16 Longer life products

with delayed replacement

In developed economies, where our demand for metal has largely stabilised, we mainly purchase metal as replacement rather than due to growth. So, if we keep our products for longer, that would slow down the rate of replacement and hence reduce our need for new metal. Could we really use products for longer?

Caversham Road Bridge[13]

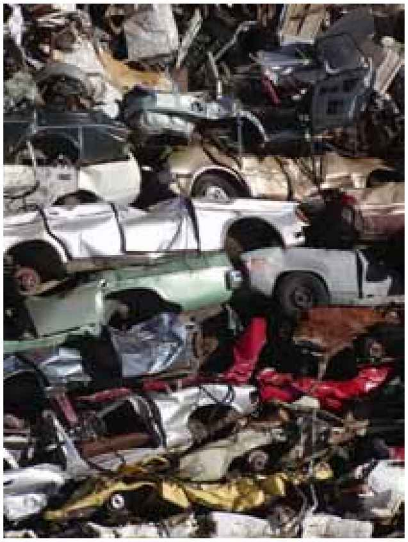
Ironbridge

Concorde

In three days during the 2011 New Year celebrations, the Caversham Road Bridge carrying nine train tracks over a road near to Reading Station in the UK was replaced, and the steel in it sent for recycling. There was no public outcry about the loss of the previous bridge, but if we proposed to replace Abraham Darby III's 1781 bridge at Ironbridge Gorge, we would incur not just public outcry, but the full legal might of the United Nations who have declared it a World Heritage Site. Every year in the UK we send 2 million cars to scrap[1], eventually to be recycled by melting, but we don't scrap old E-type Jaguars, because they epitomise a glamorous era of motoring whose aura we treasure. In total, 20 supersonic Concorde aeroplanes were built between 1966 and 1979. They no longer fly, but we'll never melt them all. NASA's four remaining space shuttles have retired to Museums in Florida, Los Angeles, Virginia and New York and we'll never discard them. The oldest surviving Watt Steam engine, the Old Bess built in 1777, is on display in the Science Museum in London, and we'll keep looking after it.

We connect with our past through stories and songs, through pictures and manuscripts, but also through physical objects. This connection is part of all cultures, and at some point objects become part of our heritage: we cease to consider whether they should be replaced by a newer or better model; we preserve them because they are part of what we are. This is as true of us individually as collectively, and in the same way that national charities and government organisations work to preserve important publicly owned buildings and goods, so privately we maintain family heirlooms and treasures.

So we know that if we choose to do so, we can maintain goods for much longer than normal, and in this chapter we'll explore whether keeping steel and aluminium products and components in use for longer would be viable or a good thing. The motivation is that, as we saw in chapter 4, in developed countries most of our demand for steel and aluminium is to replace goods rather than to expand our

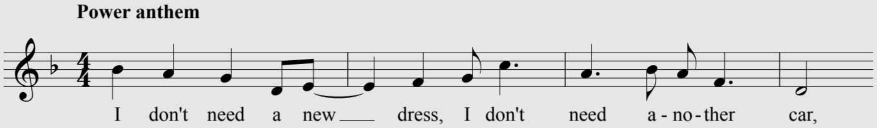


Cars that failed to achieve heritage status

total stock. If we replace them less often, we will reduce our demand for new liquid metal, and so reduce the environmental impacts of production.

We learnt an important story motivating our work on this chapter in a previous project, where we looked at the future sustainability of clothing and textiles supply to the UK[2]. Between 2000 and 2005, in the UK, we increased the number of garments we purchase each year by one third. This incredible growth in demand was not, of course, triggered by a change in weather, but by the move towards 'fast fashion.' Prior to 2000, the fashion industry had a summer and winter season, and brought out new ranges twice a year to match. 'Fast fashion' now allows the introduction of new clothing ranges every six weeks, or even faster. This is a remarkable achievement, but most people reading this book can remember living in 2000, without worrying about being short of clothes. We buy more clothes because we can, and as a consequence, we throw them away at a greater rate. During our project on clothing and textiles, we met many inspiring people, and chief among them is Kate Fletcher[3]. Kate recognised that we discard garments so easily because they are commodities: they have no personal meaning. However, if your mother embroidered a shirt while you were ill, or if your child knits a hat, it isn't a commodity and you can't replace it.

What we learnt from Kate applies across a wide range of personal purchases, but we saw in our catalogue of steel and aluminium goods, that most metal is purchased by businesses not individuals. So in this chapter, starting from Kate's inspiration, we need to work our way carefully through the environmental, technical and business realities of steel and aluminium longevity.

We can anticipate the structure of this chapter by thinking about longer life cars. Firstly, if cars are becoming more fuel efficient, is it a good thing to keep them for longer, or should we actually replace them sooner, to gain improved fuel consumption? Do we replace the car because it is broken, because there's a new one we prefer, because it no longer meets our needs, or because it's no longer legal? Do we want to replace everything about our car, or just a few components? Finally, as car owners, or as car makers, how does longer car ownership affect us?

The angel of the north[14]

Is it more sustainable to keep goods for longer?

Keeping goods for longer reduces the rate of replacement demand, and for products that don't need maintenance and require little energy in use, this will save energy compared to replacing them. With absolute confidence we can state that the best strategy for minimising emissions associated with the Angel of the North, and indeed any other metal sculpture, is not to replace it. We can say the same about any products that use energy, but which have not become more efficient, since last purchased. However, if developments in technology, legislation or consumer preferences have led to more efficient products, we must evaluate the trade-off between increasing emissions by producing new metal for the replacement, against reducing emissions in use.

Figure 16.1 explores this issue. In the first graph, a product with high embodied energy, low energy in use, and little improvement in use should be replaced less frequently. In the second graph, energy in use is greater than that in production, and efficiency is improving, so the product should be replaced more often. We'd like to generalise the message of these two graphs and will do so with a simple calculation.

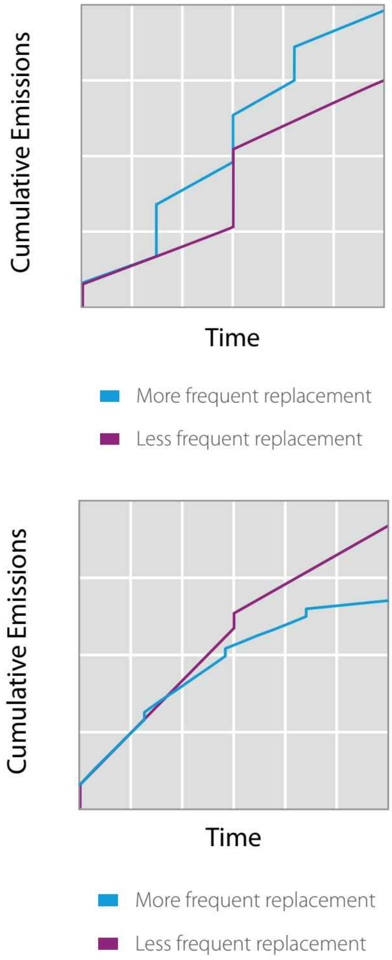


Figure 16.1—**Cumulative emissions profiles: products with low embodied energy and high rates of efficiency improvement should be replaced more frequently**

Let's assume we know the embodied energy required to make some product, and the annual energy consumed in use for this year's model. We'll also assume that each year, because of innovations, both embodied and annual use-energy are reduced at steady but independent rates—say 1% less embodied energy and 2% less energy in use per year, every year, for that year's model. Now let's assume the owner chooses to replace the product at a regular interval. For example, for the improvement rates we've given, if the user replaces the product every 5 years, then in 5 years time they will buy a model having 5% less embodied energy and 10% less annual-use energy than this year's model. For any product, if we know this year's embodied energy and annual-use energy, and the likely rates of future improvement in both, we can now calculate the replacement interval that minimises the total required energy.

We've done this for a range of these values in Figure 16.2. The graph shows us firstly that as the ratio of embodied to annual-use energy increases we should replace products less frequently (as we anticipated with the Angel of the North). But we can also see how that decision changes as either embodied or annual-use energy improve. Improvements in annual-use energy have a small effect, which is stronger at the right of the graph; improvements in embodied energy have a large effect all across the graph. This seems surprising but remember that the basic shape of the graph *already* tells us to replace products with large annual-use energy more frequently. If the annual-use energy improves, the effect of changing our replacement period is small because we will incur most of the annual-use energy anyway. However, if we reduce our replacement interval at all, the total number of times we buy the product goes up, and we incur the full embodied energy each time, so are highly sensitive to how it improves[4].

We've also shown on Figure 16.2 various familiar products—an office block, a car, an aeroplane, a train—for which we know current values of embodied and annual use energy[5]. For each product, we've shown typical replacement intervals in current practice (circles) and the replacement interval we estimate to be best—according to current rates of improvement (stars). The results show that in each case, albeit only marginally for the plane, we're replacing faster than we should do according to this criterion, so in turn, delaying the end of life for all of these products would save energy. This motivates us to explore the other reasons why we replace products, and will do so in the next section.

Figure 16.2 provides important general guidance about the value of delaying product replacement, and we could now use it as a start to exploring life extension for any particular product. In the rest of this chapter we'll assume that we're dealing with products for which life extension is beneficial, and focus on the realities of making it happen. However, before leaving the environmental case, let's anticipate one of our strategies coming up, and explore what happens if, rather than replacing the whole product, we're able to perform an upgrade to gain the benefits of improved energy requirements in use, without incurring the full

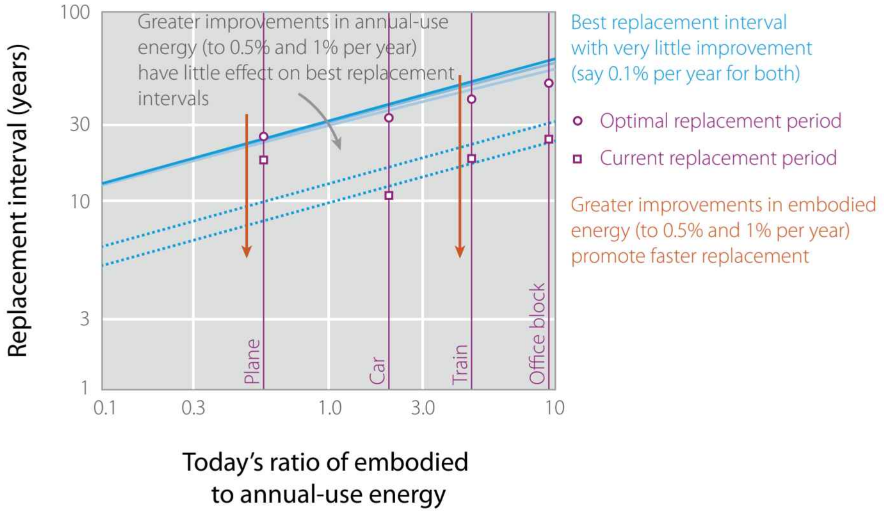
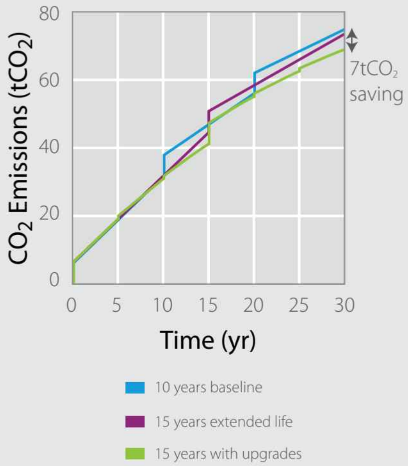


Figure 16.2—**Predicted product replacement intervals to minimise use and embodied energy**

embodied energy cost or replacing the entire product. The box story examines the options for life extension and upgrades applied to a specific vehicle, confirming the potential benefit of upgrades.

Can we anticipate how this linkage between use and embodied energy and emissions will play out in future? Figure 16.3 shows estimates of current ratios between embodied and use emissions for buildings, passenger and freight vehicles over current life spans, showing that in all cases, total energy requirements are dominated by use. This is well known, and links right back to the pie charts on global energy use in chapter 2. The use of vehicles and buildings are two of the three major categories of global energy consumption, but unlike industrial production, they are currently inefficient and we have plenty of options to improve their efficiency. As a result, annual-use emissions will in future be smaller relative to embodied emissions from making buildings and cars, so by our analysis this will increase the value of life extension in future.

The conclusion of this section is that life extension is not always a good idea, if a product has high use energy requirements compared to embodied production



Upgrade as a strategy for vehicle life extension?

In the graph to the left, the blue line represents a typical mid-size car (125 g CO_2/km tailpipe emissions) with a design life of 200,000 km over 10 years. At years 0, 10 and 20, the car is replaced creating 6.3 t CO_2 of embodied carbon emissions per car. The annual-use emissions are assumed to improve by 3.5% every year (in line with the car-maker's targets and EU regulation) giving 128 g CO_2/km for the first period, and 90 g CO_2/km and 64 g CO_2/km for the following two periods. Total emissions of the 30 year period come to 75 tCO_2. Life-extension (the purple line) to 15 years requires only two new cars. This saves just 1.5 t CO_2 (2%) of emissions, much less than the 6.3 t CO_2 embodied emissions saved, because the strategy delays upgrading to the latest engine technology. Upgrading (the green line) the car every 5 years with a new engine (at a cost of 15% of embodied emissions in a new car, 0.9 t CO_2) takes advantage of improved engine technology to reduce annual-use emissions with a minimal penalty in embodied emissions. This strategy saves 7 t CO_2 (9%) of emissions, which is more than a new car, and this could be an attractive business model for car manufacturers. In this case the total saving is relatively small compared to the cumulative emissions over the period, but greater savings will be achieved for products with higher relative embodied energy.

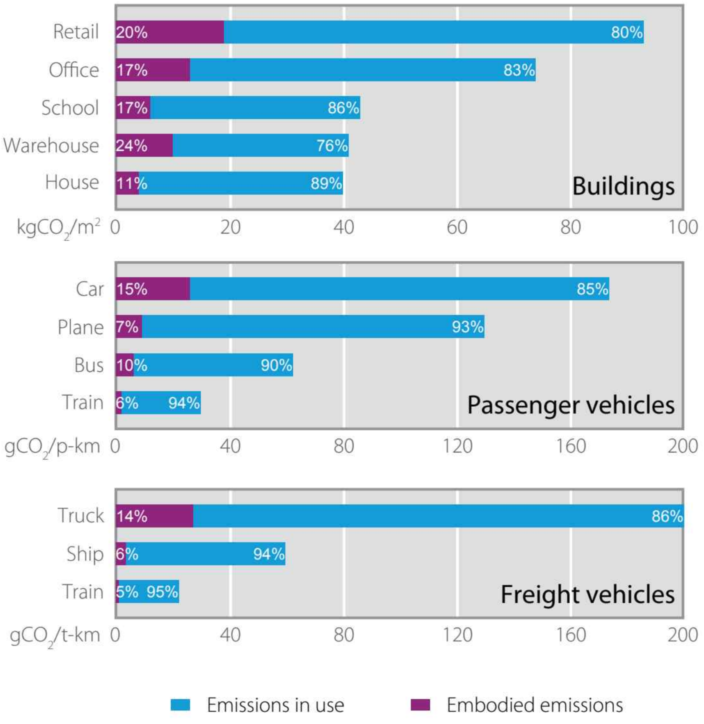


Figure 16.3—**The relative size of use and embodied emissions**

requirements, or if rapid technology change is occurring. However, for most existing products, life extension would lead to net savings. Therefore we'll now focus on life extension and the key question arising from our evidence in Figure 16.2 is 'what's making us replace things too soon?'

Why do we replace existing goods?

Some of us want new cars, with the latest styling and features, while others prefer to buy second-hand cars to have sufficient features at lower cost. Perhaps surprisingly new tractors, fridges and trucks are now all marketed with fashion and style prominent in the advertising messages while functionality is assumed. But if you're a salesman for steel rail track, your primary message will be about its life in service: we don't buy track because of its colour.

We've looked at dozens of case studies exploring why owners in different contexts replace products, and found that we can helpfully illuminate their different motivations by asking just two questions:

- is the product replaced because of its performance or because of its value?
- is the product being assessed relative to when it was purchased or relative to what's now available?

We've illustrated these options as the rows and columns of Table 16.1 to define four types of 'failure'[6].

Table 16.1—**Types of failure**

	... relative to when it was purchased	... relative to what's now available
The product's performance has declined ...	Degraded e.g. rail track	Inferior e.g. washing machines
The product's value has declined ...	Unsuitable e.g. sports car	Unwanted e.g. single hulled oil tankers

Looking in turn at each type of failure in Table 16.1:

- **Degraded** failure occurs when the product has deteriorated so can no longer perform its original function. For clothing and textiles, this obviously relates to clothes being worn out, but for metal goods, it relates primarily to surface wear (damage when two metal surfaces slide over each other) but may also occur due to fire damage, fatigue cracks (growing after repetitive cycles of loading and unloading) or over-loading or impact.
- **Inferior** failure occurs when the original product is still functioning as designed, but a newer product is more attractive. Flared purple trousers of the 1970's have largely met this failure mode, and it is also common in computing and telecommunications due to the rate of innovation. For steel and aluminium goods, this mode often drives replacement decision for cars and machinery.
- **Unsuitable** failure occurs when the users' needs have changed so that the original product is no longer as valuable to the existing owner. In clothing and textiles this failure mode occurs when (for some reason) the clothing no longer fits the owner, and perhaps relatedly, a two-seater car is of little value to a couple with a new baby. Changing customer behaviour could drive unsuitable failures in many contexts, public transport for example, or electrical distribution, or

when a building no longer meets a tenant's needs. Unsuitable failure relates to the value of the product to its current owner, but other owners may value it differently.

- **Unwanted** failure occurs when a product still functions well, but is valued neither by its current owner, nor any other. It may occur due to changes in fashion, or due to legislation: for example, legislation which now favours double hulls in an effort to reduce the risk of oil spills has caused early replacement of single hulled oil tankers, which continue to operate according to their original design, but are now unwanted.

Armed with our vocabulary of failure modes, we can now return to our product catalogue from chapter 3, to explore why each product type is replaced. To create Figure 16.4, we've pulled together all the information that we could find on the reasons for failure product by product, and then verified our estimates with experts in each industry. We found that we rarely demolish buildings because their performance has failed, and instead, their value to owners or tenants has declined so they are unsuitable or unwanted. Second hand markets for vehicles and industrial equipment are strong, so although their original owners may replace them because they are unsuitable or inferior, eventually their final owners will discard them when degraded. Aluminium packaging is degraded in use, and so is replaced. At their original design load, electric cables could last for a hundred years, but due to growth in population and power hungry technology, older cables must often transmit power beyond this design load and so become 'unsuitable': they overheat, sag, and can cause power cuts.

Table 16.2 summarises our estimates of the fraction of steel and aluminium discarded for the three modes of failure shown in Figure 16.4. Our table of four different failure modes has helped us to identify and separate the reasons why steel and aluminium goods are replaced and soon we'll use it to search for opportunities to extend product life. But before doing so we'll ask a more forensic question: we know that steel and aluminium are always used to make components, so when goods containing the two metals are replaced, has the whole assembly of components failed, or does failure really apply to just a few components?

	Steel	Aluminium
Degraded	32 %	61 %
Inferior	14 %	3 %
Unsuitable Unwanted	54 %	36 %

Table 16.2—**Failure mode shares for each metal**

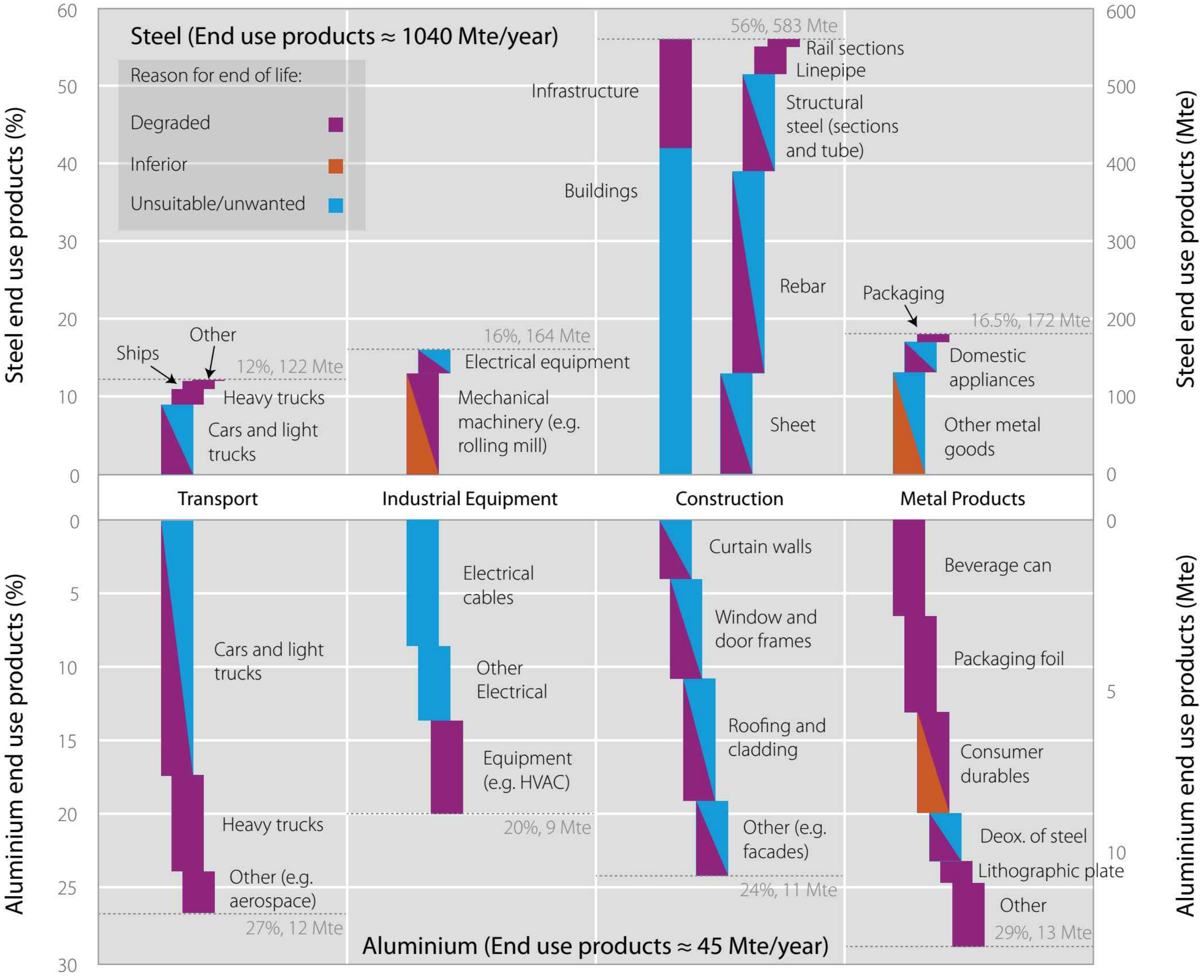


Figure 16.4—**Reasons for end-of-life**

Which specific components drive our replacement decisions?


High un-productivity in UK fridge shredding

Among the many visits we made while preparing this book, we went to a metal scrap yard with a dedicated fridge shredding line. We have about 22 million households in the UK, with a fridge in each, and we throw them away when they're 10–12 years old, so we discard about 2 million fridges per year. We must dispose of them with care to avoid releasing the refrigerants (previously CFCs and now HFCs) into the atmosphere, so we've created dedicated un-production lines to shred them efficiently. And how wonderfully efficient we are! Our best fridge shredding line in the UK can shred one million fridges per year, as we apply in reverse all the skills we've learnt from Toyota about efficient car manufacturing. In the UK we make about 1.5 million (mainly Japanese) cars per year so we must be pretty efficient at manufacturing? Peanuts! Every year we destroy at least 33% more fridges that we make cars, and while our car output is declining, our fridge destruction rates are rising. Great news: UK un-productivity goes up!

What's wrong with all those fridges. Are they unwanted? No, we all want fridges. Are they unsuitable? No, we have two basic shapes of fridge, under the counter or cabinet size, and there hasn't been much change. Inferior? A few people with low self esteem purchase identical pink fridges to demonstrate their creative individuality, but essentially fridges aren't a fashion item. So they must be degraded? Not the outer case, not the door, not the interior fittings, not the heat exchanger, not the insulation… almost all of the mass of the fridge is in excellent working order when it's discarded. We mainly discard fridges either because the rubber door seals have changed shape, or because the compressor (the electric motor and pump that drives refrigerant around) doesn't work. And has the compressor fully degraded? Has the case of the compressor broken? The metal in the rotor and stator? The copper windings? Apparently the most common cause of failure in a compressor is that the bearings wear out, and in turn this occurs because the lubricant has escaped.

So the real reason why we're discarding and shredding so many fridges is that we are short of a few millilitres of lubricant in a couple of small bearings in the fridge compressor. Replacing the compressor is labour intensive, and generally the motors were designed as sealed units, so the bearings can't be replaced. But as we look for opportunities to reduce metal demand with a different business model based on life extension, it seems that we have found an opportunity here: it looks as if we could sell a fridge with a life-time guarantee, if we identified the likely causes of failure and designed into the original product a simple means to repair them.

The fridge is an assembly of components, and in our motivating discussion we've recognised that the components have different failure modes. So now we'll try to generalise what we saw in the fridge by proposing an 'onion-skin' model of products. At the core of many products is a structural framework, often provided by steel or aluminium, with a long expected life-span. Attached to this framework are layers of other components, and we'll organise them so that as we move from inner core to outer layer of the onion, the expected life-spans of the components decrease. If products are designed so that components in the outer skin of the onion, those with the shortest life-span can be replaced easily then we may be able to extend the life of the product and exploit more of the life-span of the inner components. To make more of this idea, we will simultaneously create an onion skin model showing cost shares. If more of the metal and more of the costs are at the core of the onion, we will find more motivation to extend the life of the product, by repairing or upgrading failed components in the outer layers.

We've applied our onion skin model of metal and cost shares to four different case study products in Figures 16.5–16.8, including two using both steel and aluminium. As usual, we've done this through detailed discussion with companies working in each area. The plate rolling mill is a great example of how the onion skin model explains motivation for life extension: about half the steel in a plate mill is in its structural frame and foundations, and this is a substantial part of the cost of a mill. So rolling mill frames tend to have long life spans, while other components are repaired or upgraded on failure. In contrast, although a large fraction of its steel is used in the structural core, the cost of steel in an office block is relatively small. So offices, which mainly fail in the 'unsuitable' mode, are often replaced rather than upgraded. Similarly for the car, the body and drive-train account for most metal use, but this is a smaller fraction of vehicle material costs, so there is little commercial motivation for life extension. However, no such inhibition is clear for the fridge where it seems that it is the cost of repair, rather than the value in the components, which motivates replacement over life extension.

Of our four case studies, life extension is normal for the plate mill, and one reason for this is that the value shares in the onion skin model are more closely aligned with the metal shares[7]. In contrast, the large fraction of metal at the core of the onion skin models of offices and cars is usually still functioning perfectly when they are discarded, but has a lower fraction of total value. Can we do anything about this?

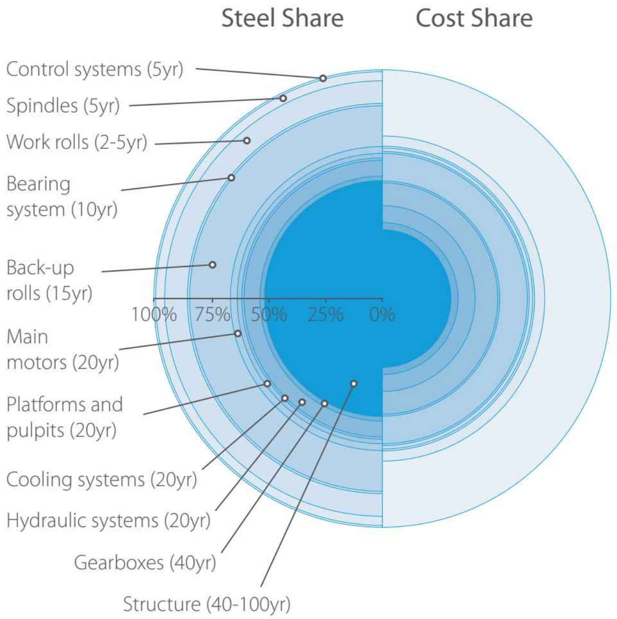


Figure 16.5—**Onion skin model for rolling mill**

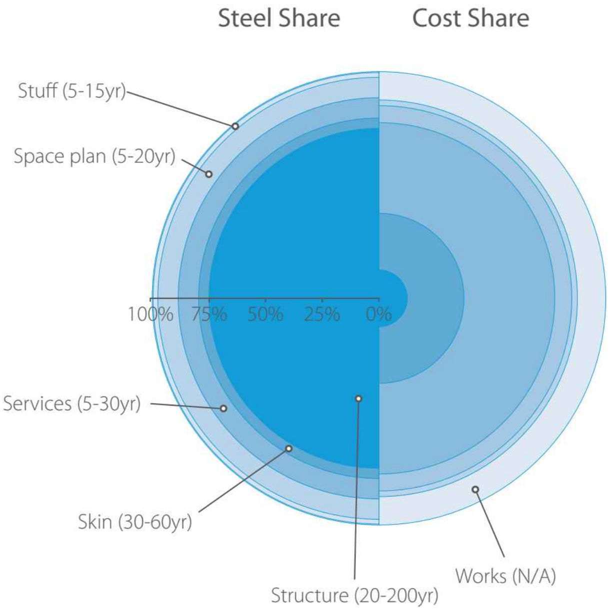


Figure 16.6—**Onion skin model for office building**

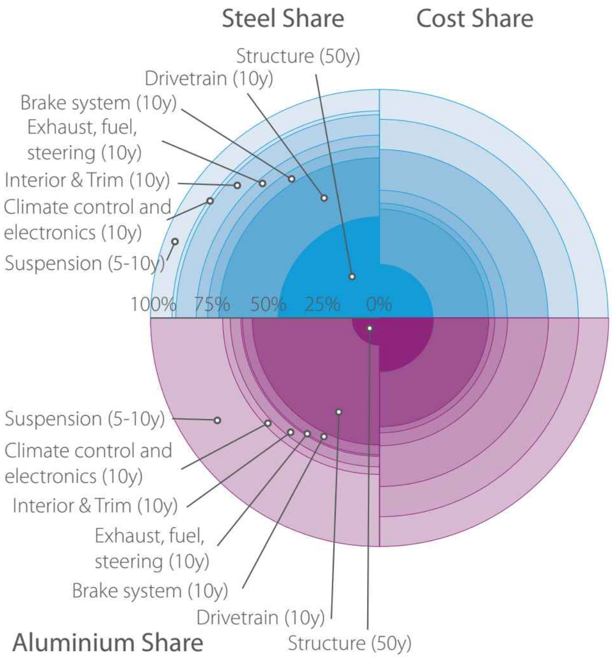


Figure 16.7—**Onion skin model for car**

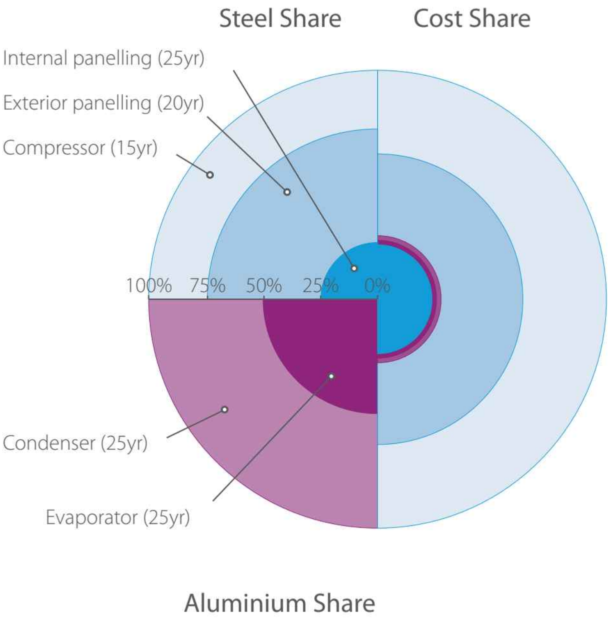


Figure 16.8—**Onion skin model for fridge**

Table 16.3—**Strategies for 'peeling the onion'**

	... relative to when it was purchased?	... relative to what's now available?
Has the product's performance declined ...	Durability when degraded	Upgrade when inferior
Has the product's value delcined ...	Cascade when unsuitable	Design for recycling when unwanted

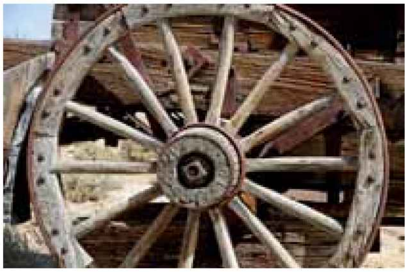
We've identified three key strategies which would help to bring down the cost of 'peeling' the onion, so that metal intensive components can be exploited for more of their functioning life. Our strategies are summarised in Table 16.3. Three solution strategies are relative to the original condition of the product: **durability** (incorporating maintenance and restoration) is about maintaining the original condition for longer; **upgrading** (including modular and adaptable design) aims to improve on the original design to compete with recent innovations; **cascading** aims to find new users for the product in its current condition which may be as good as originally designed, or partially degraded.

Edison's phonograph[15]

For **unwanted** failures—which are the hardest to deal with, we may be able to cascade or upgrade, but eventually life extension may not be viable and instead we should promote designs that enable efficient reuse or recycling of the components. We would have loved to collaborate with Thomas Edison on any of his endeavours, but had we been around in 1877 and used our contemporary engineering knowledge to work with him on a phonograph lasting for 500 years, sadly this would have had no value: it would have been better if instead we had designed it to be recycled easily.

Making components more durable

If components are degraded, we have three opportunities for intervention: design changes may delay the onset of failure; restoration may be possible to return components to their original specification; condition monitoring as part of maintenance in use may allow better prediction of when component replacement or restoration is required. All three of these practices are already in use, and could be applied more widely.



A wooden wagon wheel with a steel tyre for increased durability

Component degradation mainly occurs due to wear between sliding surfaces, crack growth due to cyclic loading, or corrosion. Blacksmiths and Wheelwrights understood the key principle of wear resistance, with strong iron horseshoes and tyres proving more wear resistant than horses feet or wooden wheels. The 'Archard equation'[8] predicts that wear will increase with load and sliding distance, and decrease with metal strength so modern rail track is made with high strength rail, and as our box story shows, this greatly extends the service life. Taking a lesson from the blacksmiths and wheelwrights, the Swedish innovation ReRail also mentioned in the box story is exploring the use of hardened but replaceable steel rail caps, to extend rail life further.

The well-painted Forth Road bridge

Corrosion may lead to failure of steel components, and a simple defence is to coat the steel: the alleged continuous re-painting of the Forth Bridge in Scotland is a well known example of this. A different problem with corrosion may occur in road bridges, if cracks in the concrete allow water to seep in so the steel reinforcing bars rust, and lose their bond to the concrete. This is a significant problem in the UK: several road bridges built in the 1960's had the wrong concrete mix, and reinforcement bars were placed too near to the surface, so water could reach the steel, cause rust and force early replacement. To avoid this problem we need better quality control in construction, or we could use stainless steel reinforcement bars which do not corrode, but cost four times as much. We've discussed wear and corrosion to show that we have good technical solutions to most cause of failure by degradation: if we correctly anticipate the loads a product must withstand, and the environment in which it will operate, we can generally find a durable design.

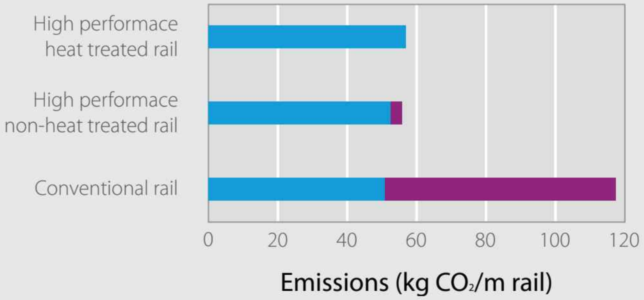
If degradation occurs, replacement may not be necessary if the component can be restored to its original condition. This is already familiar in tyre "retreading" where the worn rubber outer skin of the tyre is replaced, while the life of the highly specified steel wire in the tyre wall is extended. In this case, rubber is restored, but tram rails also wear away according to Archard's equation, and eventually will damage tram wheels, or impair safety. The cost of replacing tram rails is high, but if new metal is added to the rail in-situ in thin layers (by submerged arc welding) the temperature of the metal is carefully controlled and the right alloy is chosen, the rail can be restored with high strength. In fact, if the deposited steel has a high carbon content, the restored rail can have higher wear resistance than the original. More conventional restorations, for instance restoring coatings or other surface properties, are well established.

In safety critical applications such as flying, components may be replaced earlier than necessary, due to the terrible risks of component failure. This has led to a

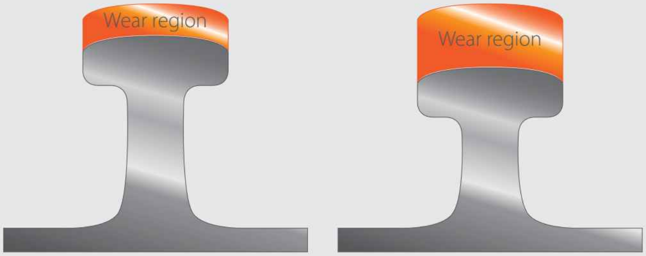
Durability and wear in rail track

Replacing and maintaining rail track is expensive, not just because of the cost of materials (which only account for about 7% of the cost of track renewal) and the logistics of transporting materials and equipment to and from the work site, but also because of the economic penalty of lost track time when the line is closed. Therefore, increasing the life of rail track and decreasing the frequency of maintenance are important economic and environmental strategies for the rail industry. Four strategies to prolong rail life are being considered by the industry:

- Using stronger rail with a higher wear resistance reduces the frequency of maintenance and extends rail life. The graph below contrasts the emissions from material production and lifetime maintenance for two types of premium rail (heat treated and non-heat treated) with conventional rail and shows that significant emissions savings can be achieved even in a single life cycle.



- Thickening the rail head (see schematic) extends rail life by increasing the amount of sacrificial material that can be worn away. Assuming the wear rate is identical for both conventional and thicker head rail, extending the rail life in this way would save metal by delaying the manufacture of a completely new rail.
- Capping rail combines the previous two options—a stronger metal is used but only for the wear surface. The Swedish ReRail system uses a wear-resistant boron steel push-fit cap. With this system only 15% of the rail is replaced, offering a total carbon saving of 92%.
- In environments where corrosion may reduce rail life, high purity zinc coated rail can be used. In one such environment, the rail life at a busy crossing was extended from 3–6 months to more than 16 months using this method.



(a) Conventional rail: wear region ~20% of weight

(b) Thicker head rail: wear region >20% of weight

Turbine blades in jet engines are monitored to detect cracks

world of technology development known as "condition monitoring" which aims to give health checks to metal components. In the same way that medical doctors use technology for early detection of health problems, metal condition monitoring technologies aim to identify potential causes of failure early and as they become more precise, will allow extended component life spans with reduced risk. Typical techniques include ultrasound scanning and use of x-ray to detect small cracks. for example in the wings and turbine blades of aeroplanes. Alternatively, a series of sensors that measure movements, strains and other influencing factors can be used to support diagnosis of concrete cracking in monitoring infrastructure.

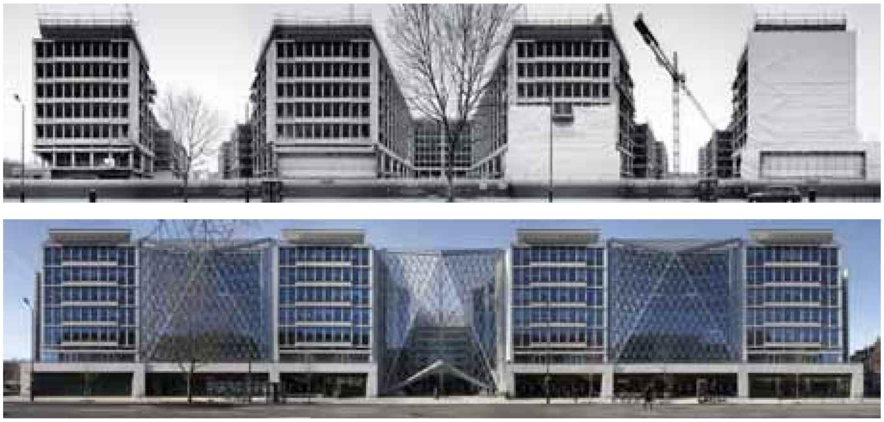
We have a wide range of options to design against degraded failures: although there will usually be a trade-off with cost, we can expect to design virtually all components to survive expected loads for indefinite time. If components fail, we have a growing range of techniques for restoring them to their original condition and we are developing diagnostic tools, to test the future health of components in service.

Upgrading products to extend the useful life of their embedded materials

When products fail because they are inferior, they can still perform their original design functions, but other products are now more attractive. We no longer make Penny Farthing bicycles for this reason. If an innovation has led to a complete change in a product design, there is little hope that we can extend the life of its predecessor. However, such radical innovations are rare. Most design progress is 'incremental' with smaller changes to an overall design used to attract new customers without the full costs of redesign, and it is more likely that upgrade can keep pace with such incremental changes.

Our onion skin model gives us clear guidance on upgrade opportunities: if the inferior components are in the outer layers of the onion, but the inner layers have significant value, upgrading will be attractive. Design to facilitate future upgrade therefore depends on anticipating which components are likely to require upgrade, and ensuring that the components can be exchanged.

To demonstrate how the structural core of products can outlast the original designers intentions we'll look at two case studies. The original office block built in the 1950's at 55 Baker Street is concrete-framed but by the early 21st Century



An exciting building upgrade at 55 Baker Street[16]

it had become unsuitable, so was upgraded: the outer layers of the building, including the windows, cladding, internal trim, and heating and water services, were stripped out; stairs and lifts were reorganised centrally; floors were expanded to connect two adjacent wings; columns were removed; a new slender heating and cooling system was installed to increase ceiling heights. Around 70% of the original building structure was reused and the upgrade took a year less than would have been required for demolition and rebuild. In a different case study, Jonathan Aylen at the University of Manchester Business School, examined the life stories of seven strip rolling mills built in the 1950s, three of which still operate today. Since the 1950s steels have become stronger and the range of strip geometries expanded, but the volume of steel rolled each year has increased by 80%. Four changes supported this upgrade: the mills are used more intensively through better co-ordination in the factory; condition monitoring and regular maintenance have reduced interruptions to production; the quality of material arriving at the mill has improved fast roll changing; and better control systems have cut unproductive time.

In both case studies, upgrades allowed life extension and prevented failure by the unsuitable mode. However, in some cases products can't be upgraded. For example, air conditioning which was originally a luxury, is now an assumed feature of new cars. Air conditioning units are bulky, so it would be difficult to upgrade a car originally built without it, because there isn't space. Should we over-design products so we have more options to upgrade them later? To answer, we need to know which failure modes will cause end of life, what other innovations will occur, and what consumers will want in future? It's unlikely we'll ever have the answer, so we must be pragmatic, and the onion skin model helps us: we should arrange the product design so that components with shorter expected life-spans are easy to separate; if we can anticipate future performance requirements we should design the core of the product to achieve them; if not, better not to over-design, and instead plan for reconfiguration.

Modular design of photocopiers allows reconfiguration

Modularity facilitates reconfiguration, and is useful in addressing all four failure modes. A modular design comprises modules connected according to some well-defined architecture so that each module can be replaced independently, and the number of modules in the product changed. Dell became the dominant supplier of personal computers in the 1990s by defining a set of rules for connecting modules: an 'architecture'. Customers choose their own modules so module suppliers can innovate independently[9]. Xerox supply photocopiers in a modular way, because owners want the latest model but the core of the copier changes slowly. Up to 80% of a new Xerox copier may actually be modules that have already been used but which are still perfectly serviceable[10]. With a related business model, Foremans in the UK refurbish building modules so that around 80% of the steel in old modules is reused after failure of the parent building.

Upgrading products that have failed because they are inferior or unsuitable is therefore also technically feasible, and already applied in some current businesses, but not a universal solution because the core of the initial design may prevent required upgrades. However, modular designs with an architecture that allows sub-products to be combined, are an attractive way to create adaptable designs that can be upgraded in response to all four failure modes.

Cascading products between users with different requirements

Owners requiring lower specification may be able to take over products that are degraded for their current owner, or may be able to adapt what was originally a higher specification product. In chapter 15 we explored the opportunities to cascade rail: by moving spent rail to lower duty branch lines and by rotating rail sections to reduce metal loss due to wear. We can also 'cascade' buildings. Typically this will involve refitting the interior and services while retaining most of the structure, but unlike the upgrade to 55 Baker Street, cascading may also involve a change in use. We interviewed a selection of structural engineers about this form of cascading and found that the key features of a structure that determine its value in different applications are the locations of entrances, stairwells and lift-shafts, the spacing of columns, the permissible loading on each floor and the height between floors. Having reviewed typical ranges for these features for different

Converting to \ Converting from	Residential	Hotel	Retail	Office	Warehouse	Factory
Residential	🟧	🟩	🟧	🟧	🟩	🟩
Hotel	🟧	🟩	🟧	🟧	🟧	🟧
Retail	🟪	🟧	🟧	🟧	🟩	🟩
Office	🟧	🟧	🟧	🟩	🟧	🟧
Warehouse	🟪	🟪	🟧	🟪	🟩	🟩
Factory	🟪	🟪	🟧	🟪	🟩	🟩

🟩 Easy
🟧 Moderate
🟪 Hard

Figure 16.9—**Building adaptation matrix**

building types, we have drawn Figure 16.9 to indicate the relative difficulty of converting buildings between uses. For example, the wide, high spaces typical of factories and warehouses allows easy adaptation to other uses. However residential buildings, which typically have smaller, more enclosed designs, cannot easily be adapted to other uses requiring greater volumes of uninterrupted space. The leading diagonal is not always green because homes and shops are often highly customised.

Cascading products between applications or user groups with different performance requirements is applicable where fashion and rapid innovation are not important drivers of demand. Cascading is already applied, and could usefully be extended, in applications where the core of the onion skin contains most of the embodied energy.

The business case for life-extension

If product life extension is technically possible, why doesn't it happen more and what could be done to promote it? In this section we'll explore how business decisions on purchasing act for or against life extension. In preparation we've conducted a series of structured interviews with producers and users of industrial machinery and equipment to find out about their purchasing and selling decisions.

Life extension in the eyes of the purchaser

If you have the opportunity to upgrade your existing equipment or to replace it with a newer model, how are you going to present the options to your boss? It's likely that you'll comment on at least five aspects of the decision: (1) how the new machine will affect other costs such as maintenance; (2) how you've taken into account future benefits; (3) whether the existing machine has already been 'written off' or not in the accounts; (4) how you think your needs will change in future, and whether the new machine is likely to meet them; (5) how much you'll get for the new machine if your needs change and you decide to sell it.

- **Which costs are taken into account as part of the purchasing decision?** More durable and reliable products are usually sold for a higher price in the hope of lower maintenance costs and delayed disposal and replacement costs. Although whole-life-costing is taught in theory, in practice many decisions are taken without fully adding up costs over time. At an extreme, when cash for investments is short, decisions are made to minimise initial purchase costs.

Failure to take into account the full benefits of longer life products also occurs if managers allow only a short time for the cost of purchase to be paid back by the benefits of ownership. Payback periods can be as low as two years.

- **How are future benefits valued?** Figure 16.10 demonstrates how investors would examine the question "what share of future replacement costs would we take into account in our decisions today?" based on discount rates between 10 and 20% which were typical of the companies we talked to: at a discount rate of 10% only a third of the cost of replacement in 10 years is taken into account in decisions made today. Therefore, for longer-lived goods such as buildings, replacement costs don't even feature in decisions today so there will be no financial benefit in purchasing a longer lasting product.

- **Has the existing product already been 'written off'?** In company accounts the value of a purchase, say a piece of equipment, depreciates over time at some chosen rate. This depreciation is shown as a cost in the profit and loss accounts, and profitable long-lived equipment can be 'written-off' in the accounts, so it has a reported value of zero. Accountants think of this as an advantage because the cost of the equipment has been fully taken into account, managers may then be less motivated to maintain the value of what they own.

- **Will the product meet your needs in future?** The amount we're prepared to pay for more adaptable products depends on how sure we are that they'll be useful to us in future. If we want to promote longer-lasting equipment we must be confident that it is sufficiently flexible for our future needs.

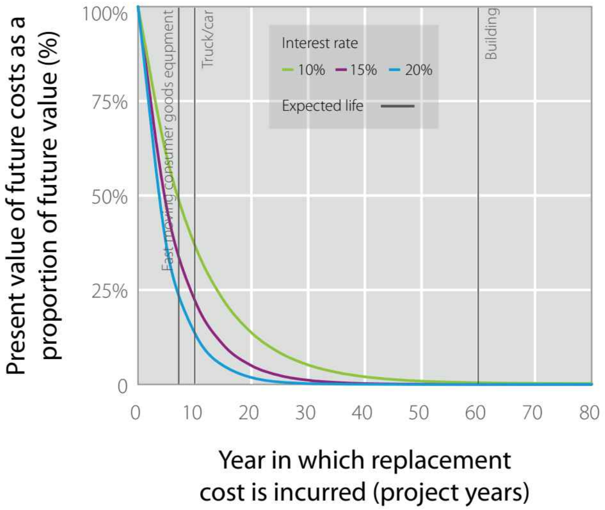
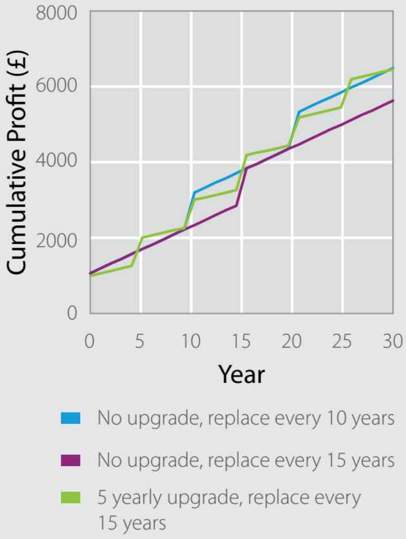


Figure 16.10—**The effect of discounting on future costs**

- **For how much will you be able to re-sell the product in future?** Concerns about low second-hand prices can limit what we might pay for longer lasting products. For example, 15% of the value of a new car is lost on purchase with another 10% lost by the end of the first year and a further 10% lost in each succeeding year. As purchasers of second-hand goods, we don't trust the owners to assure us of the condition of the product, because they have a vested interest in exaggerating quality. If that quality is not easily tested, resale prices tend to be low and in turn, this deters purchasers from buying longer lasting goods.

With our five questions we've seen that there are many reasons why purchasers might be biased against more expensive longer lasting goods. Longer lasting and more reliable goods are more valued in industries for whom interruptions are more expensive, for example train or track breakdowns cause great disruption, and electricity generators are fined if they fail to deliver as promised. So to boost business for suppliers of longer-lasting products, perhaps instead it would be better to sell upgrades? We've seen that upgrades are already sold for some products such as rolling mills. We've seen in our case studies that the benefits of upgrades include reduced replacement costs, faster replacement and continuity in operation. In particular, for products with slow rates of innovation, upgrades may be particularly attractive.



The business case for upgrade of vehicles

The graph shows cumulative profit margins for three replacement and upgrade strategies for cars. We assume that an upgrade costs 20% of a new vehicle and increases fuel efficiency in line with the energy efficiency technology available in the year of upgrade (using the same fuel efficiency assumptions as the box story at the beginning of this chapter). Regular upgrade halves annual maintenance costs and yields a 20% profit for the producer (this is in line with profit margins after-sales automotive services). The upgrade strategy is found to be as profitable as the 10 yearly replacement cycle and offers more regular cash flows. If profits are not as high as those in after-sales automotive services then the producer will lose out unless they can increase prices.

Having looked at the business case for purchasers, and seen that it might be easier to choose upgrades when products fail than to pay extra for longer lasting products at the outset, are sellers able to exploit this opportunity?

Life extension in the eyes of the seller

Now put yourself in the shoes of a producer. Would you choose to sell a more or less durable product? What if you could make money as your product cycles through different owners[11]?

- **Deliberate shortening of product life?** If you are serving a 'saturated' market, where most purchases are for replacement, you are more likely to want to shorten product life to generate more sales. But this means that you have to recoup any product research and design spending over a shorter period, which is easier in an industry with fast-changing technology development. How can you persuade your customers to keep buying a short-lived product? They're more likely to agree to this if the market is concentrated so you don't have too many competitors. So planned obsolescence, the deliberate shortening of product life, is more likely in saturated, concentrated markets with fast-changing technologies. In contrast, amongst our interviewees in the industrial equipment sector, which does not have these characteristics, we found that planned obsolescence would not succeed due to global competition, and the importance of building a reputation for quality.

- **Strategic, profitable product life extension?** Alternatively as a producer you can sell your product with a contract, such as a lease, a long-term maintenance contract or an upgrade contract, that gives you access to potentially lucrative downstream markets[12]. Such contracts also expose you to the costs of product failure and so increase your incentive to produce durable, adaptable and modular designs. The potential benefits of such contracts are far reaching, including more regular cash flows, better customer retention, greater differentiation from competitors, and, in some cases, higher profits. However this is a very different business model from the usual one in which producers focus solely on initial sales. It also moves away from the core capabilities of a traditional producers. Only if you change strategy to a service model can you profitably pursue product life extension, with these types of contract.

Outlook

We started this chapter celebrating the heritage objects that tell our national and personal stories, which we happily pay to maintain indefinitely, and throughout the chapter we've seen that we have plenty of options to maintain most of our steel and aluminium intensive goods for much longer. We can make them more durable, can upgrade them if their relative performance falls off, or we can cascade them between owners with different requirements. We've also seen that the environmental case for keeping goods for life depends on the ratio of embodied energy to annual energy in use, and on the likely rates of improvement in each. In looking at the business model for longer life goods, we've seen that it would be easier for purchasers to choose upgrades than to pay extra for longer-lasting initial purchases, and we've seen that producers will only promote longer-lasting offerings if they can replace sales related to replacement demand with income from servicing, maintaining, and upgrading existing stocks. As purchasers, we could choose now to treat everything we own as heritage objects to be maintained indefinitely, and in most cases this would be a more sustainable practice. That gives us the opportunity to dictate terms to producers—to encourage the development of new longer lasting goods, supported by different contracts. If we can purchase a standard new fridge for around £200, expecting it to last 10 years but guaranteed for only 3, we're unlikely to agree to pay £2,000 for a fridge with a 100 year guarantee, but we might agree to pay £40 per year indefinitely for a fridge that would always be maintained and upgraded to the latest standards. And if that's the case, we can offer the supplier double their income over a much longer period, compared with a single purchase with no commitment—and that might get them excited.

Notes

1. Approximately 1 million Certificates of Destruction and Notices of Destruction were issued under the UK End-of-Life Vehicles Regulations (2003) in 2006 but over 2 million cars were taken off the road in that year (Car Reg, n.d).

2. 'Well Dressed?' by Allwood et al. (2006) describes a government funded project that explored practical changes in the textiles and clothing industry that would improve the sector's performance on a range of sustainability metrics.

3. Kate Fletcher is a fashion designer who has developed the concept of slow fashion. Her book (Fletcher, 2008) explores the life-cycle impacts of fashion and textiles and presents practical alternatives, design concepts and social innovation. More information about Kate's work can be found on the website www.katefletcher.com.

4. Assume that in year *t* the embodied energy to make the product is $E(t)=\alpha^t E_0$ where α is the annual fractional improvement each year, which must be less than one, but only just. A 1% improvement each year would mean $\alpha=0.99$. Similarly the use phase energy per year for a product made in year *t* is $U(t)=\beta^t U_0$. Provided α and β are strictly less than 1, we can then sum to infinity the total energy Z required if we replace the product every T years, giving:

   $$Z = \frac{E_0}{1-\alpha^T} + \frac{TU_0}{1-\beta^T}$$

   The optimum life span T is the value at which the derivative of this with respect to T is zero, which is when:

   $$\left(\frac{E_0}{U_0}\right)\frac{\alpha^T \ln\alpha}{\left(1-\alpha^T\right)^2} + \frac{1-\beta^T + T\beta^T \ln\beta}{\left(1-\beta^T\right)^2} = 0$$

   For given values of (E_0/U_0), α and β, we can solve this and so plot T against (E_0/U_0).

5. We make the following assumptions: the office has embodied emissions of 3,200 kWh per m^2 and annual use 340 kWh it has a life of 40 years based on Ramesh (2010); the car has embodied emissions of 5.6 tCO$_2$ based on VW LCA reports (VW, 2006, 2010), annual use phase emissions of 2.6 tCO$_2$ and an expected life of 14 years; the train has embodied emissions of 17 tCO$_2$, annual use phase emissions of 3.7 tCO$_2$, and an expected life of 30 years (Chester & Hovath, 2009); the plane has embodied emissions of 52 tCO$_2$, annual use phase emissions of 100 tCO$_2$, and an expected life of 25 years; we assume use phase improvement rate of 2% and an embodied improvement rate of 0.1% for all products bar the plane for which the use phase improvement rate is assumed to be 0.1% and the embodied improvement rate 0.1%.

6. The matrix is based on the observation by Solomon 1994 that "replacement decisions arise from a deterioration in the actual value of the product or an upgrade in the desired state" and on the distinction between relative and absolute obsolescence made by Cooper 2004.

7. Aylen (2011) briefly discusses the possibility that mill stretch has been facilitated by initial over-design, e.g. the mill in Linz had a low initial rolling capacity but was contained in an excessively large building allowing the rolling line to increase within the building by just under 40%. In their paper on plate mill upgrade Bhooplapur et al. (2008) point to a second reason why mill upgrade has been possible. Micro-alloying is the favoured process for making modern high strength plate grades and in this process the greater strength of the steel is exhibited only in the late stages of rolling and cooling, limiting pressure on the mill stand and so allowing high strength steels to be rolled on mill stands that where built before these grades were envisaged.

8. The Archard equation states that the volume of worn material produced under sliding contact is proportional to the load on the surfaces times the sliding distance divided by the hardness of the softer of the two surfaces. John Archard, who after six years in the RAF subsequently moved on to working on the erosion of heavily loaded contacts and their lubrication, defined the most widely used prediction of metal wear under sliding contact.

9. Magretta (1998) interviews Michael Dell who stresses the importance of Dells "virtual integration" strategy in the company's success. This strategy is based on a customer focus, supplier partnerships, mass customisation and just in time delivery.

10. Kerr & Ryan (2001) explore the environmental benefits of the Xerox remanufacturing model and find that remanufacturing reduces resource consumption by a factor of 3.

11. We know that durable goods, such as cars, trucks, machinery and equipment often have multiple users over their lifetimes: yellow goods typically go through 3-6 ownership cycles before they are finally scrapped and Land Rover estimate that up to two-thirds of all Land Rover Defenders ever built are still on the road.

12. Moving downstream in this manner can be lucrative. Research by Dennis and Kambil (2003) has shown that, in the automotive sector, after sale service margins, including customer support, training, warranties, maintenance, repair, upgrades, product disposal and sale of complementary goods, are three to four times greater than new product sales margins.

Images

13. Image credit: Network Rail (sourced by Ramboll).

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16. Image credit: Zander Olsen, Make