Prolonging Our Metal Life

Making the most of our metal services

WellMet 2050

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WellMet 2050

WellMet2050 is a £1.4m 5–year 8–person research programme at the University of Cambridge, funded by the Engineering and Physical Science Research Council (EPSRC) of the UK government to look at all options to reduce global carbon dioxide emissions associated with steel and aluminium. The project is supported by a consortium, of over 20 global companies, with whom we are developing case studies, demonstrators and analysis to reveal the emissions benefit, business opportunities and technical challenges of a raft of emissions reduction strategies.

WellMet2050 is focused mainly on long-term strategies related to material efficiency, and is now exploring four themes:

- re-using metal without melting
- less metal, same service
- longer life and more intense use of metal assets
- compression of the metals manufacturing process chain

This report presents the findings from the third theme.

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Our story in one page

A third of the world's energy is used in industry, to make buildings, vehicles, equipment and products. Demand for these goods comprises both new demand in growing economies, and replacement demand in developed countries. If we're concerned about future global energy use—whether because of prices, availability, or due to climate change—would keeping goods for longer reduce our need for energy? This report examines this question for goods made with steel and aluminium, accounting for around 10% of global carbon emissions from energy and processes.

Is it always a good idea to keep goods for longer? If the goods not only require energy in production, but also in use—as happens with cars and offices for example—then might it be better to replace them sooner not later if efficiency in use is improving? We've examined this question and found, of course, that the answer depends both on the ratio of energy required in production to that in use, and the rate at which the requirement for energy in use is improving. If car fuel consumption reduces at 3.5% per year—which is the rate required to meet EU regulations for future vehicle efficiency, then for a current typical car, there is a small benefit to be had from extending vehicle life from 10 years to 15 years. However, if in addition we could upgrade the engine every 5 years, to take advantage of new fuel economies, the total saving would be greater than the energy required to make a new car. So, in exploring life-extension, we need to be aware of opportunities to upgrade the performance of goods, through more frequent replacement of key components.

There is then a potential benefit to keeping goods for longer, but as we know, for many goods we're doing just the opposite—and discarding them more frequently. Why's that? We find that products are discarded for four different reasons: because their performance diminishes over time ("degraded"); because other products out-perform them ("inferior"); because the demands of their user changes ("unsuitable"); and because of more systemic changes in preferences ("unwanted"). Using these categories, we've made an assessment of the reasons that users discard goods across the whole range of steel and aluminium products. Our evidence suggests that the majority of products are not broken when they are discarded, and therefore we must either use our products more intensively to fully realise the physical properties of the metals we make, or extend the lives of our products by replacing the obsolete functions with upgrades. This latter strategy also allows replacement of the broken functions when physical failure has occurred. We've examined four case studies in detail to explore this—a steel plate mill, an office block, a car and a fridge—and described each design using an "onionskin" model based on the life expectancy, metal share and cost share of different key components. We find that upgrade is more likely for products for which metal substructures make up a significant share of total costs.

In fact we have the technology to design almost any steel or aluminium product to stand the test of time: several museums have examples of steel swords more than 2,000 years old; the famous Iron Bridge at Ironbridge Gorge near Coalbrookdale, built by Abraham Darby III and opened in 1781, still stands and is now a UNESCO World Heritage Site; just over a decade later the Ditherington Flax Mill in the outskirts of Shrewsbury is thought to have been the first building to use iron for its columns and cross beams and still survives today; Oriel Chambers, an iron-framed office building in Liverpool designed by Peter Ellis in 1864, is still in daily use. So clearly the constraints to long life are not primarily about durability—we already have good solutions to most problems with corrosion or wear for instance, and modern condition monitoring and maintenance practices can make these cost effective. Instead, the challenge is to find ways to maintain the value of older goods through pursuit of technical strategies that realise the physical separation of the product functions (modular design), allow products to adapt to changing needs (adaptable design), and extend product life beyond first use (through restoration, upgrades and cascading reuse).

So given that we have the technology to use our metal products for longer, why don't we? When taking a closer look at commercial and industrial replacement decisions we find biases that act against consumers choosing more durable products. We also find that producers like replacement demand as it increases sales. Does this mean that nothing can be done? We think not. Greater durability may not be a desirable tack-on strategy to business as usual, but as part of a rethink in business strategy can become viable and even lucrative: modular designs may allow cheaper model changes, take-back may inhibit a competitive 'grey-market', regular servicing and upgrades may provide more predictable cash-flow than replacement sales as well as better customer lock-in. Government policy could support the appropriate development of life-extension opportunities through high quality information and certification, through a rebalancing of tax incentives towards extension rather than replacement, and through promotion of whole life costing.

Making the environmental case

The environmental case for product life extension is subtle—we get more service out of our products and so save embodied energy, but we have fewer opportunities to exploit advances that save use phase emissions. This section explores how we might increase the services we get from our products and explains how to evaluate the trade-offs associated with life extension.

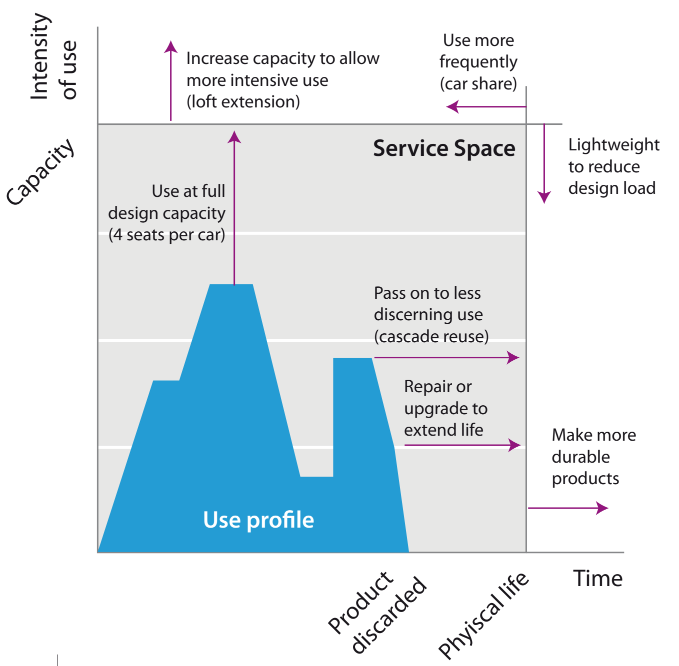
Let's just use our products more

A third of our global energy is used to make the buildings, vehicles, equipment and products we use. This energy is expended to make products that provide a service over a period of time. If we could get better at exploiting the services our products offer we could reduce these production emissions. The graph below shows, in grey, the total service that is offered by a product. The blue use profile shows that the product is underutilised—it is not used to capacity and is discarded before the end of its physical life.

What can be done to address this under utilisation? There are three options: the use profile can be extended by using the product at full design capacity or ensuring the product is only discarded when broken; the service space can be shrunk to more accurately reflect the product's use and to avoid over specification; finally, the service space could be extended by making longer lasting higher capacity products. Which option is best depends on the relationship between the use profile and the service space: increasing capacity or product life only makes sense if it results in an increase in use; using a product more intensively can shorten its physical life but still be beneficial if it increases overall service output. So what's the relationship between intensity of use and product life?

Using them more may shorten their life?

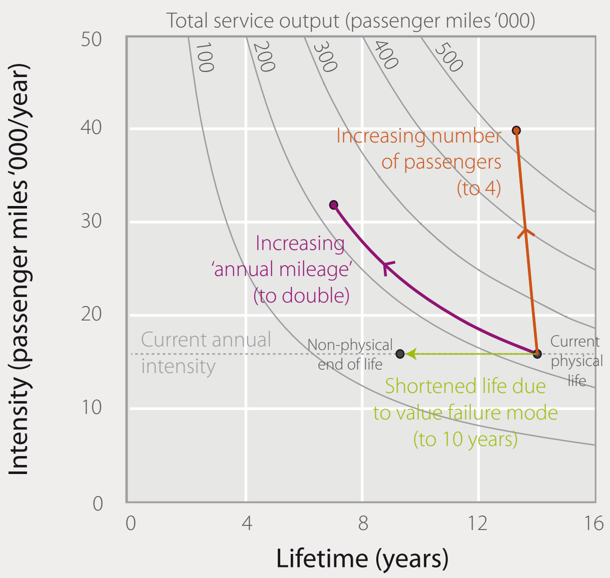
Perhaps what we win in greater intensity of use we lose in shorter life? Firstly there are different ways that we can increase intensity (we have to distinguish between using products more frequently and using them to capacity) and secondly because different products are more or less sensitive to use (depending, for example, on whether they have wear dependent moving parts). We explore this in the box story below and see that it is possible to increase the service we get from our products through greater intensity of use. This is particularly the case for products such as buildings where there is little trade-off between product life and how often we use them. For wear-constrained products, such as cars, we find that product life is more sensitive to changes in frequency of use than to changes in load. As a result increasing load (for example by increasing the number of passengers in a vehicle) increases the service we get. Increasing frequency of use has a neutral impact on physical life, but can still be beneficial if it prevents products being discarded for non-physical reasons.



Using vehicles more intensively

We can see that increasing average passenger loading from 1.6 to 4 (the orange line) makes little difference to the physical life of the car (because the car weighs more than the passengers) but more than doubles service output. Doubling the annual mileage (the pink line) halves the physical life of the car but does not change the service output. This reduces the chance that a car is discarded before the end of its physical life e.g. because it is outdated. Finally reducing the average life of a vehicle from 14 years to 10 years with no change in utilisation (e.g. due to an accident or as promoted, for example, by the expired UK scrappage scheme) decreases total service output by 30% (the green line).

Similarly, increased loading on trucks, trains, ships and washing machines causes a disproportionately small loss in product life, though the ratio will vary widely by product type. Offices are currently used less than a quarter of the time and could be used more frequently with no effect on building life.



What about use phase emissions?

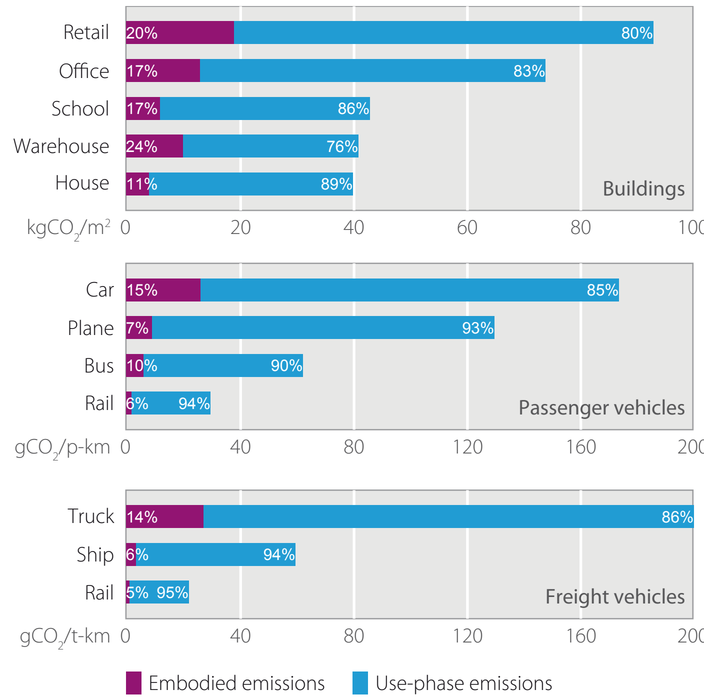
So far we've only explored part of the story. Product life extension saves emissions embodied in production but it also means that we have fewer opportunities to exploit advances that save use phase emissions. The trade off between use phase and embodied emissions is similar to that faced by Formula 1 racing teams: a car may be losing 2 seconds each lap due to worn tyres, but changing to new tyres will take 20 seconds, so it is only worth pitting for a tyre change if there are more than 10 laps left in the race.

In order to take into account use phase emissions we need to look at a string of successive purchases and make assumptions about improvements in the best available technology. For each string of purchases we can plot cumulative emissions (that's the embodied emissions from making the product including repairs and upgrades, and the sum of the annual use phase emissions) over time. We can then compare different product life and upgrade strategies as we've done for the case in the car in the box story below. A key variable that determines the saving of emissions is the relative size of use phase and embodied emissions.

Is product life extension becoming more important?

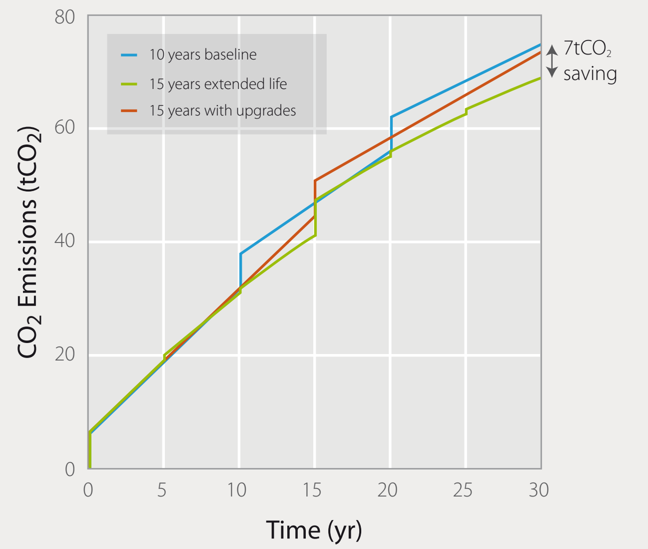
We expect product life extension to become more important over time as the embodied energy share of key metal intensive products is increasing over time. What is causing this trend?

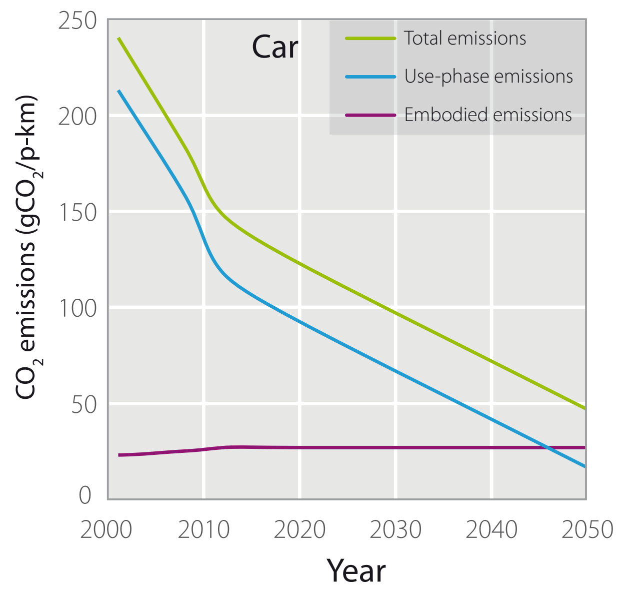
Well, use phase emissions currently dominate (see bar chart below) for buildings (76–89% per square metre), passenger vehicles (85–94% per passenger-kilometre) and freight vehicles (86–95% per tonne-kilometre) and so have been targeted by environmental legislation. For example the EU's tailpipe emissions targets demand that average fleet emissions are reduced from 160gCO_2/km in 2008, to 120gCO_2/km in 2012 and 95gCO_2/km by 2020, with a further reduction required to reach the UK's 80% reduction target by 2050 (see graph car on following page), and the Part L building regulations and the UK's Zero Carbon targets for new buildings aim to reduce use phase emissions to net-zero by 2019. Meanwhile embodied emissions are predicted to remain constant. This doesn't mean that there's a lack of innovation in this area.



Upgrade as a strategy for vehicle life extension?

In the graph shown, the base-case (blue) is a typical mid-size car (125gCO_2/km tailpipe emissions) with a design life of 200,000km over 10 years. At years 0, 10 and 20, new cars are purchased creating 6.3 tCO_2 of embodied carbon emissions per car (no technology improvement rate is applied to E). The use-phase emissions are assumed to improve by 3.5% every year (in line with the car-maker's targets and EU regulation) giving 128 gCO_2/km for the first period, and 90 gCO_2/km and 64 gCO_2/km for the following two periods. Total emissions of the 30 year period come to 75 tCO_2. The life-extension strategy (orange) extends the product life to 15 years, with only two news cars. This saves only 1.5tCO_2 (2%) of emissions, much less than the 6.3tCO_2 embodied emissions saved, because the strategy delays upgrading to the latest engine technology. The upgrade strategy (green), each car is again held for 15 years but is upgraded every 5 years with a new engine at a cost of 15% of embodied emissions in a new car (0.9tCO_2). This takes advantage of the improved engine technology to reduce use-phase emissions with a minimal penalty in embodied emissions (additional changes to the vehicle may be required to achieve these use phase changes but are not taken into account here). The strategy results in a 7tCO_2 (9%) emissions saving, which is more than a new car, and could offer an acceptable life extension model for car manufactures. This is relatively small compared to the cumulative emissions over the period. Greater savings will be achieved for products for which embodied energy is more important.





In fact, constructors and manufacturers will need to work hard to hold embodied emissions at current rates, as many use-phase improvements require more complicated solutions with energy intensive materials, for example: using aluminium in cars provides use-phase benefits from light-weighting but increases embodied emissions considerably; efficient buildings require extra insulation, triple glazed windows and mechanical ventilation systems, which also increase the embodied emissions.

Together, the anticipated reduction in use phase emissions and steady embodied emissions mean that the share of embodied emissions increases (see graph above). See *Making the Environmental Case*[WP1] for more details. This increase in embodied energy share strengthens the case for product life extension.

How do we attribute emissions?

How do we attribute emissions to product life extension and increased intensity of use? Increasing the intensity of use reduces demand for products as the same product provides additional services that would otherwise have to be met by new or replacement demand. The ongoing additional service offered by a series of more intensively used products usually outweighs the effect of shorter product life, reducing overall demand. Life extension only reduces replacement demand. If we reduce replacement demand, we don't have to melt metal saving the associated emissions (approximately 0.5tCO_2/t for steel and 0.3tCO_2/t for aluminium). The benefit of extending product life then is equal to the emissions associated with secondary production of the metal within the product, multiplied by the reduction in metal demand.

This section has shown that blindly increasing product life or product capacity with no understanding of use profiles is ill advised. We need to understand why products fail and the extent to which they are used (the next two sections) in order to target actions that extend product life.

Trade-offs with product weight

How much over-specification would we be willing to tolerate in order to increase product life? Well, the extra metal for the over-specification calls on primary production, but life extension saves secondary production by reducing the amount of remelting required. We can say that for over specification to be environmentally justified, the ratio of the proportionate increase in life to the proportionate increase in mass must be greater than the ratio of primary to secondary emissions— approximately 3 for steel, 20 for aluminium. That is to say it is worth over specifying a new building up to a third of its mass in order to double its life. These numbers assume a scrap constrained supply and are applicable for only one life cycle. See *Life Expectancy Trade-Offs with Product Weight*[W2] for more details.

Design life vs. physical life

Structures are built to a 'design life' but this does not necessarily mean they are physically degraded or unfit for purpose after this time has elapsed. Eurocode 0 defines the design life for buildings as the period for which the structure can be "used for its intended purpose with anticipated maintenance without major repair being necessary". Buildings are built to withstand the worst-case scenarios (e.g. wind loads, concrete degradation and seismic activity) expected within this time frame. If a likely event does not happen, the building will stand beyond its design life. Equally extreme unforeseen events can bring about physical failure, e.g. outbreak of war, terrorist attacks.

Types of failure

Overtime the performance of most products declines: productivity may fall, operating and maintenance costs rise, aesthetics degrade and safety is compromised. But this isn't true for all products; sometimes products fail due to a change in the value placed on them by their users. Businesses will value products differently depending on their appetite for risk, access to credit, liquidity preference, customer base, strategy and the search effort they put into evaluating alternative products. The table below distinguishes between four different types of product failure. The first row relates to changes in performance and the second to changes in value. The columns refer to absolute obsolescence (failure that is due to the current product or user) and relative obsolescence (failure that is due to the performance of other products and the values of other users).

	Absolute	Relative
Performance	**Degraded**	**Inferior**
Value	**Unsuitable**	**Unwanted**

Performance – Absolute

Degraded

This type of failure is to do with the performance of the product itself. A product fails in the "degraded" category because its functional or aesthetic performance diminishes over time, because it is spent, or because it fails accidently. Examples of products that fall into this category include work rolls, rail, cans, and cars that have been written off in accidents. Solutions, centre around increasing the design life of products through technical strategies such as superior material choice, modular design and improved maintenance, and through policy measures that deter planned obsolescence and encourage preferences for more durable initial purchases by consumers.

Performance – Relative

Inferior

Choosing to keep a product for longer means not choosing to buy the best available replacement. This means that products can fail due to their performance relative to other alternatives. They may still be functioning but are discarded because they are "inferior". This type of failure is caused by improvements in the performance of substitutes, and also by input and product market developments that alter the landscape in which the product competes Examples of products that fail in the 'inferior' category include industrial control systems and consumer appliances. Dealing with this type of failure requires greater adaptability, as put forward by the "onionskin" approach outlined later in this report.

Value – Absolute

Unsuitable

Products are there to meet the needs of their users and these too might change making the product "unsuitable". Just because the needs of the current consumer are no longer met does not mean that the product has to be discarded. One response to absolute value obsolescence, exploits the different needs of different consumers through cascading reuse. Examples of metal intensive products that may fail in the 'unsuitable' category include filling and packaging machinery for fast moving consumer goods, tooling for past car designs and the demands placed on aluminium electric cables. Products fail in the "unsuitable" category if they no longer meet their current users' needs and no effort is made to resell them.

Value – Relative

Unwanted

Consumers are different, but they do not behave indepen-dently and this herd-like behaviour can cause product failure that is more systemic than the 'unsuitable' category. In this case the product is said to be "unwanted". This category includes changing trends (less important for metal intensive goods than, e.g. fashion items), any negative connotations associated with use and reuse and legislation that applies globally. An example of metal intensive goods that fail because they are "unwanted" would be the accelerated phase out of single hulled oil tankers in line with legislation. Addressing 'unwanted' failures is difficult: more adaptable products could serve other uses; advertising and awareness raising efforts could address any negative connotations associated with reuse; any legislation that prohibits use could be managed in a way that allows conversion.

Steel and aluminium product life

To understand how to use our steel and aluminium products to capacity and for longer, we must first determine what the significant steel and aluminium end use products are, and then examine their use and failure modes. The chart below gives our estimate of the volumes of new products being made annually, with the colours indicating causes of failure.

Creating the chart

The chart presents a breakdown of metal intensive end use steel and aluminium products produced in 2008. The most metal intense end use products were identified through a combination of top-down and bottom-up analyses from a range of data sources. The most significant top-down data sources are the "World Steel Association 2008 Sustainability report of the World Steel Industry", "EUROFER" and "International Aluminium Institute Material Flow Data for 2008". Bottom-up calculations were derived from data received from relevant companies, predominantly within the WellMet2050 consortium. Studies on volumes of semi-finished products were used to further calibrate the end use tonnages.

To establish failure modes, we have compiled a catalogue of representative product descriptions containing pertinent use and end of life information at a component level. The product descriptions have been verified in industry, and are being used in structured interviews with relevant experts. The causes of disposal are determined from the product descriptions and interviews, and abstracted to the reasons for end of life presented in the end of life framework. It is difficult to discriminate between the various failure modes to attribute a specific failure to a product, therefore the chart is an estimate, but can be used to make general statements about the scale of product failure modes. 'Unsuitable' and 'Unwanted' types of failure have been combined to form 'Unsuitable/unwanted obsolescence' as discrimination is too subjective for many products. Product-specific details on failure modes can be found in the working paper *Steel and aluminium product life*[WP3].

The end-use of steel is dominated by construction (56%), whereas a more even distribution is found across the 4 sectors for aluminium. The average life expectancy for a steel product is 34 years, and for aluminium is 21 years, predominantly due to the use of steel in longer lasting construction and the use of aluminium in short-lived one-way packaging.

The table below shows the relative importance of each failure mode to the metals. 'Unsuitable' and 'unwanted' reasons for end of life dominate steel product obsolescence, accounting for 54% of products by steel mass. The largest contributors to this value are buildings and their components. The structural integrity of a building is typically unchanged throughout life. However, if the building cannot be adapted economically to suit a new use, it must be replaced and its constituent components (e.g. structural sections), disposed of despite the fact that they have neither deteriorated nor been technically superseded. This is also found for aluminium used in buildings, with product end of life often due to building rather than component failure.

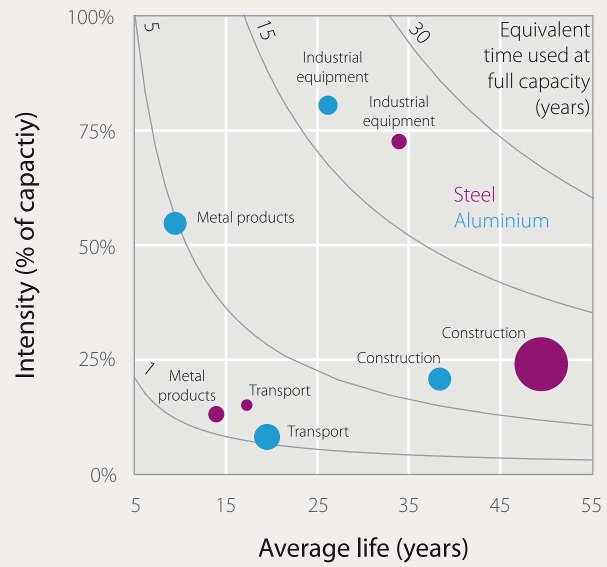
	'Degraded'	'Inferior'	'Unsuitable' or 'unwanted'
Steel	32%	14%	54%
Aluminium	61%	3%	36%

The majority (61%) of aluminium products fail because they are 'degraded', often because they are designed for single use or due to parent product failure. For example, aluminium beverage cans are designed to be 'spent' after first use.

Clearly, we are not fully exploiting the physical properties of our metal products; we discard functional products because of a change in need and discard 'degraded' products that still contain functional components. In order to address changing needs, we have seen on page 2 that we can use products more intensively, shortening their physical life and ensuring that 'degraded' becomes the predominant failure mode. We can also explore life extension at the component level, but in order to do this, we need to know more about the sub-assemblies that make up our products, as explored in the next section.

Do our products live life to the full?

On average, a steel product can expect to last for 34 years before being scrapped, and an aluminium product 21 years, but how much service do they provide in that time? The chart below shows how intensively we are using our products, with contours showing the equivalent time the products spend being used at full capacity. The radius of the data points is proportional to the annual end use breakdown.



Industrial equipment stands out as providing the highest equivalent years of service for both steel and aluminium. Products in this sector are typically used intensively, and only discarded when the physical condition is deteriorated through use. For example, electric transmission cables are in near-constant use throughout a circa 30 year life, and only discarded when they become 'unsuitable': the higher power demands over time causing greater transmission losses and physical weakness of a given cable.

The diverse set of metal products considered provide a short service. Appliances such as washing machines we use infrequently and one-way beverage packaging, although used to full capacity, has a life expectancy of only 6 weeks from production to recycling.

See *Steel and Aluminium Product Life*[WP3] for more details.

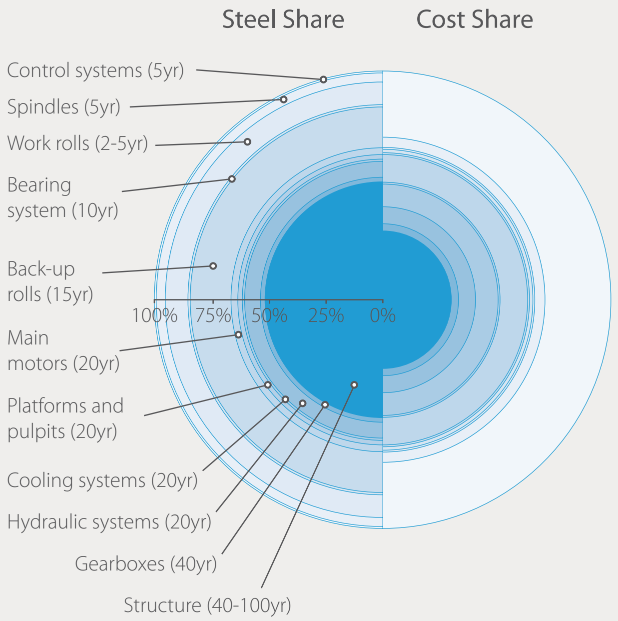
Examining product end-of-life by function

The different components and sub-assemblies of a product fail at different rates and for different reasons. For example: structural components (e.g. I-beams and mill stands) tend to be long lived; moving parts and those subjected to wear are not; and, those which serve an aesthetic purpose (typically casings for small products and surfaces for large products) inevitably degrade over time. Failed parts can be repaired or replaced, but in many cases, a subset of components still function when the product is ultimately discarded. Why are functioning metal intensive components being discarded due to parent product failure?

Imagine that a product is made out of different layers with longer lasting, structural sub-assemblies at the core and those that are shorter lived, e.g. aesthetic components, in the outer layers. By looking at the metal share and the cost share of each of these layers we can understand how much metal and cost could be saved by reusing the core to it's full life. The onionskin approach, used here, is a way of describing the composition of a product and a way of understanding the likelihood of significant metal saving through component reuse: metal savings through component re-use are technically feasible for products with easily distinguishable layers and large core metal shares (on the left hand side of the onion); component re-use is more likely for those that also have a significant core cost share (on the right hand side).In this section we look at four metal intensive products: a rolling mill, an office block, a car and a fridge. We have drawn an onionskin for each based on data collected with the support of our industrial partners.

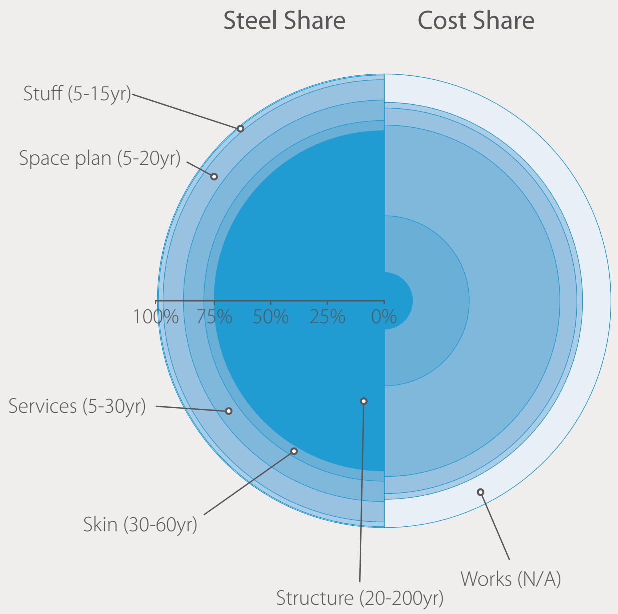
Rolling mill

Over half of the total steel in a 4,700t plate mill lies in the structural housing and foundations. The next largest contributors are the rolls that are much smaller in size but are replaced more regularly. Some of the most short-lived components—work rolls, spindles and back up rolls—fail due to wear. The control systems and the main motors are typically replaced to improve mill performance in line with technological developments. Bearing systems, gearboxes, hydraulic systems and cooling systems have an accumulated duty and fail in line with their scheduled life—based on a statistical decision relating to their likelihood of failure. Sub-components (e.g. e.g. nozzles within hydraulic systems and gear teeth) are replaced more regularly. The steel cost share of the structural components (housing and foundations) is only 11%, however once the civil engineering in the foundations is included, the housing and foundations account for 30% of the total costs. This high cost share helps to explain why rolling mills have been successfully upgraded to increase productivity, roll higher grade steel and meet and more stringent quality standards[WP4:14].



Office block

A 400t office block steel frame accounts for ¾ of the steel in the building but only for 10–15% of building costs. Structural components typically undergo very little degradation over a building's life. A building façade may suffer from corrosion or failure of the seals allowing water in, or it may be replaced before this if it discolours or a higher quality skin is required. Services fail because seals or moving parts are worn or because rival technology becomes preferable. The space plan and building content are typically adaptable and change with needs. Modern buildings tend to fail because they become 'unsuitable'—typically triggered by a change in use or a change in desired density. Because the different layers of the building are relatively easily separable and because the vast majority of the metal is in the long-lived structural components, buildings are a good candidate for upgrade or re-use of structural parts. However, this is tempered by the low cost share of these components that means that there is a relatively small gain from component life extension that has to be weighed up against reduced flexibility.

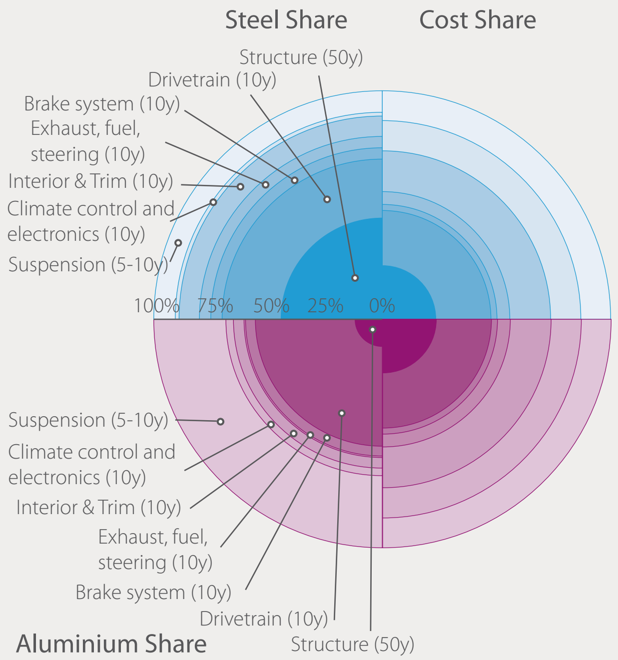


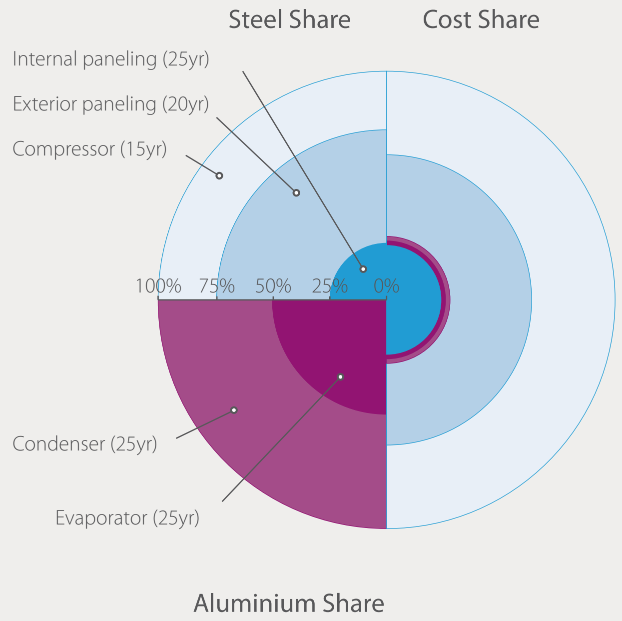
Car

With good maintenance, engines will last approximately 150,000-300,000 miles or about 10 years. The likelihood of premature engine failure increases when maintenance is neglected, for example if the cam belt fails whilst driving the engine will seize and have to be replaced. Modern well-maintained structural components (the car body and chassis) can be expected to last in excess of 50 years but usually vehicles are discarded before this point due to high maintenance costs. Components within the suspension system (e.g. shocks and struts) are typically replaced over the life of the vehicle. There is a strong second hand market for vehicles meaning that the vast majority of vehicles are ultimately discarded because they are degraded beyond economical repair. Legislation restricts reuse of structural components from cars that have been damaged in accidents by prohibiting "cut and shut" techniques on safety grounds. Non-structural panels can be reused. Upgrade strategies that prolong the life of the core metal structure by allowing engine upgrades could be explored.

Fridge

Most of the steel in a fridge is in the exterior panelling; the aluminium is shared equally between the condenser and the evaporator. Refrigeration tube alloys are highly susceptible to corrosion and fridges typically fail because corrosion either reduces heat transfer (forcing the compressor to work harder and burn out) or causes refrigerant leakage. Once the compressor has failed, the whole product is scrapped as one despite the fact that all parts, other than the compressor, are typically still functioning and account for 75% of the cost share. The likely reasoning here is that replacing the compressor would only increase product life by 5 years. In order to increase the likelihood of component life extension in fridges, the failure of both the compressor and of the exterior panelling has to be addressed.





This section has demonstrated that the cost and metal share of product sub-assemblies are disproportionate, with the metal in the long-lived structural components not always a significant share of the cost faced by the customer. For this reason there is relatively little value to compensate for the possible inconvenience of life-extension, and as a result some components are still functioning when the product is discarded. Just because the cost savings are relatively small doesn't mean that they can't be profitably exploited. Can technical strategies help bring down the cost of 'peeling' the onion and so prevent functioning components failing due to parent product failure?

Strategies to maximize product service

The service we get from our products is maximized by extending product life or, in some cases, by increasing intensity of use. This section looks at technical strategies to achieve these goals. The strategies are grouped by stage of life running from design, to use, to post first use. In each case we discuss which failure mode the strategy addresses and give examples of where the strategy is applied. More information on the case study examples can be found in the working paper *Maximizing product services – technical case studies*[WP4]. Together the case studies show that we have the technical capabilities and the wherewithal to produce long lasting products that can adapt to changing needs. Not only that but that we have a choice over which strategy to apply.

The choice between strategies depends on the degree of uncertainty over the cost and functionality of future rival products (that risk the incumbent product failing because it is 'inferior') and over changes in user requirements (that risk the product becoming 'unsuitable'). The schematic (below right) shows which strategy applies where. It also shows how the availability of information changes across the product life stages. At the design stage there is perfect information about the original product specification but little is known about future needs (especially for long lived products), at the post first use stage needs are evident but information on providence and specification is typically sparse.

Design

Durability: Increasing durability guards against 'degraded' failures by delaying physical decline. Durability is improved by appropriate material and coating selection in design and by eliminating flaws in manufacture. More durable products require less maintenance and repair at the expense of higher upfront costs. Durability is only appropriate for products for which few changes in requirements are expected.

Examples: corrosion of rebar in motorway bridges can be reduced through better quality workmanship[WP4:1]; high strength steels have been developed to reduce wear of rails[WP4:2]; composite materials, used in the Boeing 787 Dreamliner, allow complicated sections to be made as single pieces, eliminating the need for fasteners and extending the life of the aircraft[WP4:3].

Adaptability: Adaptability guards against products becoming 'unsuitable' or 'inferior'. Greater adaptability is achieved by over-specifying capacity and through design with future upgrade in mind. Co-benefits include quicker delivery-times, as adaptable products are more customizable through fabrication. Adaptability is only justified if the greater flexibility it offers is later exploited.

Examples: a building at Canary Wharf has been designed with 15% more piles in order to accommodate three different superstructure arrangements[WP4:4]; building floor systems can be similarly over-specified to double the loading or double the spans[WP4:5]. In these examples the extra cost of adaptability was small relative to total project costs and justified relative to prohibitively high retrofit costs.

Modularity: By subdividing a product and allowing its constituent parts to be removed, replaced or upgraded independently, modular design guards against all four types of failure. Modular design prevents the failure of one component from causing failure of the product as a whole. Modules can be fabricated and assembled in parallel, saving time, but must adhere to a standard architecture and interface.

Examples: Foreman's Relocatable Building Systems is a UK company that refurbishes and resells modular buildings, retaining 80% of their steel content[WP4:6]; sleeves have been developed to extend the life of work rolls in steel mills that currently are replaced every two years[WP4:7].

Use

Maintenance: Regular maintenance and care taken in use makes products last for longer. For some products such as aircraft[WP4:8] and transport infrastructure[WP4:9] condition monitoring (that involves routine collection and analysis of data on product performance) is used to identify problems early in an effort to allow more efficient, targeted maintenance to save time and cost and reduce disruption.

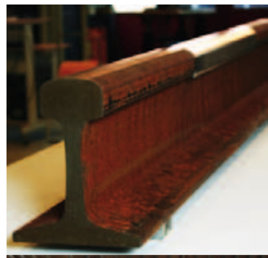
Increased intensity: As discussed on page 2, using products to capacity makes the most of the energy that is embodied in products; using them more frequently can shorten product life whilst delivering the same product service. The latter is preferable if there is a chance that the product will fail for reasons other than being 'degraded'. For example if the product is likely to be discarded due to changing trends or changing needs then a shorter, more intense product life is preferable.

Importance of information

A recurring theme across all strategies is the need to have accurate documentation so that new users can have confidence in the quality of the product: modular buildings are greatly reduced in value without BAA Certificate of Approval; the Baker Street refurbishment was greatly aided by original calculations and drawings; when installing 'flexible' foundations Canary Wharf commissioned an additional 'Close-out' report from the engineers to document the exact specification of the foundations and to collate the many construction documents. Having product information readily available saves testing and certification costs and so increases the likelihood that product life is extended.

(Photo credit: Zander Olsen, Make)

Post first use



Restoration: Degraded products can be restored to their original condition. Restoration can save replacement and disposal costs. However, restored products can be perceived as inferior, especially if the restored aesthetics are not 'as new'.

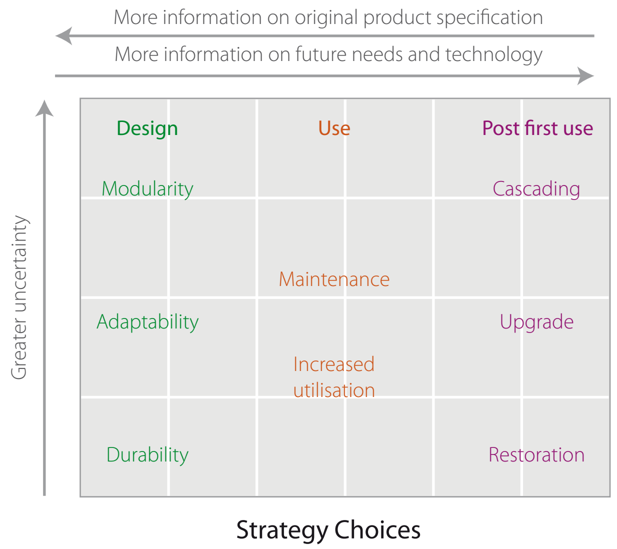
Examples: Tyres can be re-treaded twice to more than double their life[WP4:10]; a new arc rail welding process has been developed to restore worn tram rails with minimal disruption by depositing steel onto the worn surface in situ[WP4:11]; supermarket fittings are regularly replaced but could instead be rejuvenated[WP4:12].

Upgrade: It may be possible to upgrade 'inferior', 'unsuitable' or 'unwanted' products. Upgrade offers a cheaper alternative to product replacement and becomes more viable if the product has been designed to be modular or adaptable. Information on the original design aids upgrade but drastic changes in needs limit the scope of product upgrade.

Examples: a refurbishment at 55 Baker Street involved gutting the entire building, extending the floor area, and remodeling the circulation, stability and servicing systems[WP4:13]; steel mills have been successfully upgraded close to doubling productivity compared to design capacity[WP4:14]; city centre building foundations[WP:15] can be reused provided that there is enough information to allow a party to take on the liability that they are suitable.

Cascading: Because all consumers have different needs, 'degraded' or 'unsuitable' products may be passed on to a new user. This happens where restoration and upgrade are not viable. Cascaded products are cheaper but by definition of lower quality. Products that are most suited to cascading typically have many different users.

Examples: worn rails are cascaded from mainline to branch tracks after being tested for integrity[WP4:16]. Building frames can be cascaded between end-uses as shown in the matrix below[WP4:17].



The business case for longer life products

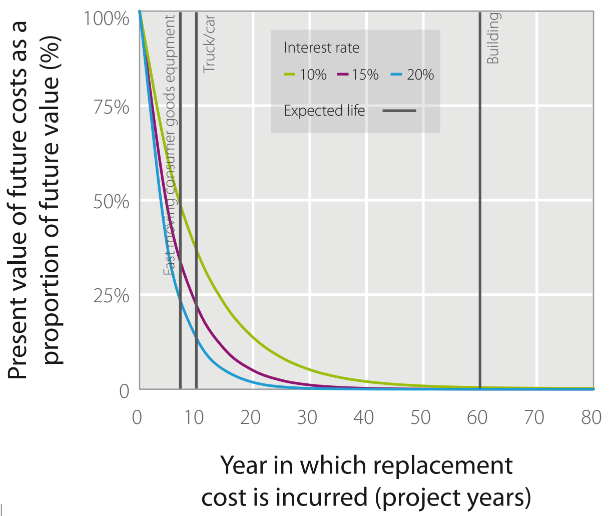
We have seen that product life extension is technically possible, so why doesn't it happen more and what could be done to promote it? We treasure heritage objects; can we extend this sentiment to a wider range of goods, not out of nostalgia, but because these goods meet our needs cost effectively? Most uses of steel and aluminium are governed by business-to-business decisions as opposed to business-to-consumer decisions, so this section explores how the different commercial purchasing and replacement decision-making rules act for or against greater durability. This section is informed by a series of structured interviews with producers and users of industrial machinery and equipment.

The consumer choice

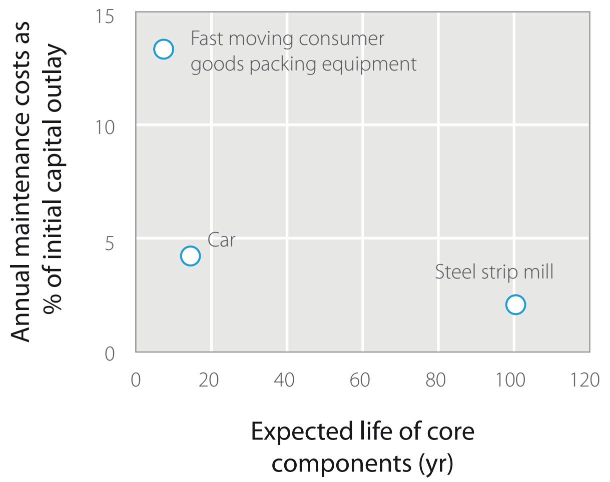
There are many aspects of commercial decision making that deter purchase of durable products:

The types of costs taken into account: More durable and reliable products usually incur a higher upfront cost in return for lower maintenance costs and delayed disposal and replacement costs. In order to allow fair comparison all costs must be taken into account. Although the principle of whole-life-costing is generally understood, in practice, features such as residual value, disposal costs, replacement costs and expected future variable cost trajectories are often not taken into account in replacement decisions.

The effect of discounting: The chosen discount rate (found to be 10–20% for companies interviewed) reflects the cost of capital and the expected risk of a project, with more risky projects demanding higher expected cash flows that can withstand higher discount rates. The graph below shows the effect of the discount rate on the current value of future expenditure. At 10%, if an asset is to be replaced in 10 years time only 37% of its replacement costs counts towards its present value; at 15% this proportion is 22%. This means that, for long lived assets, even if future replacement costs were to be properly taken into account in decision-making, their value would be small due to the eroding effects of the discount rate; the longer an asset's life, the less we care about the benefits of greater durability.



Fixed vs. variable costs: The benefit of long-lived assets is that high upfront costs can be smoothed over a longer life, however neo-classical economics teaches that past costs that cannot be recouped should be considered sunk and not feature in decision-making. In line with this theory one replacement decision rule demands that the average cost of a replacement asset should be compared to the marginal cost of an existing asset (including operating costs, maintenance costs, opportunity cost and salvage value). By not taking into account average capital costs of the incumbent asset, this method does not account for the benefits of durability. Where both capital and maintenance costs are taken into account in decision-making, the relative size of the two is expected to influence asset life, with more capital-intensive assets lasting longer. This relationship is explored in the chart below, which appears to show that more capital intensive assets do indeed last for longer.



Uncertainty and the value of flexibility: The pricing of more adaptable products crucially depends on the confidence that future requirements will lie within the scope of the more expensive, more durable, adaptable asset. For example dedicated packers and fillers used in the fast moving consumer goods sector have to be replaced in line with product cycles—typically every 7 years. More flexible robotic packers and fillers are available but 2 to 3 times more expensive. As they are not expected to serve in-house demand for more than 10 years (despite having an expected physical life of 20–30 years) robotic packers are not considered cost effective. The solution lies not only with bringing down the cost of the robotic packer, but with increasing the expected in-house life of the robotic packer through greater adaptability.

Time horizon: The failure to take into account the full range of costs and benefits of different durability options is in part a problem of time horizon. Binding capital budgets and liquidity constraints lead to capital rationing and a focus on short payback periods that can be as low as two years according to interviewees. This sort of myopic decision-making is suboptimal over a longer time horizon as shown top right for case of durable rail.

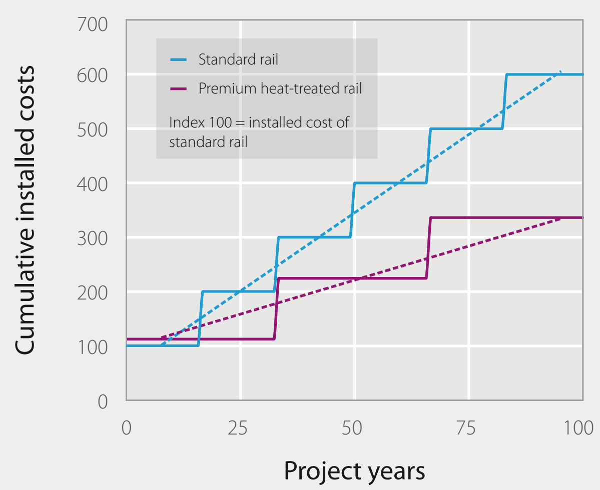
Expectation of residual value: Concerns about low residual value can limit what consumers are willing to pay for longer lasting products that they expect to resell. Data on resale prices shows that around 15% of the value of a vehicle is lost on purchase with another 10% lost by the end of the first year and a further 10% lost per annum thereafter. For structural components that show little degradation as little as 20% is lost over a life that exceeds 50 years with the lower price reflecting search costs and compromises in design. Owners are in a poor position to assure future purchasers of the condition of the product as they have a vested interest in exaggerating quality. Where quality is not easily verifiable, resale value is low and so buyers are deterred from buying durable assets.

There are many biases against the purchases of more expensive more durable assets and that the greater expense will often be hard to justify. A move away from shortsighted decision-making, to take into account whole-life-costs over a longer time horizon is important, but will only solve part of the problem; the punishing effects of discount rates mean that selling durability is inherently difficult. Of course there are exceptions. Durable, reliable assets are more sought after in industries that face high costs of downtime, services (e.g. rail) that cause great disruption when they are halted, and industries (e.g. utilities) that are fined for failure to deliver contracts. Privately owned companies, that are not bound to the stock market, are more likely to be able to take a longer-term view. Perhaps the solution is not to focus on selling durability to consumers, but instead to explore the options for selling upgrade.

Upgrade strategies are already successfully applied to some products such as rolling mills. The benefits of upgrade include a reduced logistics burden in sourcing material and potential life cycle cost savings. An upgrade strategy that manages consumer concerns (such as perceptions of inferior quality, concerns over a higher risk of failure and confidence that the upgradeable asset will be flexible enough to respond to changing needs), is likely to be interesting to consumers in markets where technology changes slowly. Are producers in a position to pursue such a policy?

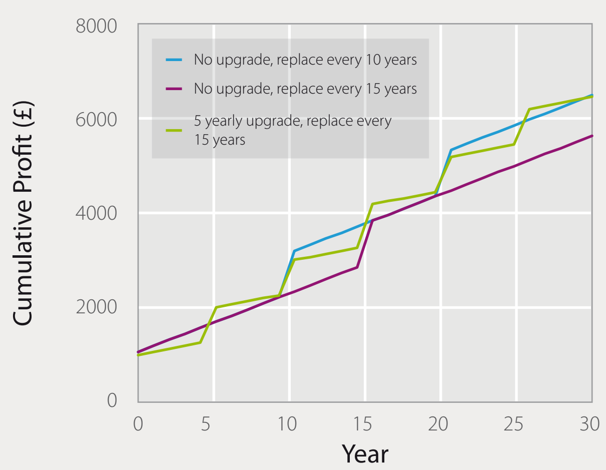
Durable rail

Premium heat-treated rail can be used to increase rail life, reducing disruption, downtime costs and saving on cumulative long term costs. The graph below plots cumulative installed cost taking into account the price premium charged on heat-treated rail. The life of the heat treated rail is assumed to be double that of the standard rail. Because the premium rail is 12% more expensive, it will not be chosen on the basis of lowest first cost even though the average annual costs are 40% lower. If the NPV of the two streams are compared, more time is required to justify the higher investment in premium rail, for a higher discount rate. With a discount rate of 10%, at least 17 years is needed to justify the change; with a discount rate of 13% the required time increases to 34 years; and, with a discount rate of 15% the change is not justified even after 170 years.



The business case for upgrade of vehicles

The graph below shows cumulative profit margins for three replacement and upgrade strategies for vehicles. 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 on page 3). Regular upgrade halves annual maintenance costs and yields a 20% profit margin for the producer (this profit assumption is in line with profit margins achieved by after-sales automotive services). The upgrade strategy is found to be as profitable as the 10 yearly replacement cycle and offers more regular cashflows. If profits on the scale of those secured by after-sales automotive services cannot be achieved then the producer loses out unless they can increase market share or increase the price of the upgrade service.



The producer's choice

Producers make decisions on how products are designed and under what sort of contracts they are offered to consumers.

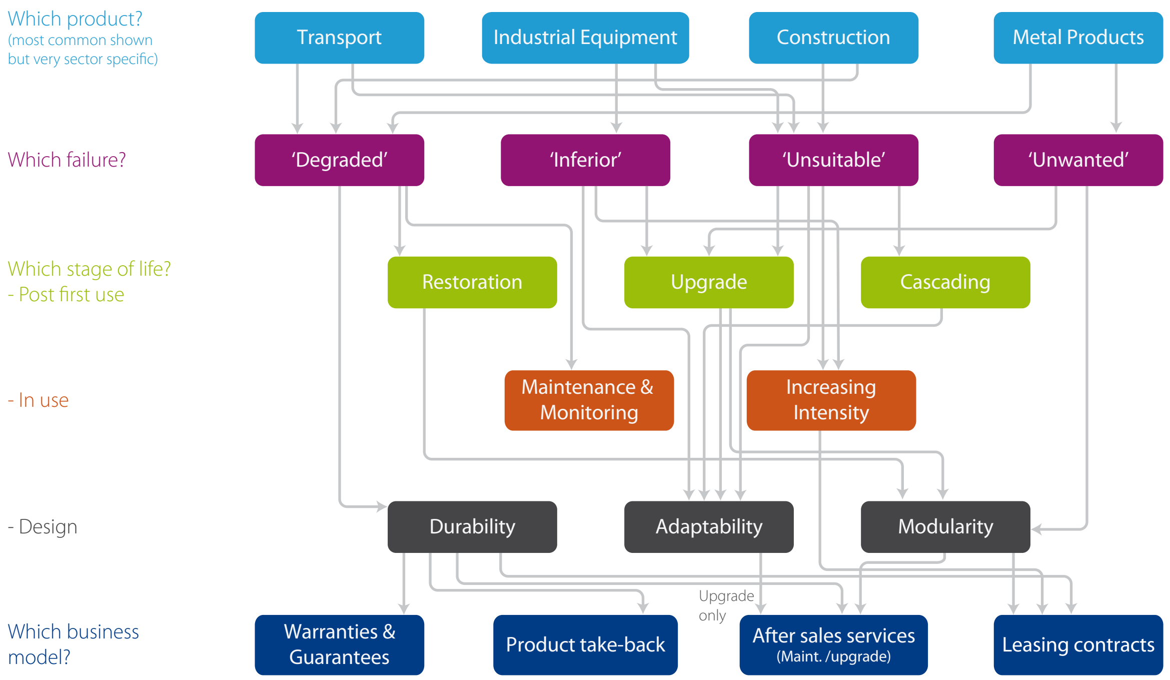
Deliberate shortening of product life? Increasing product durability, keeping everything else constant, is not in the producer's interest as it reduces sales. This is the root of fears over planned obsolescence (the concept that producers may deliberately curtail product life) and is also the reason for the policy paralysis surrounding product life extension. Planned obsolescence is theoretically more likely in saturated markets (where higher sales require higher replacement rates), in concentrated markets (where monopolists have an incentive to kill-off the second hand market) and in technologically dynamic industries (where increasing returns allow R&D investment to be recouped over a shorter period). In the industrial equipment sector, global competition, increasing demand from BRIC countries (accounting for 20–50% of sales of companies interviewed), and the fact that it is easy to entice replacement (rather than induce it) where technology changes quickly, all guard against planned failure. Planned obsolescence is not thought to be a problem in the sector, different products will have different durability but this is the result of a cost-quality trade-off not planned obsolescence. Competition means that deliberate obsolescence is likely to be punished with a poor reputation. Can manufacturers make money from offering longer lasting products?

Strategic, profitable product life extension? Producers can choose to offer contracts that expose them to costs and benefits further along the supply chain and so enhance their incentives for durable, adaptable and modular design. The table (top right) evaluates three different product design and contract combinations from both a consumer and a producer perspective. The potential benefits of upgrades are far reaching, including more regular cash flows, better customer retention and greater differentiation from competitors, and, in some cases, higher margins. The trade off is that the strategies represent a fundamental strategic shift away from the core capabilities of a traditional manufacturer and away from a focus on initial sales. Only if businesses are willing to embrace this strategic shift can they profitably pursue product life extension.

Producer motivations				Consumer motivations			
	Strategies			Strategies			
Motivation	Durable product with maintenance	Upgradeable product with service	Modular, leased product	Durable product with maintenance	Upgradeable product with service	Modular, leased product	Motivation
High replacement sales	● compromised	● compromised		● compromised	● compromised	● met	Lower initial capital outlay
High new market sales	● significantly affected	● significantly affected		● met	● met	● met	Lower replacement capital outlay
Unit production cost saving	● compromised	● compromised	● met	● compromised	● met		Lower use phase emissions & energy costs
Inventory cost saving through scale economics			● met	● met	● met		Greater reliability
Higher value added	● met	● significantly affected	● met	● significantly affected	● met	● met	Lower maintenance cost
More regular cash flow	● met	● met	● met	● compromised	● met		Higher productivity/better performance
Greater customer retention	● met	● met		● met	● met		Maintain and exploit residual value
Differentiation from competitors	● met	● met	● met	● met	● met	● met	Reduction of disposal costs
Elimination of grey remanufacturing market			● met		● compromised	● compromised	Avoidations of upgrade and leasing costs
Protection of confidential information & IP			● met	● compromised	● met	● met	Flexibility to adapt to changing needs
Operation within core capabilities of OEM	● met		● met	● met	● significantly affected		Productivity gains with product familiarisation
Reduced exposure to risk of product failure	● met		● compromised	● compromised	● compromised	● compromised	Better informed cost planning
Better understanding of customer need	● met	● met	● met	● met			More info to optimize use & manage workers
Core brand & reputation building	● significantly affected	● significantly affected	● significantly affected	● met	● met		Customisation & greater attachment
Compliance with legislation			● significantly affected	● compromised	● significantly affected		Superior aesthetics & knowing it's new

● = Motivation met ● = Motivation significantly affected ● = Motivation compromised

The figure below maps the technical strategies to failure modes and the appropriate business models in answer to the question, 'Which strategy applies where?'



Policy to support longer life products

There is little government policy aimed at encouraging longer life, more intensively used goods. Usually, where policies do act on the decisions discussed in this report, they are otherwise motivated and influence product life only indirectly. The focus has instead been on reducing environmental impacts in the factory, diverting product waste from landfill, and anti-competitive behaviour laws, that are mainly aimed at deterring monopoly pricing. Direct intervention on product life is rare because: (1) product life extension is not universally environmentally beneficial and so policies have to be targeted for specific products/eventualities; (2) product life extension may reduce GDP growth and reduce consumer choices; (3) there is no data on time series trends in product life on which to justify intervention. A relatively new strand of economics, behavioural economics, states that not every purchasing decision reveals true preferences—just because consumer purchasing contributes to the "throw away society" does not mean that this is what consumers want. It may be possible to "nudge" consumers towards purchasing longer lasting products. The table below suggests government policies that encourage: producers to design long life products and offer contracts that support this design choice; consumers to purchase durable products and use them to capacity; and both consumers and producers to make the most out of products post-use.

	Information	Incentives	Standards and requirements
Producer design and contracting	Agreed methodologies for measuring embodied emissions in preparation for extended reduction targets that take into account embodied emissions.	Durable design awards possibly as part of existing sustainable design certification schemes e.g. BREEAM for buildings. Higher VAT on disposable products, lower VAT on more durable products. Varying rates of VAT depending on the length of guarantee offered .	Government stipulated minimum durability and eco-design standards as authorized by the EU EcoDesign Directive. Emission reduction targets, such as the EU emissions targets for tailpipe emissions from vehicles, extended to take into account embodied energy. Government stipulated minimum product guarantees as authorized by the EU EcoDesign Directive. A revised UK Waste Strategy to include a waste prevention framework and provide incentives at the top of the waste hierarchy.
Consumer purchase and replacement	A rating and labelling system to provide information on expected product life or expected average life cycle cost of ownership. Consumer awareness raising initiatives that identify the need to reduce embodied energy as the next environmental challenge. Government demonstrators of cost savings due to decision-making that favours durable design.	Removal of incentives to replace products: capital allowances allow the bulk of capital expenditure on machinery and equipment to be deducted from tax upfront (as opposed to in line with the incomes generated) making replacement cheaper. Scrappage schemes, such as the recent UK offer of a £2,000 discount to new car purchasers that trade in cars over 10 years, that only allow purchase of low emitting vehicles.	Bans, where required (e.g. the UK Control of Asbestos Regulations and the IMO Marine Environment Protection Committee' mandated accelerated phase out of single hull oil tankers), that allow for conversion of existing assets where possible.
Consumer use	Consumer awareness raising initiatives that stress the emissions and cost savings associated with using products to capacity.	Improvements in public transport provision including incentives for employers and business park owners to provide shuttle services from stations. Lanes for multi-use vehicles e.g. the M606/M62 car sharing lanes that use cameras to check for multiple occupancy.	
Replacement & post use	Greater clarity from Government and from the insurance industry on the legislative requirements for reusing and upgrading products e.g. clarifying how structural steel can be recertified and reused in construction and to which safety standards an upgraded car must adhere. Demand that prices be displayed for after-sales services to avoid people being charged beyond the odds because they are under-informed on going rates.	Removal of disincentives to prolonging product life: VAT of 20% is currently charged on building refurbishment and at a reduced rate (5%) on conversions that create new single household dwellings, but new build is zero-rated, skewing decisions towards demolition and new build. Fiscal instruments that lower the cost of upgrade services e.g. planning regulations, business rates and national insurance contributions could be used to favour companies that offer after-sales services.	Extended producer responsibility legislation (e.g. the EU Waste Electrical and Electronic Equipment Directive and the EU End-of-life vehicles directive) that include targets for reuse, not just recycling Government stipulated minimum availability of spare parts and on design using standard parts as authorized by the EU EcoDesign Directive

Actions and opportunities

The table below summarises actions that could be taken by suppliers, designers and users of durable goods and by government to deal with each of the four types of obsolescence identified at the beginning of the report.

Absolute | **Relative**

Performance

Degraded

Suppliers should:

- look at warranties and leasing contract business models
- include information on durability at purchase e.g. labelling
- improve maintenance: guaranteed availability of spare parts; modular design to reduce maintenance costs; condition monitoring to understand performance and plan maintenance

Designers should practice durable design and pursue quality fabrication.

Clients/users should consider upgrade and restoration.

Government should:

- mandate minimum durability and eco-design standards
- implement innovative fiscal measures – e.g. varying VAT depending on length of guarantee

Industry bodies should instigate voluntary minimum durability and eco-design standards.

Inferior

Suppliers should offer product upgrades:

Designers should provide adaptability to cater for changing input and product market conditions and technological development of rival products. They should also pursue modular design to reduce the cost of upgrade.

Clients/users should employ whole life costing of replacement options over a long time horizon.

Developers of product rating systems and regulations should introduce incentives or requirements for appropriate adaptable features.

Government should:

- incentivize more intensive use to induce early physical failure
- coordinate with insurance industry to provide greater clarity on legal requirements for upgrade
- address tax distortions that favour replacement: capital allowances; VAT
- enact emissions standards that consider embodied energy
- avoid scrappage schemes

Industry bodies or government should provide data repositories to store sufficient product design information (e.g. building plans) to aid safe reuse in future.

Value

Unsuitable

Designers should:

- implement adaptable and upgradeable designs to cater for changing customer needs
- customise and design for emotional attachment

Clients/users should consider cascading reuse

Government should:

- coordinate with insurance industry to provide greater clarity on legal requirements for upgrade and cascading reuse
- introduce take-back legislation and fiscal instruments to reduce the cost of upgrade
- incentivize more intensive use to induce earlier physical failure

Unwanted

Suppliers should market longevity.

Designers should pursue iconic design and design against aesthetic degradation.

Where product bans are necessary, e.g. UK Control of Asbestos Regulations and the accelerated phase-out of single hull oil tankers, government should aim to minimize the metal loss by ensuring that targets for conversion and/or reuse of metal subcomponents are built into legislation that prohibits use.

The WellMet2050 team will raise awareness on embodied carbon, including recommendations on how embodied emissions should be included in analyses.

WellMet2050 working papers

The working papers contain more detailed analysis to support the findings of this report, and are available for download from www.wellmet2050.com

WP1 Cullen J (2011) *Making the Environmental Case*. WellMet2050

WP2 Cooper D (2011) *Life Expectancy Trade-Offs with Product Weight*. Wellmet2050

WP3 Cooper D (2011) *Steel and Aluminium Product Life*. WellMet 2050

WP4 Moynihan M (2011) *Maximizing product services – technical case studies*. WellMet2050

References with colons refer to a specific location within a working paper, e.g. [WP4:5] refers to section 5 in working paper 4.

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