CHAPTER 4

End of first life: a problem or a resource?

CONTENTS

4.1 Introduction and synopsis

When stuff is useful, we show it respect and call it *material*. When the same stuff ceases to be useful, we cease to respect it and we call it *waste*. Waste is deplorable, and it is much deplored, that from packaging particularly so. Is it inevitable? The short answer is *yes*—it is a consequence of one of the inescapable laws of physics: that entropy can only increase. A fuller answer is *yes, but*. The "but" has a number of aspects. That is what this chapter is about.

First, a calibration. We (the global we) are consuming materials at an ever faster rate (Chapter 2). The first owner of a product, at end of life, rejects it as waste. So waste, too, is generated at an ever growing rate. What happens to it? In five words: *landfill, combustion, recycling, re-engineering,* or *reuse*. That sounds comprehensive—it must be feasible to find a home for cast-off products in one of these. Ah, but. The capacity of a channel for dealing with products at end of first life, to be

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Is this waste or is it a resource?. (Image courtesy Envirowise - Sustainable Practices, Sustainable Profits, a UK Government programme managed by AEA Technology Plc.)

Materials and the Environment.

effective, must match the rate of rejection. Only one of the five has any real hope of achieving this. And then there are the economics. End of life is not simple.

To start at the beginning: why do we throw things away?

4.2 What determines product life?

The rapid turnover of products we see today is a comparatively recent phenomenon. In earlier times, furniture was bought with the idea that it would fill the needs not just of one generation but of several—treatment that, today, is reserved for works of art. A wristwatch, a gold pen, these were things you used for a lifetime and then passed on to your children. No more. Behind all this is the question of whether the *value* of a product increases or decreases with age.

A product reaches the end of its life when it's no longer valued. The cause of death is, frequently, not the obvious one—that the product just stopped working. The life expectancy is the least of[1]

- The *physical life*, meaning the time in which the product breaks down beyond economic repair;
- The *functional life*, meaning the time when the need for it ceases to exist;
- The *technical life*, meaning the time at which advances in technology have made the product unacceptably obsolete;
- The *economical life*, meaning the time at which advances in design and technology offer the same functionality at significantly lower operating cost;
- The *legal life*, meaning the time at which new standards, directives, legislation, or restrictions make the use of the product illegal;
- And finally the *desirability life*, meaning the time at which changes in taste, fashion, or aesthetic preference render the product unattractive.

One obvious way to reduce resource consumption is to extend product life, making it more durable. But durability has more than one meaning: we've just listed six. Materials play a role in them all—something that we return to later. Accept, for the moment, that a product *has*, for one reason or another, reached the end of its first life. What are the options?

4.3 End-of-first-life options

Figure 4.1 introduces the choices: landfill, combustion for heat recovery, recycling, re-engineering, and re-use.

Landfill. Much of what we now reject is committed to landfill. Already there is a problem—the land available to "fill" in this way is already, in some European countries, almost full. Recall one of the results of Chapter 2: if the consumption of materials grows by 3% per year, we will use and—if we discard it—throw away as much stuff in the next 25 years as in the entire history of industrialization. Landfill is not going to absorb that. Administrations react by charging a landfill tax—currently somewhere near €50 per metric ton and rising, seeking to divert waste into the other channels of Figure 4.1. These must be capable of absorbing the increase. None, at present, can.

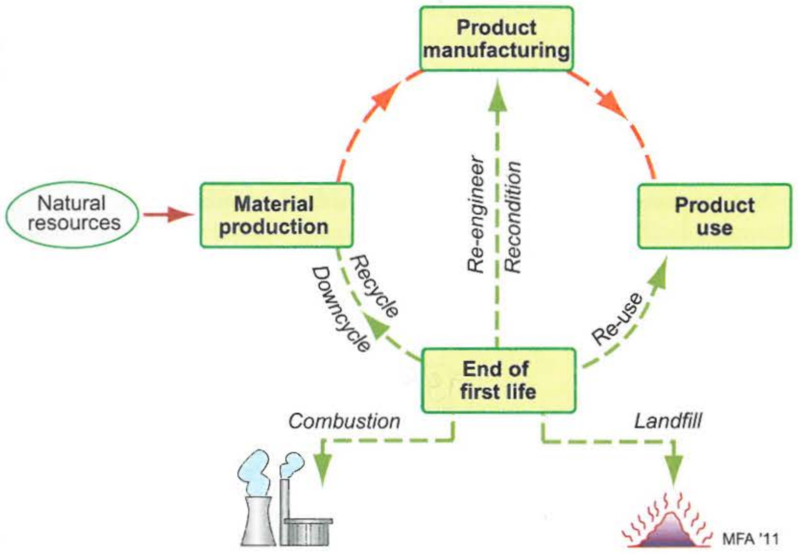

FIGURE 4.1 *End-of-life options: landfill, combustion, re-engineering, reconditioning, and reuse*

Combustion for heat recovery. Materials, we know, contain energy. Rather than throwing them away it would seem better to retrieve and reuse some of their energy by controlled combustion, capturing the heat. But this is not as easy as it sounds. First, combustibles must be separated from non-combustible material (Figure 4.2). Then the combustion must be carried out under controlled conditions that do not generate toxic fumes or residues, requiring high temperatures, sophisticated control, and expensive equipment. The energy recovery is imperfect partly because it is incomplete and partly because the incoming waste carries a moisture content that has to be boiled off. The efficiency of heat recovery from the combustion process is at best 50%, and if the recovered heat is used to generate electricity, it falls to 35%. And communities don't like an incinerator at their back door. Thus useful energy *can* be recovered by the combustion of waste, but the efficiency is low, the economics are unattractive, and the neighbors can be difficult.

Despite all this, combustion for heat recovery is, in some circumstances, practical and attractive. The most striking example is the cement industry, one with an enormous energy budget and CO_2 burden because of the inescapable step of

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[1] This list is a slightly extended version of one presented by Woodward (1997), "Life-cycle costing," *Int. J. Project Management*, 15, pp 335–344.

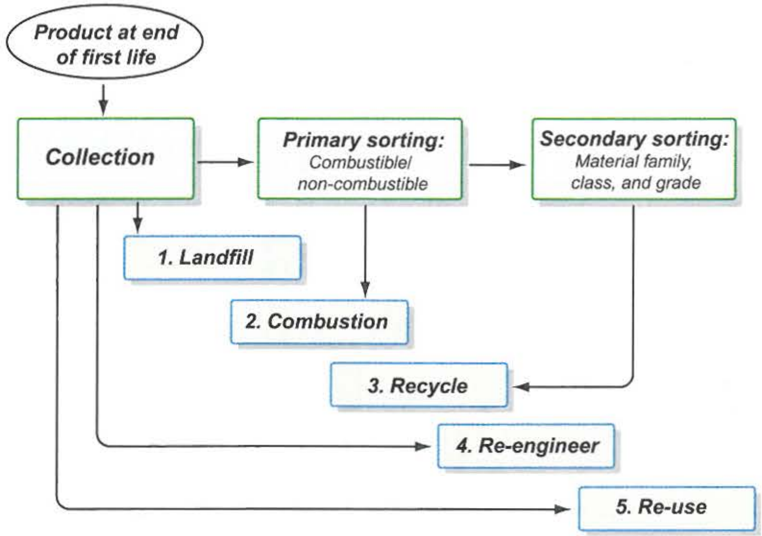

FIGURE 4.2 *End-of-life scenarios: landfill, combustion for heat recovery, recycling, refurbishment, and reuse. Different levels of sorting and cleaning are required for each.*

calcining in its production. Increasingly, combustion of vehicle tires and industrial and agricultural wastes are used as a heat source, reducing the demand on primary fuels, but not of course the attendant release of CO_2.

Recycling. Waste is only waste if nothing can be done to make it useful. It can also be a resource. Recycling is the reprocessing of recovered materials at the end of product life, returning them into the use-stream. It is the end-of-life scenario that is best adapted to extracting value from the waste-stream. We return to this in Section 4.5 for a closer look.

Re-engineering or refurbishment. There is the story of the axe—an excellent axe—that, over time, had two new heads and three new handles. But it was still the same axe. Refurbishment, for some products, is cost-effective and, compared with total replacement, energy efficient. Aircraft, for instance, don't wear out; instead, replacement of critical parts at regular inspection periods keeps the plane, like the axe, functioning just as it did when it was new. The Douglas DC3, a 70-year-old design, is still flying, though not, of course, in the hands of its original owner. Premium airlines fly premium aircraft, so older models are sold on to operators with smaller budgets.

Re-engineering is the refurbishment or upgrading of the product or of its recoverable components. Certain criteria must be met to make it practical. One is that the design of the product is fixed—as it is with aircraft once an airworthiness certificate is issued—or that the technology on which it is based is evolving so slowly that there remains a market for the restored product. Here are some examples: housing, office space, road and rail infrastructure; all are sectors with enormous appetites for materials. Some more examples: office equipment, particularly printing equipment and copying machines and communication systems. These are services; the product providing them is unimportant to those who need the service as long as it works well. It makes more sense to lease a service (as we all do with telephone lines, mobile phones, Internet service, municipal fresh water, and much else) because it is in the leasers' interests to maximize the life of the equipment.

And there is another obstacle to re-engineering: that fashion, style, and perceptions change, making a reconditioned product unacceptable even though it works perfectly well. Personal image, satisfaction, and status are powerful drivers of conspicuous consumption.

Reuse. The cathedrals of Europe, almost all of them, are built on the foundations of earlier structures, often from the 10th or 11th century, built, in turn, on still earlier 5th or 6th century beginnings. If the structure is in a region that was once part of the Roman Empire, then columns, friezes, fragments of the forum, and other structural elements of yet greater antiquity have found their way into the structure too. Reuse is not a new idea, but it is a good one.

Put more formally: reuse is the redistribution of the product to a consumer sector that is willing to accept it in its used state, perhaps to reuse it for its original purpose (a second-hand car, for instance), perhaps to adapt to another use (converting the car to a hot-rod or a bus into a mobile home).[2] The key issue here is that of communication. Housing estate (realtor) listings and used car and boat magazines exist precisely to provide channels of communication for used products. Charity shops pass on clothing, objects, and junk,[3] acquiring them from those for whom they had become waste and selling them to others who perceive them to have value. The most effective tool ever devised to promote product reuse is probably eBay, successful in this precisely because it provides a global channel of communication.

4.4 The problem of packaging

Few applications of materials attract as much criticism as their use of packaging. The functional life of packaging ends as soon as the package is opened. It is ephemeral, it is trite, it generates mountains of waste, and most of the time, it is unnecessary.

Or is it? Think for a moment about the most highly developed form that packaging takes: the way we package ourselves. Clothes provide protection from heat

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[2] What most of us see as waste can become the material of invention to the artist. For remarkable examples of this, visit the Museé International des Arts Modestes, 23 quai du Maréchal de Lattre de Tassigny, 34200 Sète, France (www.miam.org).

[3] I remember a sign above a store in an English town: "We buy junk. We sell antiques."

and cold, from sun and rain. Clothes convey information about gender and ethnic and religious background. Uniforms identify membership and status, most obviously in the military and the church, but also in other hierarchical organizations: airlines, hotels, department stores, and even utility companies. And at a personal level, clothes do much more: they are an essential part of the way we present ourselves. While some people make the same clothes last for years, others wear them only once or twice before—for them—they become "waste" and are given to a charity shop.

Fine, you may say, we need packaging of that sort; but products are inanimate. What's the point of packaging for them? The brief answer: products are packaged for precisely the same reasons that we need clothes: protection, information, affiliation, status, and presentation.

So let us start with some facts. Packaging makes up about 18% of household waste, but only 3% of landfill. Its carbon footprint is 0.2% of the global total. Roughly 60% of packaging in Europe, a bit less in the United States, is recovered and used for energy recovery or recycling. Packaging makes possible the lifestyle we now enjoy. Without it, supermarkets would not exist. By protecting foodstuffs and controlling the atmosphere that surrounds them, packaging extends product life, allows access to fresh products all year round, and reduces food waste in the supply chain to about 3%; without packaging, the waste is far higher. Tamper-proof packaging protects the consumer. Pack information identifies the product, its sell-by date (if it has one), and gives instructions for use. Brands are defined by their packaging—the Coca-Cola bottle, the Campbell's soup can, Kellogg's products—essential for product presentation and recognition.

The packaging industry[4] is well aware of the negative image that packaging holds and it strives to minimize its weight and volume. There are, of course, exceptions but there has been progress in optimizing packaging—providing all its functionality with the minimum use of materials. The most used of these—paper, cardboard, plastic, glass, aluminium, and steel—have established recycling markets (see below). Much packaging ends up in household waste, the most difficult type to sort. The answer to this is better waste-stream management in which the sorting is done by the consumer via marked containers. The protective function of much packaging requires material multilayers that cannot be recycled but that, if sorted, are still a source of energy.

So, the bottom line. Legislating packaging out of existence would require major adjustments to lifestyles, greatly increase the waste stream, and deprive consumers of convenience, product protection, and hygienic handling. The challenge is that of returning as much of it as possible into the materials economy at end of life.

The role of industrial design. What have you discarded lately that still worked or, if it didn't, could have been fixed? Changing trends, promoted by seductive advertizing, reinforce the desire for the new and urge the replacement of the old.

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[4] See, for instance, the Packaging Federation, www.packagingfedn.co.uk, or the Flexible Packaging Association, www.flexpack.org.

Industrial design carries a heavy responsibility here—it has, at certain periods, been directed toward creative obsolescence: designing products that are desirable only if new, and urging the consumer to buy the latest models, using marketing techniques that imply that acquiring them is a social and psychological necessity.

But that is only half the picture. A well-designed product can acquire value with age, and—far from becoming unwanted—can outlive its design life many times over. The auction houses and antique dealers of New York, London, and Paris thrive on the sale of products that, often, were designed for practical purposes but are now valued more highly for their aesthetics, associations, and perceived qualities. People do not throw away things for which they feel emotional attachment. So there you have it: industrial design both as villain and as hero. Where can it provide a lead?

When your house no longer suits you, you have two choices: you can buy a new house or you can adapt the one you have, and in adapting it, you make it more personally yours. Houses allow this. Most other products do not. An old product (unlike an old house) is often perceived to be incapable of change and to have such low value that it is simply discarded. That highlights a design challenge: to create products that can be adapted and personalized so that they acquire, like a house, a character of their own and transmit the message "keep me, I'm part of your life." This suggests a union of technical and industrial design to create products that can accommodate evolving technology, but at the same time, are made with a quality of material, design, and adaptability that give them a lasting and individual character, something to pass on to your children.[5]

4.5 Recycling—resurrecting materials

Of the five end-of-life options shown in Figure 4.1, only one meets the essential criteria:

- that it can return waste materials into the supply chain and
- that it can do so at a rate that, potentially, is comparable with that at which the waste is generated.

Landfill and combustion fail to meet the first criterion, and re-engineering and reuse fail the second. That leaves *recycling* (Figure 4.2).

Quantification of the process of material recycling is difficult. Recycling costs energy, and this energy carries its burden of emissions. But the *recycle energy* is generally small compared to the initial embodied energy, making recycling—when it is possible at all—an energy-efficient proposition. It may not, however, be one that is cost-efficient; that depends on the degree to which the material has become dispersed. In-house scrap, generated at the point of production or manufacturing, is

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[5] For an organization with such an ideal, see www.eternally-yours.nl.

localized and is already recycled efficiently (near 100% recovery). Widely distributed "scrap"—material contained in discarded products—is more expensive to collect, separate, and clean. Many materials cannot be recycled, although they may still be reused in a lower-grade activity; continuous-fiber composites, for instance, cannot yet be re-separated economically into fiber and polymer in order to reuse them, though they can be chopped and used as fillers. Most other materials require an input of virgin material to avoid build-up of uncontrollable impurities. Thus the fraction of a product that can ultimately re-enter the cycle of Figure 4.1 depends both on the material itself and on the product into which it has been incorporated.

Metals. The recycling of metals in the waste stream is highly developed. Metals differ greatly in their density, in their magnetic and electrical properties, and even in their color, making separation comparatively easy. The value of metals, per kilogram, is greater than that of other materials. All this helps make metal recycling economically attractive. There are many limitations on how recycled metals are used, but there are enough good uses that the contribution of recycling to today's consumption is large.[6]

Polymers. The same cannot be said of polymers. Commodity polymers are used in large quantities, many in products with short lives, and they present major problems in waste management, all of which, you would think, would encourage effective recycling. But polymers all have nearly the same density, have no significant magnetic or electrical signature, and can take on any color that the manufacturer likes to give them. They can be identified by X-ray fluorescence or infrared spectroscopy, but these are not infallible and they are expensive. Add to this that many are blends and contain fillers or fibers. Add further that the recycling process itself involves a large number of energy-consuming steps. Unavoidable contamination can prevent the use of recycled polymers in the product from which they were derived, condemning them to more limited use. For this reason the value of recycled polymers—the price they command—is typically about 60% of that of virgin material.

A consequence of this is that the recycling of many commodity polymers is low. Increasing the recycle fraction is a question of identification, and here there is progress. Figure 4.3 shows, in the top row, the standard recycle marks, ineffective because they do not tell the whole story. The lower row shows the emerging identification system. Here polymer, filler, and weight fraction are all identified. The string, built up from the abbreviations listed in the Appendix of this chapter, gives enough information for effective recycling.

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[6] A recent study reveals that the concentration of gold in the circuit boards and microprocessors of mobile phones and personal computers averages 0.2% by weight. The ores from which gold is currently extracted contain only 0.002% of the metal.

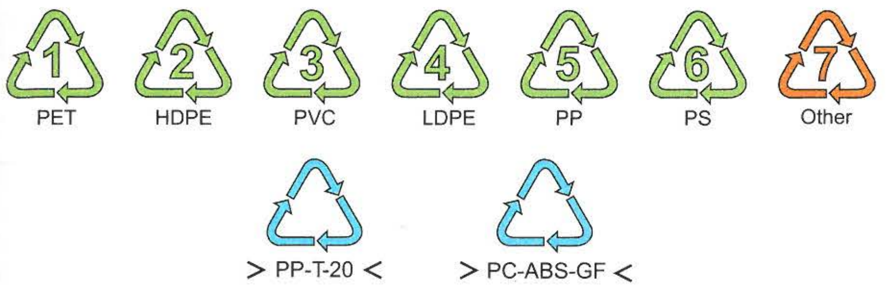


FIGURE 4.3 *Above: Recycle marks for the most commonly used commodity polymers. Below: More explicit recycle marks detailing blending, fillers, and reinforcement. The first is polypropylene with 20% talc powder. The second is a polycarbonate-ABS blend with glass fiber. The coding is explained in the Appendix to this chapter.*

Identifying polymers

Example: A product contains components with the recycle marks *TPA* and *PMMI-CF-30*. What are they?

Answer: Refer to the Appendix at the end of this chapter. It identifies the first as polyamide thermoplastic elastomer and the second as polymethylmethylacrylimide with 30% carbon fiber.

The economics of recycling. Although recycling has far-reaching environmental and social benefits, it is market forces that—until recently—have determined whether or not it happens. Municipalities collect recyclable waste, selling it through brokers to secondary processors who reprocess the materials and sell them, at a profit, to manufacturers. The recycling market is like any other, with prices that fluctuate according to the balance of supply and demand. In a free market the materials that are recycled are those from which a profit can be made. These include almost all metals but few polymers (Table 4.1).

Scrap arises in more than one way. *New* or *primary scrap* is the cutoffs from billets, risers from castings, and turnings from machining that are a by-product of the manufacturing of products; it can be recycled immediately, often in-house. *Old* or *secondary scrap* appears when the products themselves reach the end of their useful life (Figure 4.4). The value of recyclable waste depends on its origin. New scrap carries the highest value because it is uncontaminated and easy to collect and reprocess. Old scrap from commercial sources, such as offices and restaurants, is more valuable than that from households because it is more homogeneous and needs less sorting.

Producers of secondary materials must, of course, compete with those producing virgin materials. It is this that couples the price of the first to that of the

Table 4.1 Recycling markets

Material family	Developed end-uses for recycled materials	Secondary uses exist but are not developed as a market
Metals	Steel and cast iron Aluminum Copper Lead Titanium All precious metals*	Paper—metal foil packaging
Polymers and elastomers	Polyethylene terephthalate (PET) High density polyethylene (HDPE) Polypropylene (PP) Polyvinylchloride (PVC)	All other polymers and elastomers, notably tires
Ceramics and glasses	Bottle glass Brick Concrete and asphalt	Non-bottle glass
Other materials	Cardboard, paper, newsprint	Wood Textiles: cotton, wool, and other fibers

**Typical concentration of gold in ores from which it is extracted: 5 grams/metric ton. Typical concentration in a mobile phone: 150 grams/metric ton.*

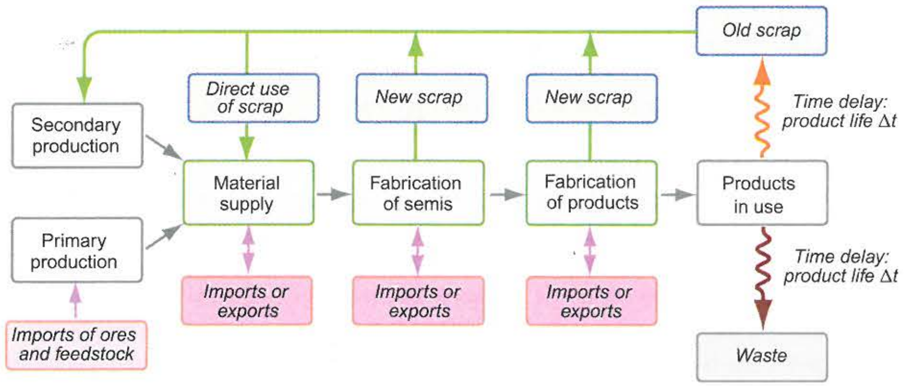


FIGURE 4.4 *The material flows in the economy, showing recycling paths. New scrap arises during manufacturing and is reprocessed almost immediately. Old scrap derives from products at end of life; it re-enters production only after a delay of Δt, the product life.*

second. Virgin materials are more expensive than those that have been recycled because their quality, both in engineering terms and that of perception, is greater. Manufacturers using recycled materials require assurance that this drop in quality will not compromise their products.

The profitability of a market can be changed by economic intervention: subsidies, for instance, or penalties. Legislation setting a required level of recycling for vehicles and for electronic products at the end of their lives is now in force in Europe; other nations have similar programs and plans for more. Municipalities, too, have recycling laws requiring the reprocessing of waste that, under free market conditions, would have zero value. In a free market these would end up in the landfill, but the law prohibits it. When this is so municipalities sell the waste for a negative price—that is, they pay processing firms to take it. The negative price, too, fluctuates according to market forces and may, if technology improves or demand increases, turn positive, removing the need for the subsidy.

Where laws requiring recycling do not exist, recycling must compete also with landfill. Landfill, too, carries a cost. What is recycled and what is dumped then change as market conditions—the level of a landfill tax, for instance—change and businesses seek to minimize the cost of managing waste.

News-clip: The fluctuating value of waste

Back at junk value, recyclables are piling up.
The economic downturn has decimated the market for recycled materials, leaving more headed for landfills.

***The New York Times*, December 8, 2008**

The value of recycled materials can go down as well as up, at least in the short term. As landfill charges rise, the economics of recycling become more attractive. But a recycling plant requires investment, and investors do not like unstable markets.

News-clip

Japan recycles rare earth minerals from used electronics.
Recent problems with Chinese supplies of rare earths have sent Japanese traders and companies in search of alternative sources. [The new source] is not underground, but in what Japan refers to as urban mining—recycling metals and minerals from the country's huge stockpiles of used electronics. "We've literally discovered gold in cellphones," said Tetsuzo Fuyushiba, a former land minister.

***The New York Times*, October 5, 2010**

. . . and the value of recycled materials can go up as well as down. Japan's National Institute for Materials Science (NIMS), estimates that used electronics in

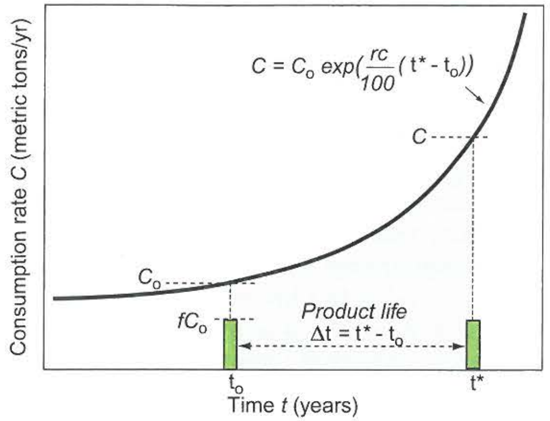


FIGURE 4.5 *Material dispersed as products does not appear as scrap for recycling until the product comes to the end of life. If consumption grows, long-lived products contribute less than those with short lives.*

Japan hold an estimated 300,000 tons of rare earths. They have a vital role in battery, electric motor, and laser technology. Restricted supply of virgin materials makes their recovery from waste products increasingly attractive.

All this may give the impression that waste management is a local issue, driven by local or national market forces. But the insatiable appetite of the fast-developing nations, particularly China and India, turn the "waste" of Europe and the United States into what, for them, is a resource. Low labor costs, sometimes less restrictive environmental regulation, and different manufacturing quality standards drive a world market in both waste and recycled materials.

The contribution of recycling to current supply. Suppose that a fraction f of the material of a product with a life of Δt years becomes available as old scrap. Its contribution to today's supply is the fraction f of the consumption Δt years ago. Material consumption, generally, grows with time, so this delay between consumption and availability as scrap reduces the contribution it makes to the supply of today. Figure 4.5 illustrates this. Suppose, for the moment, that a material exists that is used for one purpose only in a product with a life span Δt and that, at end of life, a fraction f (about 0.6 in the figure) is recycled into supply for current consumption, which has been growing at a rate r_c% per year. If the consumption rate when the product was made at time t_0 was C_0 metric tons per year, then the consumption today, at time t^*, is

$$C = C_0 \exp\left(\frac{r_c}{100}(t^* - t_0)\right) = C_0 \exp\left(\frac{r_c}{100}\Delta t\right) \tag{4.1}$$

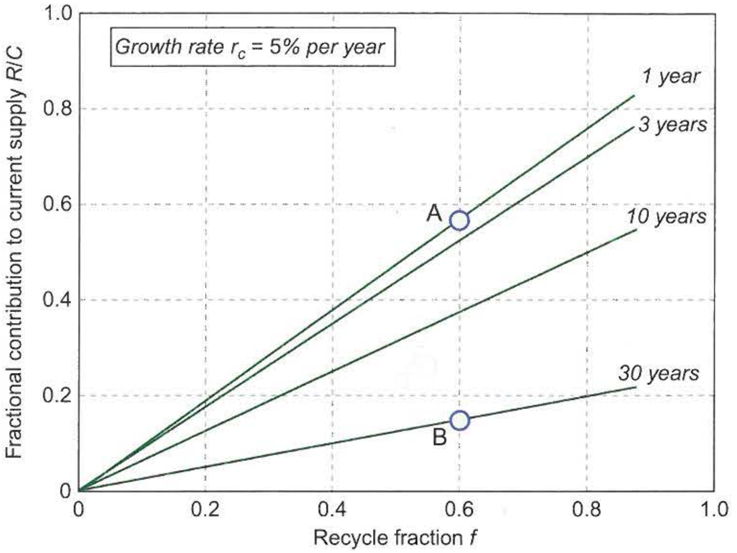


FIGURE 4.6 *Plot of equation (4.3) for recycling effectiveness when the growth rate in consumption is 5% per year, for various product lives and recycle fractions.*

where $\Delta t = t^* - t_0$. The recovered fraction R is

$$R = fC_0 \tag{4.2}$$

shown as a green bar on the figure. Its fractional contribution to supply today is

$$\frac{R}{C} = \frac{f}{\exp\left(\frac{r_c}{100}\Delta t\right)} \tag{4.3}$$

Figure 4.6 shows what this looks like for a product with a growth rate of 5% per year. If the fraction is $f = 0.6$, and the product life Δt is 1 year, the contribution is large, about 0.58 of current supply (Point A on Figure 4.6). But if the product life is 30 years, the contribution falls to 0.17 (Point B). The recycle contribution increases with f, of course. But it decreases quickly if the product has a long life or a fast growth rate.

In reality most materials are used in many products, each with its own lifespan Δt_i, recycle fraction f_i. Consider one of these—product i—that accounts for a fraction s_i of the total consumption of the material. Its fractional contribution to supply today is

$$\frac{R_i}{C} = \frac{s_i f_i}{\exp\left(\frac{r_c}{100}\,\Delta t_i\right)} \tag{4.4}$$

where r_c is the overall growth rate of consumption of the material. The total contribution of recycling is the sum of terms like this for the material in all the products that use it.

Recycle contribution of gizmos and widgets

Example: A material is used to make both gizmos and widgets; each accounts for 25% of the total consumption of the material. Gizmos last for 20 years; their sales have grown steadily at 10% per year. At the end of life gizmos are dismantled and all the material is recovered ($f_{gizmo} = 1$). Widgets, on the other hand, have an average life of 4 weeks and are difficult to collect; their recycle fraction is only $f_{widget} = 0.5$. Their sales have grown slowly at 1% per year for the recent past. Which contributes most to today's consumption?

Answer: If we insert these data into equation 4.3, we find an unexpected result: gizmos, all of which are recycled, contribute the tiny fraction of 0.03 to current supply whereas widgets, only half of which are recycled, contribute a much larger fraction of 0.125. The main effect here is the product lifetime: products with short lives make larger contributions to recycling than those that last for a long time. This reveals one of the many unexpected aspects of the materials economy: making products that last longer can reduce demand, but it also reduces the scrap available for recycling. If, in making them last longer they have to be made more robust, meaning that they need more material, the effect can actually increase the demand for primary materials.

4.6 Summary and conclusions

The greater the number of us that consume and the greater the rate at which we do so, the greater is the volume of materials that our industrial system ingests and then ejects as waste. Real waste is a problem—a loss of resources that cannot be replaced—and there has to be somewhere to put it and that, too, is a diminishing resource.

But waste can be seen differently: as a resource. It contains energy and it contains materials, and, since most products still work when they reach the end of their first life, waste contains components or products that can still be useful. There are a number of options for treating a product at the end of its first life: extract the energy via combustion, extract the materials and reprocess them, replace the bits that are worn and sell it again, or, simplest of all, put it on eBay or other trading system and sell it as-is.

All have merit. But only one—recycling—can begin to cope with the volume of waste that we generate and transform it into a useful resource.

4.7 Further reading

Chapman, P.F., and Roberts, F. (1983), *Metal resources and energy*, Butterworth's Monographs in Materials, Butterworth and Co., Thetford, UK. ISBN 0-408-10801-0. *(A monograph that analyzes resource issues, with particular focus on energy and metals)*

Chen, R.W., Navin-Chandra, D., Prinz, F.B. (1993), "Product design for recyclability: a cost benefit analysis," Proceedings of the IEEE International Symposium on Electronics and the Environment, Vol. 10–12, pp. 178–183. ISEE.1993.302813. *(Recycling lends itself to mathematical modeling. Examples can be found in the book by Chapman and Roberts (above) and in this paper, which takes a cost-benefit approach.)*

Guidice, F., La Rosa, G., and Risitano, A. (2006), *Product design for the environment*, CRC/Taylor and Francis, London, UK. ISBN 0-8493-2722-9. (*A well-balanced review of current thinking on eco-design*)

Hammond, G., and Jones, C. (2010), *Inventory of carbon and energy (ICE), Annex A: methodologies for recycling*, The University of Bath, Bath, UK. *(An analysis of alternative ways of assigning recycling credits between first and second lives)*

Henstock, M.E. (1988), *Design for recyclability*, Institute of Metals, London, UK. *(A useful source of background reading on recycling)*

Imhoff, D. (2005), *Paper or plastic: searching for solutions to an overpackaged world*, University of California Press. ISBN-13: 978-1578051175. *(What it says: a study of packaging taking a critical stance)*

PAS 2050 (2008), *Specification for the assignment of the life-cycle greenhouse gas emissions of goods and services*, ICS code 13.020.40, British Standards Institution, London, UK. ISBN 978-0-580-50978-0. *(This Publicly Available Specification (PAS) deals with carbon-equivalent emissions over product life, with a prescription for the way to assess end of life.)*

4.8 Appendix: designations used in recycle marks

(a) Base polymers

E/P	ethylene-propylene plastic
EVAC	ethylene-vinyl acetate plastic
MBS	methacrylate-butadiene-styrene plastic
ABS	acrylonitrile-butadiene-styrene plastic
ASA	acrylonitrile-styrene-acrylate plastic
C	cellulose polymers
COC	cycloolefin copolymer
EP	epoxide; epoxy resin or plastic
Imod	impact modifier
LCP	liquid-crystal polymer
MABS	methacrylate-acrylonitrile-butadiene-styrene plastic

MF	melamine-formaldehyde resin
MPF	melamine-phenolic resin
PA11	homopolyamide (Nylon) based on 11-aminoundecanoic acid
PA12	homopolyamide (Nylon) based on ω-aminododecanoic acid or on laurolactam
PA12/MACMI	copolyamide (Nylon) based on PA12, 3, 3-dimethyl-4, 4-diaminodicyclohexylmethane and isophthalic acid
PA46	homopolyamide (Nylon) based on tetramethylenediamine and adipic acid
PA6	homopolyamide (Nylon) based on ε-caprolactam
PA610	homopolyamide (Nylon) based on hexamethylenediamine and sebacic acid
PA612	homopolyamide (Nylon) based on hexamethylenediamine and dodecanediacid (1,10-decandicarboxylic acid)
PA66	homopolyamide (Nylon) based on hexamethylenediamine and adipic acid
PA66/6T	copolyamide based on hexamethylenediamine, adipic acid, and terephthalic acid
PA666	copolyamide based on hexamethylenediamine, adipic acid, and ε-caprolactam
PA6I/6T	copolyamide based on isophthalic acid, adipic acid, and terephthalic acid
PA6T/66	copoylamide based on adipic acid, terephthalic acid, and hexamethylenediamine
PA6T/6I	copolyamide based on hexamethylenediamine, terephthalic acid, adipic acid, and isophthalic acid
PA6T/XT	copolyamide based on hexamethylenediamine, 2-methyl-penta-methylenediamine, and terephthalic acid
PAEK	polyaryletherketon
PAIND/INDT	copolyamide based on 1, 6-diamino-2,2,4-trimethylhexane, 1, 6-diamino-2, 4, 4-trimethylhexane, and terephthalic acid
PAMACM12	homopolyamide based on 3,3′-dimethyl-4,4′-diaminodicyclohexyl-methane and dodecandioic acid
PAMXD6	homopolyamide based on m-xylylenediamine and adipic acid
PBT	poly(butylene terephthalate)
PC	polycarbonate
PCCE	poly(cyclohexane dicarboxylate)
PCTA	poly(cyclohexylene dimethylene terephthalate), acid
PCTG	poly(cyclohexylene dimethylene terephthalate), glycol
PE	polyethylene
PEI	polyetherimide
PEN	polyethylene naphthalate
PES	polyethersulfone
PET	polyethylene terephthalate
PETG	polyethylene terephthalate, glycol

PF	phenol-formaldehyde resin
PI	polyimide
PK	polyketone
PMMA	poly(methyl methacrylate)
PMMI	polymethylmethacrylimide
POM	polyoxymethylene, polyacetate, polyformaldehyde
PP	polypropylene
PPE	poly(phenylene ether)
PPS	poly(phenylene sulfide)
PPSU	poly(phenylene sulfone)
PS	polystyrene
PS-SY	polystyrene, syndiotactic
PSU	polysulfone
PTFE	polytetrafluoroethylene
PUR	polyurethane
PVC	polyvinyl chloride)
PVDF	poly(vinylidene fluoride)
SAN	styrene-acrylonitrile plastic
SB	styrene-butadiene plastic
SMAH	styrene-malefic anhydride plastic
TEEE	thermoplastic ester- and ether-elastomers
TPA	polyamide thermoplastic elastomer
TPC	copolyester thermoplastic elastomer
TPO	olefinic thermoplastic elastomer
TPS	styrenic thermoplastic elastomer
TPU	urethane thermoplastic elastomer
TPV	thermoplastic rubber vulcanisate
TPZ	unclassified thermoplastic elastomer
UP	unsaturated polyester

(b) Fillers

CF	carbon fiber
CD	carbon fines, powder
GF	glass fiber
GB	glass beads, spheres, balls
GD	glass fines, powder
GX	glass not specified

K	calcium carbonate
MeF	metal fiber
MeD	metal fines, powder
MiF	mineral fiber
MiD	mineral fines, powder
NF	natural organic fiber
P	mica
Q	silica
RF	aramid fiber
T	talcum
X	not specified
Z	others not included in this list

4.9 Exercises

E4.1. Many products are thrown away and enter the waste stream even though they still work. What are the reasons for this?

E4.2. Do you think manufacturing without waste is possible? "Waste," here, includes low-grade heat, emissions, and solid and liquid residues that cannot be put to a useful purpose. If waste is inevitable, why?

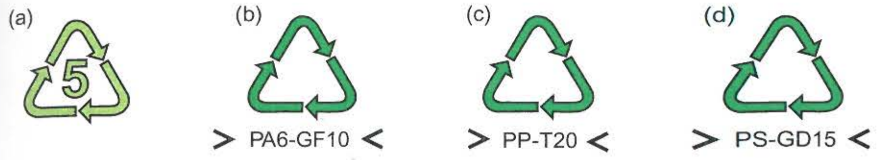
E4.3. What options are available for coping with the waste-stream generated by modern industrial society?

E4.4. Recycling has the attraction of returning materials into the use-stream. What are the obstacles to recycling?

E4.5. Car tires create a major waste problem. Use the Internet to research ways in which the materials contained in car tires can be used, either in the form of the tire or in some decomposition of it.

E4.6. List five functions of packaging.

E4.7. As a member of a brain storming group, you are asked to devise ways of reusing polystyrene foam packaging—the sort that encases TV sets, computers, appliances, and many other things when they are transported. Use free thinking: no suggestion is too ridiculous.



E4.8. You are employed to recycle German washing machines, separating the materials for recycling. You encounter components with the recycle marks seen in Figure 4.7:

How do you interpret them?

Answer. (a) Polypropylene. (b) Polyamide 6 (Nylon 6) with 10% glass fiber. (c) Polypropylene with 20% talc. (d) Polystyrene with 15% glass fines (powdered glass).

E4.9. The consumption of lead is growing at 4% per year. It has a number of uses, principally as electrodes in storage batteries, as roofing and pipe-work on buildings, and as pigment for paints. The first two of these allow recycling, the third does not. Batteries consume 38% of all lead, have an average life of 4 years, a growth rate of 4% per year, and are recycled with an efficiency of 80%. Architectural lead accounts for 16% of total consumption. The lead on buildings has an average life of 70 years after which 95% of it is recycled. What is the fractional contribution of recycled lead from each source to current supply?

E4.10. A material M is imported into a country principally to manufacture one family of products with an average life of Δt years and a growth rate of r_c% per year. The material is not currently recycled at end of life, but it could be. The government is concerned that imports should not grow.

(a) What recycle fraction, f_{crit}, is necessary to make this possible?
(b) The longer the average product life, Δt, the smaller is its fractional contribution to future supply. What is the limiting life beyond which recycling cannot keep up with increased demand?

E4.11. The rare-earth metal neodymium is an ingredient of high-field permanent magnets. Its consumption is growing at $r_c = 5$% per year. If 50% of all neodymium entering service is used for the electric motors of hybrid and electric cars with an average life of 15 years, what fraction will recycling 95% of the neodymium in these cars contribute to future consumption? Computer hard disk drives, too, contain neodymium magnets. If 15% of current neodymium consumption is that in hard disk drives with an average life of 3 years, what fraction will they contribute to future consumption if they, too, have a 95% recycle rate?