (20)$$

Similarly, the total mass of material in that stream can be calculated as,

$$m_{j+n} = m_j (c_j r^n + (1-c_j)(1-q)^n) \ , \quad (21)$$

where n again represents the number of separations (Albino 2006, Branham 2006).

Note that (20), given a target concentration, c_t, can be solved for n, yielding,

$$n = \frac{\log\left(\frac{1-c_t}{c_t}\right) - \log\left(\frac{1-c_j}{c_j}\right)}{\log(1-\beta)} \quad . \tag{22}$$

Thus, the number of separation steps required, n, to reach a target concentration, c_t, can be calculated, given an input concentration, c_j, and properties of the separation process. This calculation can then be used to make an estimation of how separation costs would scale for different situations. For example, for very dilute solutions, it can be shown that cost would scale as

$$cost \sim n \sim \log\left(\frac{1}{c_j}\right) \quad . \tag{23}$$

This result gives a scaling very similar to that of the Sherwood plot, first formulated in 1959 by Thomas Sherwood, which shows that price scales linearly with $1/c_j$ for the separation of target materials from dilute mixtures (Sherwood 1959, NRC 1987, Grübler 1998).

The Effect of *r* and *q*

While the analysis presented in Figures 5 through 8 feature values of r equal to q, the different effects of these two parameters is important to point out. Since q represents the ability of the separation process to reject the non-target material, A^c, the value of q has a very strong effect on the purity of the concentrated output stream. If q is low, a large amount of non-target material will be accepted, and the concentrated stream will not be very pure; if q is high, most non-target material will be rejected, and the concentrated stream will be very pure. Figure 10, in which r is set to a high value, namely 0.99, and q is allowed to vary, shows this purifying effect of q.

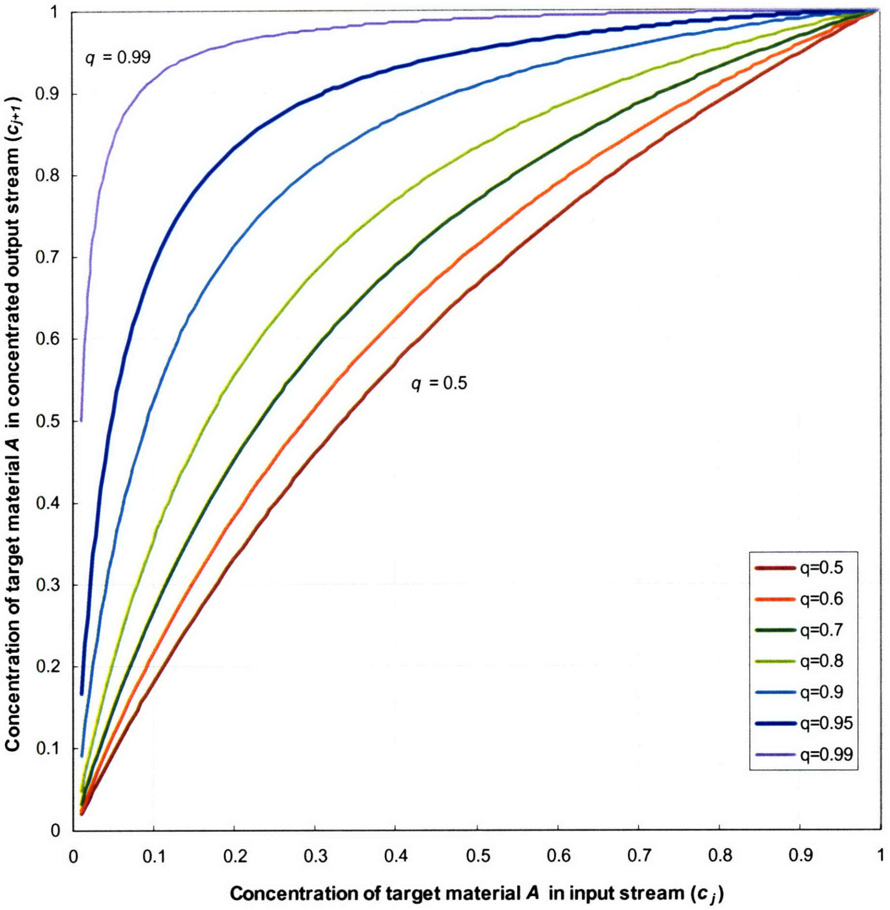

Figure 10: The performance of a separation process for various values of q while holding $r = 0.99$.

While q controls the purity, r has a different effect. Since r represents the ability of the separation process to accept the target material, A, the value of r has a very strong effect on the yield of the target material in the concentrated output stream. If r is low, a large amount of target material will be rejected, and the yield of target material in the concentrated output stream will be low; if r is high, a large amount of target material will be accepted, and the yield of target material in the concentrated stream will be high. The role of r is perhaps not surprising, particularly in light of (14), in which the value of r determines how much of the target material will be captured. Figure 11, in which q is set to a high value, namely 0.99, and r is allowed to vary, shows the effect of r on yield. Note that because q is held at a high value in Figure 11, the purity of the output stream remains high, despite changing r.

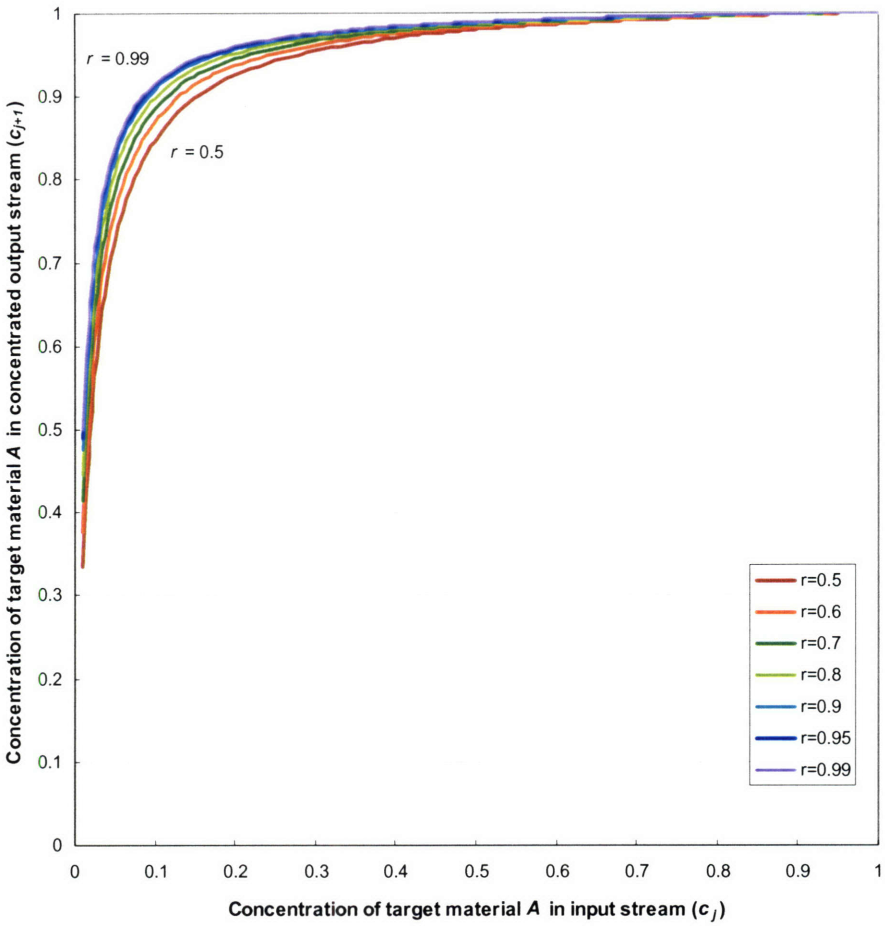

Figure 11: The performance of a separation process for various values of r while holding $q = 0.99$.

From published data regarding material separation processes, various values for r, q, and β can be obtained. Table 1 shows some of these values for the electrostatic separation of two types of plastics, the electrostatic separation of metals from non-metals, and the centrifugal separation of metals from non-metals (Xiao et al. 1999, Wen et al. 2005). The difference in values between the three separation scenarios confirms the fact that the separation of plastics is more difficult than the separation of metals. It is also important to note the range of values for r, which, in the case of the electrostatic separation of plastics, includes values less than 0.5. While the earlier assumptions for separation processes set $0.5 < r \leq 1.0$ and $0.5 < q \leq 1.0$, r can in fact be less than 0.5. As shown above, r controls the yield of a separation process. Thus, while values of r less than 0.5 indicate a process with low yields, the process can still be viable, meaning that it is capable of purifying materials. Further research by Albino sets the requirements on r and q, in order to have a viable separation process, to be $r>(1-q)$ (Albino 2007).

Separation Method	Materials Separated	r		q		β	
		min	max	min	max	min	max
electrostatic	ABS, HIPS	0.414	0.798	0.608	0.946	0.509	0.870
electrostatic	metals, non-metals	0.576	0.753	0.974	0.998	0.964	0.997
centrifugal	metals, non-metals	0.530	0.823	0.970	0.998	0.952	0.998

Table 1: Values for r, q, and β for different material separation processes.

Conclusion

This paper presents a simple mathematical model that can be used to analyze a range of material separation and purification processes, including those that occur as part of material recycling. This model has shown a good ability to reproduce well-known results. Further development and expansion of this model, and additional application of this model, should further the utility of this work.

Notes

1. Throughout this paper, the term "concentrated stream" will refer to the output stream with the higher concentration of target material than in the incoming stream. The term "dilute stream" will refer to the output stream with the lower concentration of target material than in the incoming stream.

2. The concentration of target material, A, is simply

$$c = \frac{m_A}{m_A + m_{A^c}} .$$

3. The concentration of non-target material, A^c, is simply

$$1 - c = \frac{m_{A^c}}{m_A + m_{A^c}} .$$

4. This assumption will be modified later, since r and q actually control different aspects of a material separation process. However, for the time being, setting these limits on r and q provides a simple set of working assumptions for the model.

5. The reprocessing of waste streams assumes that the target materials that are originally sent to the waste stream are sent there due to chance events, and not due to physical abnormalities such as entanglement or shape factors. If such physical differences lead to this misidentification of target materials as non-target materials, reprocessing may not improve overall yields.

   It should be noted that the symmetry seen in Figures 5 and 6, namely that the concentration of target material in the concentrated output stream of separation step n is identical to the concentration of target material in the dilute output stream of separation stem $n+2$, occurs as a result of having identical r and q values. This symmetry does not represent an inherent result of this model.

References

Albino, D.K., 2006. Laboratory for Manufacturing and Productivity Report 2- TGG-LMP- 2006. Massachusetts Institute of Technology, Cambridge, Massachusetts, USA. August 2006.

Albino, D.K., 2007. Bayesian Material Separation: Analysis of Multiple Recycling Streams. Senior Project in Applied Math, Yale University, New Haven, Connecticut, USA.

Ang, A. and W. Tang, 1975. Probability Concepts in Engineering Planning and Design. New York, New York, USA: John Wiley and Sons.

Branham, M., 2006. Laboratory for Manufacturing and Productivity Report 4- TGG-LMP- 2006. Massachusetts Institute of Technology, Cambridge, Massachusetts, USA. October 2006.

Grübler, A., 1998. Technology and Global Change. Cambridge, UK: Cambridge University Press.

Gutowski, T., J. Dahmus, D. Albino, and M. Branham, 2007. Bayesian Material Separation Model with Applications to Recycling. Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment, Orlando, Florida, USA. May 7-10, 2007: 233-238.

Hagelüken, C., 2005. Recycling of electronic scrap at Umicore's integrated metals smelter and refinery. Proceedings of the 2005 European Metallurgical Conference, Dresden, Germany. September 18-21, 2005.

Hagelüken, C., 2006. Improving metal returns and eco-efficiency in electronics recycling – a holistic approach for interface optimization between pre-processing and integrated metals smelting and refining. Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, San Francisco, California, USA. May 8-11, 2006: 218-223.

Murphy, C.F., P.S. Dillon, and G.E. Pitts, 2001. Economic and Logistical Modeling for Regional Processing and Recovery of Engineering Thermoplastics. Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment, Denver, Colorado, USA. May 7-9, 2001: 229-235.

National Research Council (NRC), 1987. Separation and Purification: Critical Needs and Opportunities. Washington, DC, USA: National Academy Press.

Sherwood, T.K., 1959. "Mass Transfer Between Phases," *Phi Lambda Upsilon*. University Park, Pennsylvania, USA: Pennsylvania State University.

Wen, X., C. Duan, H. Jiao, Y. Zhao, X. Zhou, and S. Song, 2005. Study on Metals Recovery from Discarded Printed Circuit Boards by Physical Methods. Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment, New Orleans, Louisiana, USA. May 16-19, 2005: 121-128.

Xiao, C., L. Allen, M. Biddle, and M. Fisher, 1999. Electrostatic Separation and Recovery of Mixed Plastics. Society of Plastics Engineers Annual Recycling Conference, 1999. Available online at http://plasticsresource.com/s_plasticsresource/docs/900/852.pdf. (Accessed January 31, 2007.)