Going on a metal diet

Using less liquid metal to deliver the same services
in order to save energy and carbon

WellMet 2050

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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 analyses 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 currently exploring four themes:

- reusing 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 research findings from the second theme.

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Going on a Metal Diet in one page

Producing steel and aluminium is energy intensive, and releases 10% of the world's CO_2 emissions related to energy and processes. Most of this energy is required at the early stages of the process—to create liquid metal from ore or recycled scrap, and 100 years of intense efforts by the industry have made this extremely efficient. However, having invested so much effort to make the liquid, it seems that we are rather extravagant in our use of it: around one quarter of all liquid metal never makes it through the supply chain into a product, but becomes scrap and is internally recycled with further high-energy melting; for most products we could use around a third less metal without seeing any loss of performance during product use. Making products lighter can also give co-benefits for instance through saving energy in use or by allowing lower weight design of other components in a system. We know that global demand for the services provided by these top two metals will continue to grow strongly, but it seems clear that our consumption of liquid metal is already unhealthy. If we want to make significant reductions in global carbon emissions we need to consider **Going on a Metal Diet**.

We've found two key strategies for reducing our intake of liquid metal: designing products that use less metal and improving the 'yield ratio' of metals manufacturing. We examined product design with five detailed case studies—universal beams in construction, food cans, car bodies, reinforcing bars and deep sea oil and gas pipeline. In each case, we found we could deliver the same final service with less metal, by pursuing one of four strategies: avoiding over-specification; selecting the best materials; optimising whole products; optimising individual components. We found plenty of examples to demonstrate this happening in practice, including the Velodrome for the London 2012 Olympic Games, planned innovation in car doors, and the great success story of weight reduction in drinks cans in the past 20 years. However, even though our study suggests that we could potentially reduce product weights by around a third, this hasn't occurred because of a range of constraints: the risk of under-design is often much greater than the cost of over-design so clients, designers and producers all tend to favour over-specification; even if metal requirements to deliver a final service can be reduced, there may be other drivers for increased use—such as robustness in handling, or stiffness required during assembly; manufacturing/installation costs tend to be reduced if parts are standardised and so over-specified; end-users see other benefits in over-design. Most of these constraints can be overcome, but today's practices reflect individual cost-optimisation by existing businesses operating along long supply-chains. The key to unlocking opportunities for saving weight in design is to foster collaborative examination of component and product designs along the whole supply chain.

We explored the opportunity for yield improvement by looking at four related case studies, and we've walked backwards up the supply chain—from the point at which the final user takes over each product, back to where liquid metal was produced—and added up the yield losses (scrap) and process energy involved. The results are astonishing. For bulk metal products—universal beams and castings, for instance—we lose only 10–20% of metal on this journey. But for some products made from sheet metal, the mass of liquid metal required is more than double the final weight of the product. This arises particularly from losses in blanking and trimming. In exploring how we could reduce this waste, we've found that there are plenty of technical options available—although also some clear requirements for developments in manufacturing processes—but we've also seen that most companies operating within component supply chains are unaware of the total mass being lost.

Our evidence suggests that for current uses of steel and aluminium, we could reduce metal production by up to a third, through better product design, and then by a further quarter through reducing losses in manufacturing—and if both steps were achieved this could halve our global requirement for liquid metal. The carbon emissions consequence of this would be equivalent to halving the number of cars used in the world. Yet this strategy hasn't yet had the profile of other, less significant abatement options. To understand the business case for making this change, we've examined the costs of material saving and predicted how much manufacturers would be willing to pay for materials savings: they would save on purchasing costs, could deliver user benefits particularly in transport, but might incur additional manufacturing costs. We found that, apart from aerospace, manufacturers are more responsive to material cost savings than to use phase savings. Further, it is generally the percentage of total costs rather than their absolute value that determines manufacturers' interest in lightweight design and yield improvement. We also examined the influence of existing UK government policies on material use, and as a result have made policy recommendations that focus on supply chain initiatives and raising awareness to create an appetite for change.

Going on a Metal Diet has much greater potential for CO_2 emissions abatement than the pursuit of further efficiency measures in an already efficient liquid metals production process. This report aims to raise awareness of that potential, to report case studies of success, to identify specific opportunities, and to propose means to overcome existing barriers.

Global flows of steel and aluminium

Before we can begin to count the metal or carbon emission savings from lighter products and more efficient manufacturing processes, we need to first visualise the flow of steel and aluminium through the production system.

Imagine the flow of steel and aluminium through society, starting with the metal ores and scrap as sources and ending with the end-use products purchased by consumers. But instead of grouping the metal flows by country, or company, or even economic sector, think of the technical process steps that transform the metals sources into final goods. Drawing global maps of this flow of metal allows us to understand where large amounts of steel and aluminium are being handled and therefore focus our efforts in the areas which will make a big difference.

In our two maps—steel flow (right) and aluminium flow (following page)—the flow of metal is traced from its source as ore or scrap (left), through the production system, to the end-use products purchased by consumers (right). Table 1 summarises the two maps showing that in 2008, globally we produced 1400 million tonnes (Mt) of liquid steel (including cast iron), and delivered 1040 Mt of end-use products to consumers. One quarter of the liquid steel is lost in the steel production system as scrap, most of which is returned to electric furnaces, for recycling. For aluminium, the tonnages are much lower, with 45 Mt of end-use products being produced from 76 Mt of liquid metal, resulting in overall scrap loss along the supply chain of 40%.

Process	Steel		Aluminium	
	Output (Mt)	Yield	Output (Mt)	Yield
Liquid metal	1400		76	
Forming	1280	91%	54	72%
Fabrication	1040	82%	45	82%
Overall		74%		59%

Table 1—Material yields for steel and aluminium production

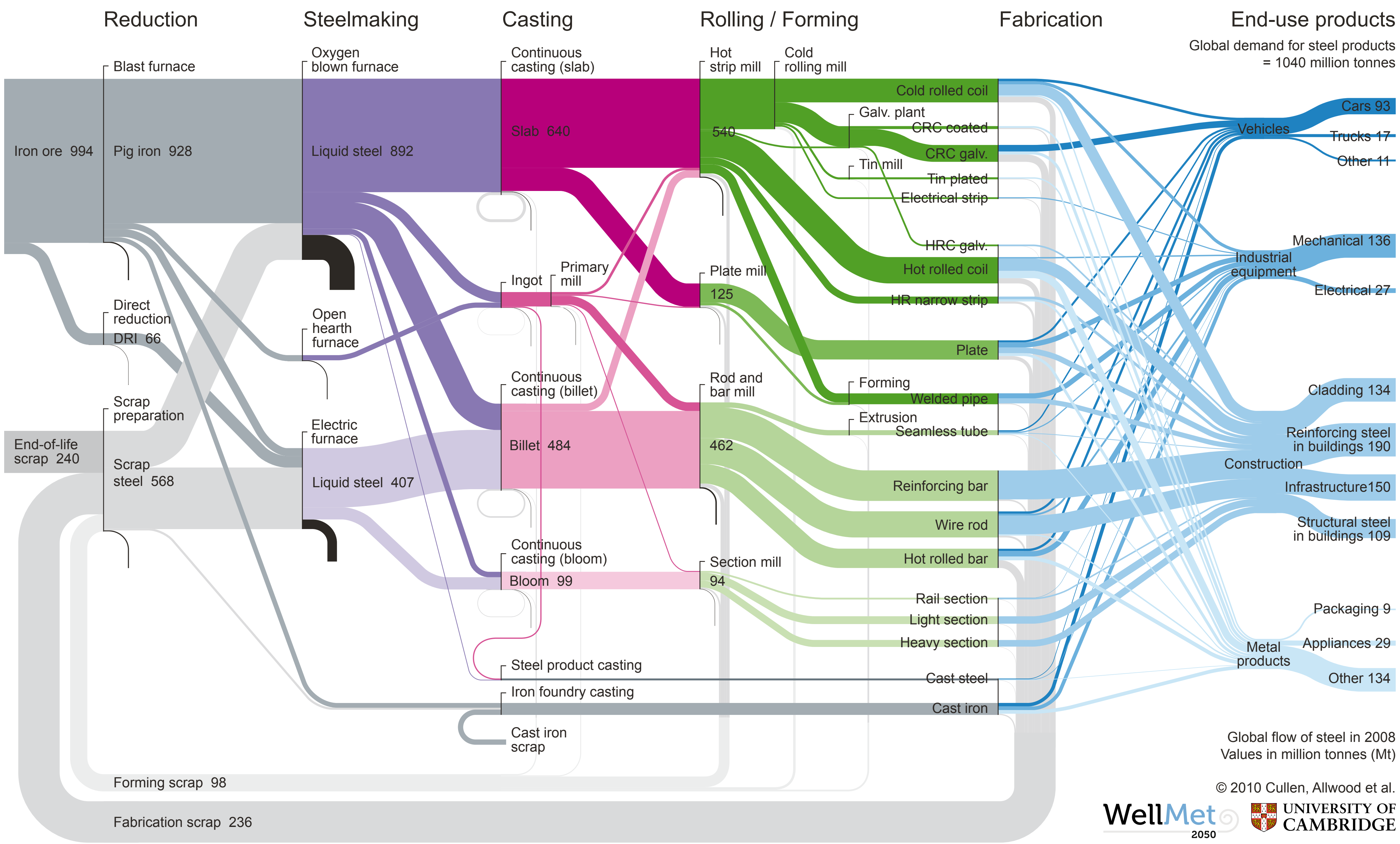
Observations from the metal maps

There is a vast difference in scale between the two maps of metal flow, with the steel production system producing 23 times more final goods than the aluminium system. In addition, a quick look at the maps shows that the flow of steel is more complex than the aluminium flow, especially in the forming steps.

For the **map of steel flow** (working from left to right):

- two-thirds of the liquid steel comes from iron ore and one-third comes from recovered scrap
- the production of slab and billets dominate cast steel (>80%). Most of the metal for slabs comes from iron ore, where as most of the billet metal comes from recycled scrap
- the original production route from ingot casting through a primary mill has mainly been displaced by continuous casting
- the forming of slab products (i.e. rolled coil) is complex and involves many process steps—each subsequent handling of the metal results in additional energy input and yield losses
- Rod and bar mills have the highest throughput of steel, producing reinforcing bar, wire rod and hot rolled bar; hot and cold rolled coil are also significant
- Demand for products is dominated by the construction of buildings and infrastructure (56%), with reinforcing steel in buildings making up the largest fraction; further work is required to understand the specific applications of steel in infrastructure, including a breakdown of structure types and reinforcement use
- Industrial equipment (16%), metal products (16%) and vehicles (12%) are the other three major end use groups

Global flow of steel



And from the **map of aluminium flow:**

- half of the liquid aluminium comes from bauxite ore and the other half from recycled scrap
- liquid aluminium from alumina is almost entirely used in the production of wrought products, which make up two-thirds of all cast aluminium; the remaining third is used to make cast aluminium products (in contrast to only 8% of liquid iron and steel used for cast products)
- Some larger products at end of life (e.g. curtain walls and window framing) are remelted for wrought products, however most scrap cannot be cleanly separated by alloy and is suitable only for refining, where silicon is added (up to 13% by mass) preventing any future recycling to wrought products—a form of down-cycling
- the yield in forming processes is lower for aluminium (72%) than steel (91%), due to the additional scrap made when scalping and trimming aluminium ingots and because of the higher quality surface finish required for aluminium products
- cold rolled sheet/strip, extrusions and die castings are the highest volume semi-finished products
- demand for end-use products is divided into 4 approximately equal groups: vehicles (27%), industrial equipment (21%), construction (24%) and metal products (28%)
- aluminium in buildings is divided into structural applications (e.g curtain walls, sidings, entrances) and non-structural applications (e.g. window frames, guttering)

Recovery of scrap metal

Table 2 shows the breakdown of metal sources used to make liquid steel and aluminium, allowing the differences in the liquid metal production routes to be analysed. The most striking observation is that more scrap is collected from the manufacture of products (forming and fabrication scrap) than from the discard of post-consumer products (end-of-life scrap), yet the potential for reducing industrial scrap is often overlooked in discussion of efficiency options in the metals industry.

Liquid metal sources	Steel Mt		Aluminium Mt	
Ore	900	64%	38	50%
Scrap	500	36%	38	50%
Forming scrap	90	15%	20	26%
Fabrication scrap	236	6%	11	14%
End-of-life scrap	240	15%	8	10%
Less melting losses	-66		-1	
Liquid Metal	1400	100%	76	100%

Table 2—Sources of liquid steel and liquid aluminium

Scrap from the casting processes is returned immediately to the caster for remelting. Scrap from forming processes is also rarely traded but instead remelted in the casting furnace. Records of such internal scrap flows are kept by each company but are typically not reported in national or international data sets on steel and aluminium production. Internal recycling loops are typically clean and well segregated and make little difference to the overall material yield of the process, provided the scrap metal is efficiently collected and handled. However, remelting of scrap metal, often several times over in the same casting process, increases the overall energy input. Our observation is that companies are often unaware of the energy savings possible from reducing internal recycling loops.

Fabrication scrap is normally traded on the open market, but in contrast to forming scarp, is often contaminated with cutting oils and not segregated by alloy. This suggests there is an opportunity for metal producers to deliver semi-finished products that are closer to the shape required for the end-use product, thus moving some of the scrap creation from fabrication to forming, where it can be controlled more carefully. Table 2 shows the fractions of scrap derived from forming and fabrication processes are lower for steel than for aluminium.

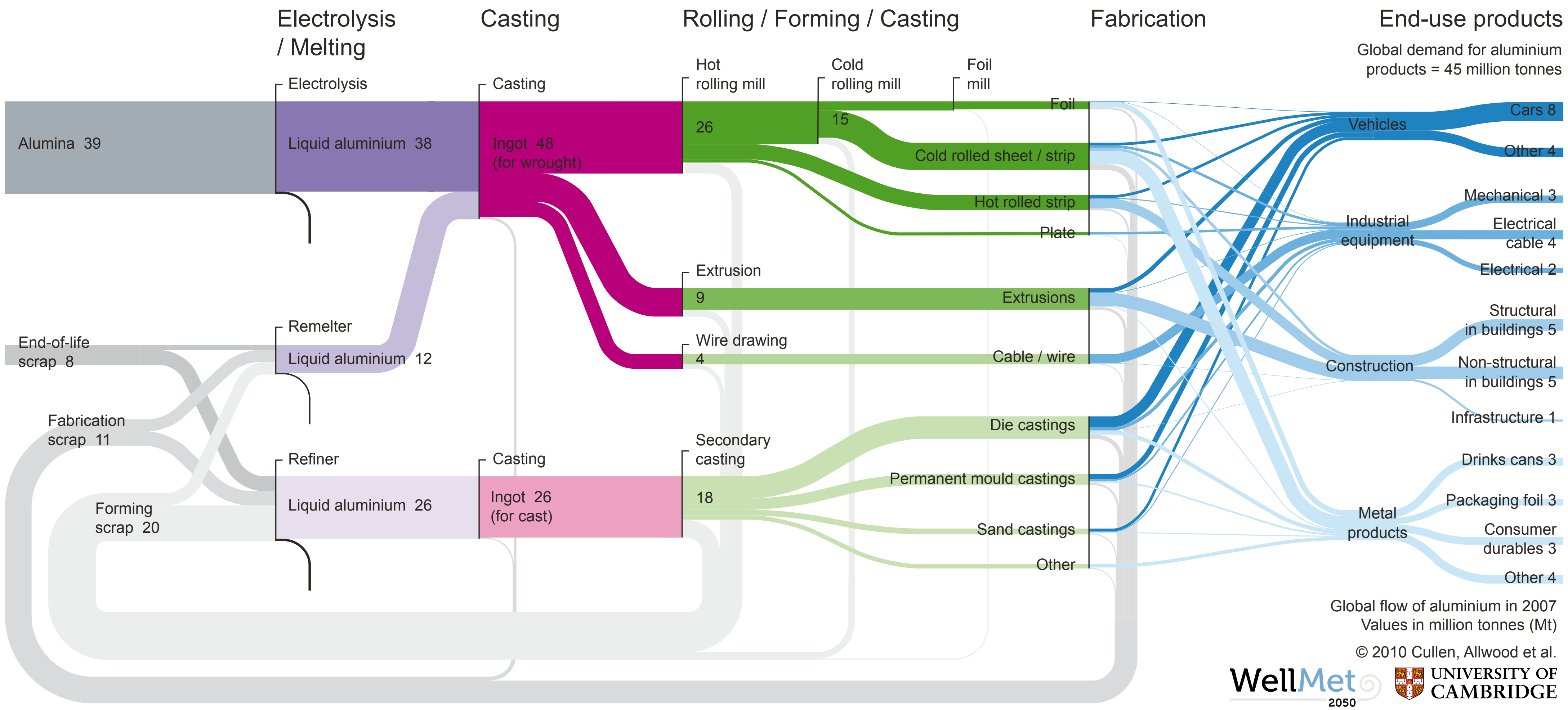
For end-of-life scrap this trend is reversed and now steel scrap makes up a larger fraction of the liquid metal input. This may result from the higher recovery rates for discarded steel products—steel products are typically larger than aluminium products and can be separated from other waste magnetically—however the amount of material recovered is also influenced by how quickly metal demand has grown in the past. Technologies to improve the recovery of aluminium from discarded goods, and in particular to separate out different metal alloys, need to be developed further.

The maps show annual flows of metal, and do not show stocks of metal in use. Scrap from forming and fabricating processes appears as loops in both diagrams, as these flows occur within a single year. However end-of-life scrap is introduced as an input to the left side of the diagrams, disconnected from the delivery of metal into use on the right side—because most metal goods last for more than one year. At present, global demand for both metals is growing rapidly, so end-of-life sources of metal are small compared to total demand. In future if global demand stabilises, the need for new primary metal will be greatly reduced.

Reducing demand for liquid metal

This report identifies two key strategies for reducing demand for liquid metal: designing products that contain less metal and reducing the scrap created in metals manufacture. If all products were re-designed to use less metal the whole map would contract, apart from the flow of end-of-life scrap entering on the left side. However, if manufacturing scrap were reduced, the total demand for liquid metal would be reduced, but this would have little impact on total primary metal production: reducing scrap leads to a reduced flow into recycling. Predicting the emissions abatement effect of these two strategies therefore depends on carefully predicting their influence on total metal flows.

Global flow of aluminium



Creating the maps of metal flow

The maps of global metal flow are presented as Sankey diagrams, a form first used by the Irish engineer Riall Sankey in 1898 to show the thermal efficiency of a steam engine. In our maps, the width of each line is proportional to the mass flow of metal. Values for the major flows are given in Mt (million tonnes). Steel flows less than 1 Mt and aluminium flows less than 0.05 Mt are not shown. Each major process step is shown by a vertical black line, with three possible outputs: useful metal (coloured), process scrap (grey) and metal losses (black). Useful metal continues to flow to the next process step, while scrap loops back to the appropriate melting stage where it is recycled. Internal recycling loops, for example from the continuous casting processes for steel, are shown as small oval loops. Most of the metal losses are due to formation of dross and scale in hot metal processes.

Several different data sources were used to create the diagrams. For the steel map, the World Steel Association publish production figures[1] and process yields[2] for reduction, steelmaking, casting, and rolling/forming. This was supplemented with data from: IPIA for the electric furnace inputs; Modern Casting for iron and steel casting; Steel Business Briefing for steel flow interactions; and EUROFER and the WellMet2050 consortium for end-use products. For the aluminium map, data is sourced primarily from the International Aluminium Institute material flow model[3] which provides an overview of the main process flows and estimates of forming and fabrication yields by end-use product. Scrap allocation to remelting and refining is scaled from European data from the EAA. The Aluminum Association provide a breakdown of end-use products which is supported by data from the WellMet2050 consortium.

The mapping of 'semi-finished products' (strip, plate, pipe, bar and sections) onto end-use products is particularly complex, with most end-use products requiring several different types of stock for fabrication. International survey data is collected for processes up until the end of the forming step, however data for the fabrication step is scarce, and is solved using regional breakdowns, mass balancing and expert opinion. The boundary between forming and fabrication is not always clear (i.e. tube welding could be classed in either category) and forming sometimes occurs in smaller facilities which fall outside the coverage of statistical surveys (i.e. hot rolled aluminium strip may be rolled further into cold rolled strip).

The working papers *Global flow of steel*[W1] and *Global flow of aluminium*[W2] give more detail about creating the Sankey diagrams.

Designing products with less material

Lightweight design aims to use less material to deliver the same services. Potentially this offers a significant opportunity to reduce demand for steel and aluminium, so could be an important abatement strategy for CO_2 emissions. To what extent are attempts being made to reduce the weight of existing products, and what is the potential for further application of lightweight design to reduce demand for liquid metal?

Our interest in lightweight design is motivated by the need to reduce requirements for liquid metal. However, lightweight design has other benefits: the fuel efficiency of road vehicles is dependent on their mass, so future efficient cars and trucks must be lighter than contemporary designs; in large static structures, such as buildings, a significant fraction of total load is self-weight, so a reduction in structural weight in some parts of a structure may allow a reduction in loading specifications elsewhere; for moving products, weight reduction may give benefits beyond energy efficiency, such as car agility and handling or aircraft range. As a result of these co-benefits, aeroplane and racing car designers are the experts on weight saving, and future gains in these applications will have limited effect. However, in other applications, weight saving has had less attention to date, and our interest is to identify opportunities for significant future savings.

The box below lays out an overview of the technical approach to designing materially efficient components: consolidate loads; don't over-specify; align components with loads to minimise bending; choose the best materials; optimise the cross-section of components subject to bending. These strategies apply at different stages of the design process, and could potentially lead to considerable reductions in metal use, without loss of service.

To what extent have these approaches been deployed to date, and how much of the liquid metal entering use per year could be saved by wide-spread pursuit of these principles for lightweight design? In order to explore the reality of material saving through efficiency design, we've examined five case studies—universal beams, food cans, car bodies/crash structures, deep-sea oil and gas pipeline, and reinforcing bar. Globally, annual production of these components accounts for around 400Mt of steel and aluminium, nearly 40% of total production.

Principles of lightweight design

The engineering basis for lightweight design is surprisingly easy to explain: it's all about bending. A metal strut, cable or bar loaded along its length is perfectly efficient—all the material is used to the limit of its capability. So, whether the design is limited by stiffness (flexibility) or strength (maximum load), loading along the length of the member is always best. However, we are often constrained in our choice about how to support a load—and whether it's the floor of an office block, the wing of an aeroplane, or the arm of a crane, we may not be able to support a load in-line, and this gives rise to bending.

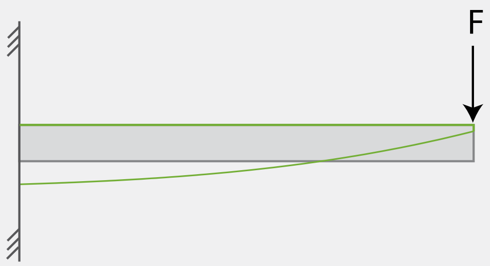
The picture (below left) shows the simplest example of this—a point load supported some specified distance from a wall. A typical requirement in design is to support the load either with only a given deflection, or to ensure that the support won't fail even if the load reaches some peak value. The cheapest way to provide the support is usually to have a beam with constant cross-section, because it's easier to manufacture standard parts than custom ones. But if the beam is constant thickness, much of it is used inefficiently—it would be better to have more depth nearer to the wall, and less nearer the load. In fact, we can show that if we are allowed to vary the depth of the beam along its length, we could provide the same stiffness with 11% less weight, but at the cost of increased depth.

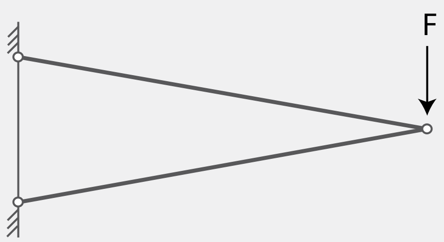
Remember that bending is the problem—it's always better to load a member along its length than to allow it to bend. So, for our simple example, what if we change the design, and use a simple pin-jointed pair of members to support the same load (below right). In this design, the loads are aligned with the members, and our material requirement depends only on the angle between them. For a given distance from the wall, it turns out that the best value of this angle is 110° and compared to the original beam we can use 98% less material and still have the same stiffness (this includes a bracing strut to prevent buckling of the compression member).

Our simple example is for a point load supported in one-dimension, but similar observations apply for more complex structures. We can also show that if two nearby loads must be supported, we always need less material if we support them in one structure, rather than supporting them separately.

Our simple example allows us to propose the following technical principles for materially efficient lightweight design with steel and aluminium:

- support multiple loads with one structure
- don't over-specify the loads
- align components with the loads as much as possible
- choose the best materials
- optimise the cross-section of any component subject to bending.





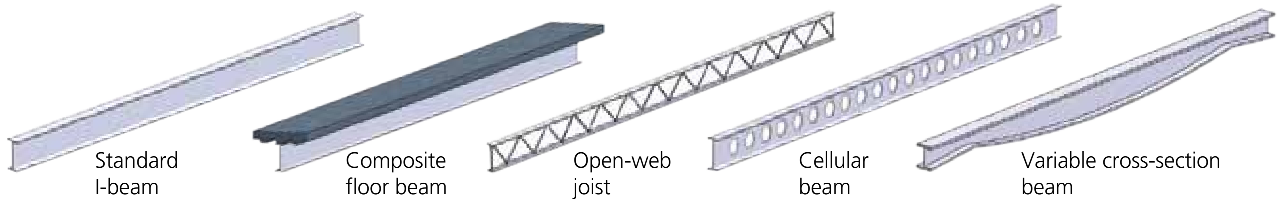
Case studies

Universal beams

Standard universal beams are the key components of steel-framed buildings. They are designed for bending stiffness, and used as horizontal beams to support floors or roofs. They are manufactured in a standardized set of geometries, listed in catalogues provided by steel producers. However, their constant cross-section geometry is chosen for ease of manufacture, so not be perfectly efficient. Furthermore, part of the building design process is a 'rationalisation' phase to reduce the number of beam sections required on site—to simplify logistics, fabrication and construction management—and this leads to further inefficient material use.

In this case study, several alternative designs of beam have been considered for a set of standard load cases, to estimate the mass saving possible through optimised design. The beam designs analysed are shown in the figure and comprise: standard I-beams; composite floor beams where the concrete floor slab is part of the bending system allowing a smaller steel section; open-web joists which are truss structures suitable for lighter loads such as roofs; cellular beams where shaped cells are cut from the web of the beam to save weight; variable cross-section beams where the beam depth or width varies and is optimised for a given loading.

Using composite floor beams as a benchmark for the floor load cases, and a standard universal beam for the roof load cases, weight savings of at least 30% could be achieved, with higher weight savings possible in cases where composite floor beams are not currently in use.



Deep-sea pipelines

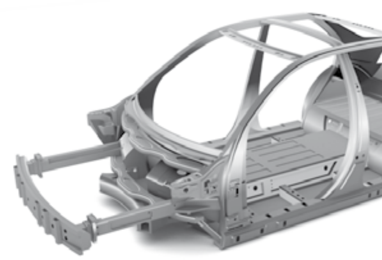
Deep-sea oil and gas pipeline consists of large diameter pipe, manufactured from high grade steel plate. Operating at depths of over 2 km, the pipe is subjected to a large hydrostatic crushing pressure, but in service the oil or gas in the pipe is pumped at a pressure similar to the external pressure, so the pipe experiences only a small differential pressure. The stresses on the pipe during installation are actually much higher than those in service, and it is these installation stresses that limit the options for reducing the weight of the pipe.

Deep-sea pipelines are frequently installed using the 'J-lay' method. The pipe 'string' is hung vertically from a laying barge and allowed to fall to the sea floor. As the barge moves forward, new pipe sections are welded to the string end. This method is chosen as it allows accurate location of the pipeline on the sea floor and reduces the barge requirements compared to other installation methods. However, installation by the 'J-lay' method generates two sources of stress: large compressive stress due to water pressure (the pipe itself is empty) and large stresses due to bending of the pipe.

In this case study, methods of pressurising the pipeline internally during installation were assessed by static analysis and the results indicate that pressurising the pipe with gas at a pressure equal to the external pressure at the sea floor could reduce the weight of the pipe by 30%. However, requirements for corrosive protection may reduce these savings to 10% and generating internal pressure in the pipe may lead to unacceptable health and safety risks.

Car body / crash structures

Car body structures include elements to improve crash safety, which deform during a collision to dissipate energy through plastic work. Body shells of modern cars are typically made of steel or aluminium and for a lightweight crash structure, both the selection of a suitable material and the design of the crash element are important. The key performance requirement for crash structures is the specific energy absorption—the amount of energy absorbed per kilogram of material. Materials such as aluminium foams, carbon fibre composites and magnesium all demonstrate high specific energy absorption when compared to high strength steels and aluminium alloys. However, replacing steel and aluminium with lighter materials does not necessarily provide an emissions saving, as production of other materials may have led to greater carbon emissions.



It is difficult to analyse the whole car body structure to find possible weight savings, however reports in the published literature suggest that savings of between 20% and 40% will be possible over the next 5–10 years, principally through the substitution of superior alloys and new materials, in particular aluminium and magnesium. This agrees with the aims of car makers such as Jaguar Land Rover, who aim to reduce the weight of car doors by 30% within 5 years.

Case studies

Rebar

Steel bar is used extensively to provide structural reinforcement for concrete in buildings and infrastructure. In China, which accounts for around 60% of global demand for reinforcing steel bars (rebar), the use of low strength rebar (~335 MPa) is still common, whereas in Europe the use of higher strength rebar (400–500 MPa) is normal. Specification of rebar is constrained by strength (rather than stiffness as in the Universal Beam example above.) There are two opportunities for steel savings in reinforcing bar. The first is to upgrade all Chinese rebar, from the current mix of strengths to 500 MPa, which we calculate would save 23 Mt or 13% of global rebar production. The second is to optimise the sizing and placement of reinforcing systems, saving a further 15% of global production, assuming optimised rebar solutions could be used in 65% of building projects and 50% of infrastructure projects. Companies such as Qube offer optimised reinforcing solutions but are yet to gain significant market penetration (see box story on page 10).

Food cans

Around 100 billion **food cans** are produced each year. In contrast to beverage cans, which have seen a weight reduction of around 20% over the past 30 years, the food can has seen only modest decreases in weight, and remains around 30% heavier than a beverage can of equivalent volume. Lighter cans could be produced using existing manufacturing equipment, simply by substituting thinner gauge material in the can bodies and ends, but this has not been done. Why is this?

The performance specifications of the food can are dictated the downstream processing requirements, where the food manufacturer fills the can, caps it, then sterilizes the contents in a cooking process known as "retorting", before stacking the cans to great heights for storage. During the retorting process, the can experiences an implosive pressure of around 1 bar, followed by an explosive pressure of nearly 3 bar, and when stacked the can must withstand large compressive forces axially. This differs from the treatment of other food packaging—aluminium pouches, plastic pots and Tetra Pak™—which are sterilized in a balanced retorting process at pressures of around ±0.5 bar, are boxed instead of stacked, and generally handled more carefully. If the same were true for food cans, the can body could be made 30% lighter, and in some cases can ends could be replaced by foil closures reducing the weight of the ends by more than half.

Further details for each of these five case studies can be found in the working papers.[W3–W7]

Lessons learnt

In all the case-studies considered here, weight savings of 15–30% were found to be possible. In the case of the I-beam and the car crash structure, this was through reconsidering the design, and in the case of the car body, through selection of higher performance materials. For the food can and deep-sea pipeline case-studies, the installation and supply chain after manufacture must also be considered, and it is redesign of these elements that enables lighter weight designs to be adopted. With reinforcing bar, the saving is provided by a combination of material upgrade and design optimisation.

Table 3 summarises our estimates of potential weight savings, and on page 14, we'll use these figures to estimate the savings in CO_2 emissions that would be achieved by reducing liquid metal requirements by this amount.

On page 6 we set out a technical basis for lightweight design, and looking at the case studies has allowed us to expand our understanding of the decisions that influence design weight, and the constraints that currently inhibit more aggressive adoption of lightweight designs. We've summarised what we've learnt from the cases on the opposite page.

Two issues have arisen in each case, which must be addressed if we are to realise the savings in liquid metal production that we believe are possible. Firstly, we've seen that the service provided by metal components is often multi-faceted—so even when components appear to be over-specified for their final use-phase, this was chosen to meet other performance criteria: the food can must withstand higher pressures during retorting than on the shelf, and the deep-sea pipe must stand higher stress during laying than when pumping gas or oil. Secondly, there is a strongly asymmetric risk associated with lightweight design—it is generally much cheaper to incur extra material costs for an over-performing component than to carry the risk of component failure. As a result, designers are inherently conservative, and in the long supply-chains of metal products, this conservatism tends to be applied additionally at several stages.

If we want to achieve the material savings that appear possible from these case studies, we need to address both these issues. It appears that the key to this is collaboration along metals supply chains – so that final product designers, components suppliers, and all decision takers between liquid material and final use, collaborate in the definition of material service and the assessment of risk.

	Universal beams	Deep-sea pipeline	Car body crash str.	Rebar	Food cans
Global demand Mt	49	25	48	170	8
Potential savings Mt	8–21	3–8	10–20	51	2
	20–50%	10–30%	20–40%	30%	30%

Table 3—Summary of lightweight design case studies

Technical strategies

Starting from the technical principles on page 6, and having learnt from the case studies and examples of successful light-weighting, we can propose a set of technical strategies for light-weight design:

Understand component service needs and avoid over-specification

Most component designs must provide more than one service, but if material use is increased by requirements prior to final use, look for alternative solutions. Ensure that use-phase design loads accurately reflect those experienced in-service with one appropriate safety factor.

Material selection

Advanced alloying has led to steady strength increases for both metals. However, many components are stiffness constrained and within the steel or aluminium family there is little possible variation in stiffness. There are few material alternatives to steel and aluminium available in similar volume, and most of those have higher embodied carbon emissions.

Product integration

Designs should be optimised at the product level, before the component level, to seek and exploit opportunities for integrating multiple functions into the same components where possible. Aim to layout components to minimise bending loads.

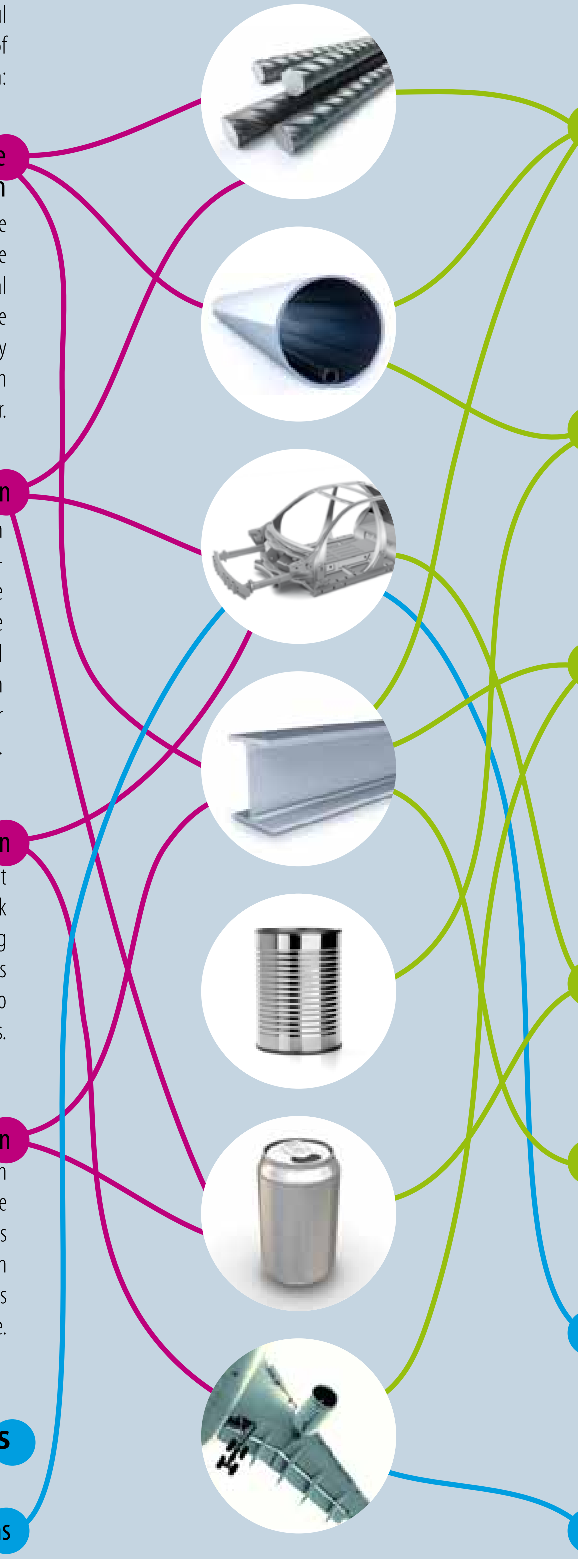
Component optimisation

Once design specifications are known for individual components, they can be optimised. For axially loaded components this is simple. For components loaded in bending, any material saving benefit depends on a materially efficient manufacturing route.

Co-benefits

Use-phase emissions

In applications where the product moves, for example cars and aeroplanes, the use phase emissions can be significantly reduced by light-weight design



Constraints

Despite opportunities to save weight, the technical strategies may not be adopted, due to constraints at every stage of a product life-cycle from specification to disposal:

Design specification and risk

Asymmetric risk tends to promote over-specification at every stage of product design and production. Uncertainty over future use requirements may lead to over-specification, and in some cases loads may not be well understood, so must be over-specified or may be specified from over-conservative codes of practice.

Component service required before use

Service requirements prior to the use-phase, for instance to withstand loading during production, distribution or installation, may drive a requirement for increased mass compared to that required purely for service loading.

Manufacturing route

Economies of scale have driven development of extremely efficient production processes for standardised components. Production of more optimised parts may be costly, or may depend on extensive material removal (as happens for example in aeroplane manufacture) so that a light-weight design does not equate to reduced material requirements.

Consumer perceptions

In some markets, final customers may have negative perceptions of light-weight designs, for example if a heavier car conveys a sense of luxury.

End-of-life trade-off

Optimised components may be more difficult to re-use than standardised components

Use-phase performance

Weight reduction in certain products leads to better use-phase performance, for example, improved braking and road-handling for light-weight cars

Compounding weight saving

The use of light-weight components in part of a product may allow a reduction in the loads and hence sizes of components elsewhere.

Reinforcing steel optimisation

Reinforced concrete designs generally include a degree of 'rationalisation' in the selection and layout of reinforcing steel, i.e. bars of same diameter and same spacing are used across large areas to facilitate detailing, identification, laying and checking of the installed reinforcement. This can typically add between 15% and 30% more reinforcing steel than is strictly required to meet performance and code requirements. Qube Design minimise this over-specification by using an advanced finite element approach for designing and detailing reinforcement using the Bamtec prefabricated rolled reinforcement carpet system. Bamtec carpets typically comprise smaller diameter bars (including in addition to normal stock ranges: 14, 18 and 22 mm dia) which are placed at a reduced spacing to achieve the same reinforcement area required by the design. Bamtec 'rolled carpets' are robotically manufactured with the reinforcement read from the detailed drawings. Complex sequences of bars are used to accurately match the moment envelope significantly reducing the degree of rationalisation in the slab, without any loss of stiffness, and with increased crack control. Each bar is spot welded to thin gauge steel straps during manufacture and rolled, pre slung for lifting and placement allowing for quick roll out on site. Using the rolled carpets, together with prefabricated edge curtailment and cages results in up to 95% of the installation being manufactured offsite. The combination of Qube's approach to design, and the Bamtec carpet system is an attractive example of intelligent innovation leading to real material savings. Significant material and fixing savings can be achieved, and the system may also give health and safety benefits and improved quality control, due to offsite manufacture.

FLEXX Eco-Bogie

Based on early bogie development work by British Rail Research in the early 90's, Bombardier's FLEXX Eco-Bogie (previously known as the B5000 bogie) is an example of successful component lightweighting in the rail industry. The integrated design reduces bogie weight by 30% (see blue verus grey in plan view), saving approximately two tonnes per bogie. More importantly for track damage, the unsprung mass—that is the mass that is in direct contact with the rail with no suspension—is reduced by 25%, approximately 1 tonne per bogie. The FLEXX Eco-Bogie was developed as part of Bombardier's ECO4 Energy, Efficiency, Economy, Ecology initiative and aims to deliver savings in energy costs, network access charges and maintenance costs. Bombardier estimate that the new bogie results in a 25% lifecycle cost saving. In the UK, where expected track damage influences network track access charges, access charges for the lightweighted bogie are expected to be reduced by 17% in the 200 km / hr 16 tonne axel load class compared to a conventional bogie. The lightweighted bogie design is suitable for commuter, regional and high-speed rail applications. Over 1000 units are in operation worldwide including in the UK under Voyager and Meridian trains. Further units are being manufactured for the Norwegian Railways (NSB) and for the new generation of Bombardier Turbostar.

London 2012 Olympic Park

As use-phase CO_2 emissions from buildings are reduced, through energy efficiency measures, more attention is being focused on the embodied carbon emissions from construction. For the London 2012 Olympic Park more than 90% of the embodied carbon comes from just three construction materials—concrete, reinforcing steel and structural steel—each accounting for approximately 30% of the total.[4] An effective means to reduce embodied carbon in construction projects is for clients to set targets early on in the design, preferably in the brief. Here the approaches to lightweighting in the Olympic Velodrome and the London Aquatics Centre are contrasted.

The architects for the Velodrome had a vision for a minimum structure building 'shrink-wrapped' around the sport and spectators. As a result the geometry was governed by the track layout and sightlines to it; this 'saddle' shape was also suitable for a lightweight cable-net roof system where the steel is used in tension to efficiently span the 130 metres between supports. Despite some initial concerns about costs and risks, the contractor saw great cost and programming savings in this system and together with the design team, convinced the client to accept it. Using the cable-net roof resulted in a 27% steel tonnage saving over an alternative steel arch option. Additional steel savings were made by combining the roof, stand and façade support systems and by undertaking advanced dynamic analysis on the seating structure to show it performed within accepted limits despite being lighter than code recommendations.

The Aquatics Centre was awarded to a signature architect to be an iconic building for the London 2012 Games. The roof is a key element—'an undulating roof sweeps up from the ground as a wave'. Its geometry constrained the structure to a conventional truss system. Despite being highly optimised during design—up to 95% utilisation in places—the roof is still over five times as heavy as the Velodrome's, which is of a similar span and area. This demonstrates the importance of having a lightweighting ethos from the very initial stages: finding a favourable form at the start yields greater savings than highly refining a heavier option later on. (Images: London 2012)

Reducing manufacturing scrap

Liquid metal production is the most energy intensive stage in making metal components, so has had most attention, and is by now highly energy efficient. However, total demand for liquid metal is driven by a combination of final product mass—the previous section explored ways to reduce this—and yield losses in production. Any scrap, whether from scalping ingots, trimming rolled coils, machining blocks, blanking sheets prior to pressing, or from errors and defects, is a form of yield loss. The global metal flow Sankey diagrams at the beginning of this report suggest that if we could reduce all yield losses, we could reduce total requirements for liquid metal production by 26% and 41% for steel and aluminium respectively.

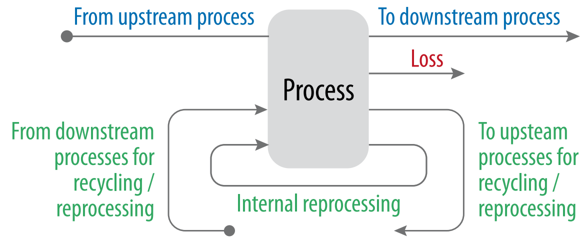
How much can we really reduce yield losses?

When we manufacture plastic toys by injection moulding, or concrete buildings by pouring into formwork, yield losses are very low. For plastic and concrete, the final properties of the material are achieved during solidification, so no other processing is required. For steel and aluminium, this isn't the case. The properties of metal that is poured and cooled with no other processing are generally very poor compared to those that can be created through a controlled sequence of heating, deformation, and cooling. As a result, the supply chain for these metals is long and is usually configured in two major stages: intermediate products of general shapes, for example bars, plates and coils, are made by a complex processing chain, to achieve high quality uniform properties; final components are manufactured from this intermediate stock, by shaping, material removal or joining, to give required geometries. This two-stage approach has evolved over a hundred years, and has allowed a steady and remarkable increase in properties, but risks considerable yield loss if intermediate products are far from the geometries of final components.

Due to the huge variety of final steel or aluminium component shapes in use, we can't provide a general analysis of all yield losses. So to gain some insight into the potential for future yield loss reduction, we've conducted a series of case studies—hoping to identify useful opportunities to modify process chains and component designs. Our case study components are:

- a steel I-beam
- a car door panel—made from either steel or aluminium
- an aluminium beverage can (excluding its lid)
- an aluminium wing skin panel for an aeroplane

In each case, we've visited production sites all along the supply chain, starting from the final component, and proceeding upstream until we reached the source of liquid metal. At every stage, we gathered data on process yield losses, energy and CO_2 emissions to try to build up a complete picture of the metal flows and energy inputs to each component. Inevitably, some of this data is commercially sensitive, some was unknown – for instance where energy metering is applied at site rather than process level, and some had to be deduced from aggregated numbers.



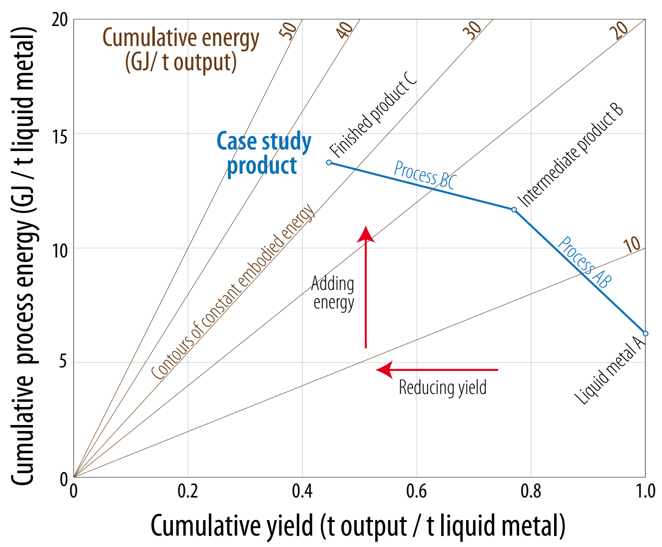
$$\text{Yield} = \frac{\text{Metal to down stream processes}}{\text{Sum of all process inputs}} \qquad \text{Loss} = 1 - \text{Yield}$$

Collecting figures for yield losses was particularly challenging as they can be defined using several different combinations of input and output flows, as shown in the graphic above. This matters most for melting processes—where it is easy to return scrap straight back into the same process. At one site, where liquid metal is cast into discrete ingots, we watched as up to 20% of each batch was poured into a pit, once the ingot was of the required size. This metal wasn't lost—once cooled, it was fed back into the next batch for re-melting—but of course the energy required is determined by the total mass melted, not the total useful mass poured. We've therefore defined yield losses as any metal entering a process that isn't immediately passed downstream to the next process.

All the case studies are described in greater detail in our working paper: *The effect of yield losses on embodied CO_2 emissions in four case study metal products.*[W8]

Understanding the link between yield losses and embodied energy

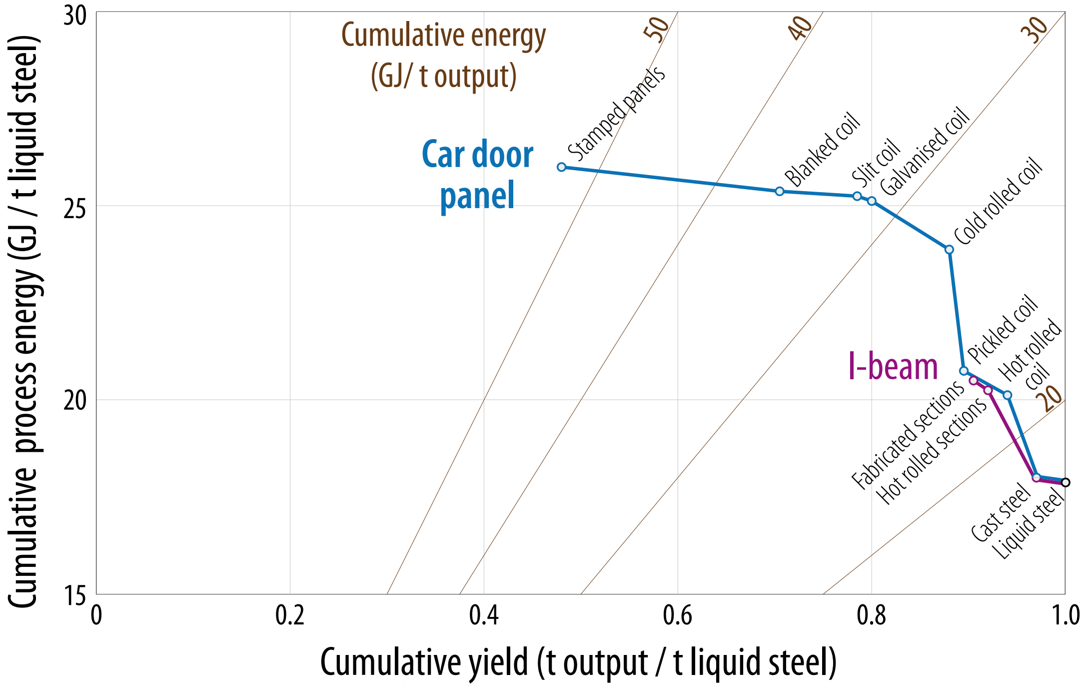
We've presented the results of our case studies on graphs showing how the 'embodied energy' in a component (the total energy required to make it) builds up while the mass of metal decreases due to yield losses. The figure below shows how these graphs work. The x-axis shows that if the production process started with



Graph of cumulative energy against cumulative yield (example)

Steel energy / yield graph

Cumulative energy versus cumulative yield for steel case study products



one tonne of liquid metal, the mass remaining reduces after each process due to yield loss. The y-axis shows how the cumulative energy embedded in the product builds up with each additional process step. We've normalised both axes by the mass of metal originally cast to give meaning to contours with a constant ratio of x to y: these contours show the energy intensity of the product—cumulative energy up to each production stage divided by the mass remaining at that stage. Typically, these graphs will show that the (already energy efficient) process of liquid metal production dominates the cumulative energy build-up, but yield losses in the downstream supply chain can increase the embodied energy in the final component by a factor of up to 10.

The steel energy / yield graph

We started by assuming that one tonne of liquid steel has an embodied energy of 18 GJ/t. This is typical for UK steel, equivalent to liquid steel produced via the blast furnace followed by oxygen blown conversion with a 20% scrap content. The graph clearly shows the impact of yield losses on the embodied energy of the products—around 23 GJ/t for the beam, but nearly 55 GJ per tonne for the car door panels. Remembering the two stages of metal supply chains, the I-beam has a much shorter chain—with standard sections rolled by the steel-maker, so the second stage (fabricating) requires only a few operations such as trimming to length and welding on end-plates. This gives yield losses of only 10%, and is in marked contrast to the 50% losses for the door panel made from cold-rolled strip, which has a longer supply chain with high yield losses in blanking (door panels do not tessellate well) and stamping (window voids are cut from the part, and edges are trimmed after deep-drawing.)

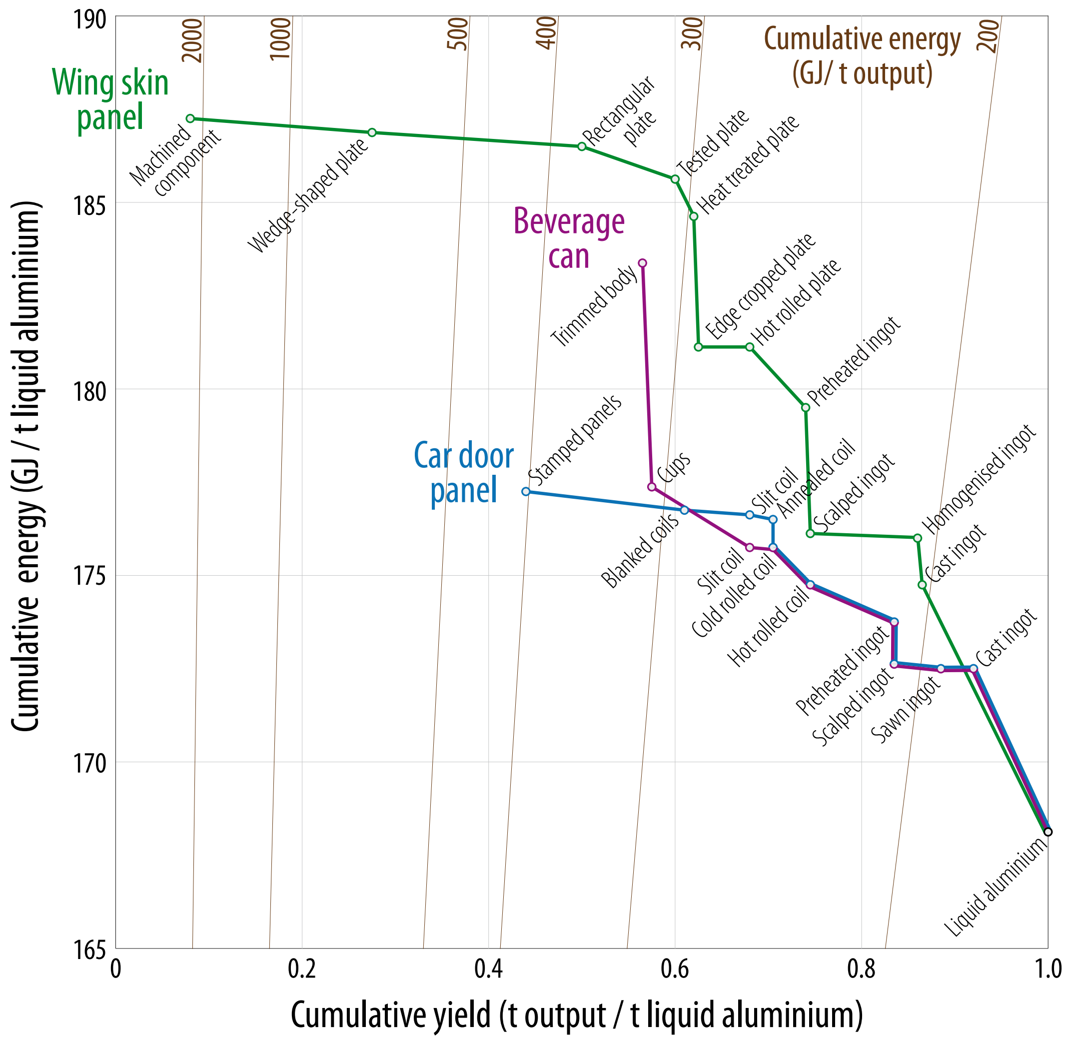
In order to draw attention to the impact of yield losses on embodied energy, we have assumed that the liquid steel is made with 20% scrap for both products. Clearly, if this fraction is changed, the energy required to manufacture liquid metal changes, and the whole graph will shift up or down. However, because this first step on the graph dominates the cumulative energy input, the interpretation of the graph remains the same – yield losses in the supply chain significantly increase the embodied energy in final components.

The aluminium energy / yield graph

The aluminium graph shows all three case-study components starting with one tonne of 100% primary liquid aluminium, with an embodied energy of 168 GJ/t. The y-axis does not start at zero, in order to show variations in downstream process energy, but for all three parts, the energy to make liquid metal accounts for more than 90% of the total

Yield losses for the aluminium parts are higher than those in steel, due to the requirement for ingot scalping (removing the outer surface after casting) and more trimming during rolling stages. Blanking for the cans (cutting circular blanks from a flat sheet) causes a yield loss of around 15% but trimming losses are small compared to those for the car door panel. However, the most dramatic yield loss is for the wing skin panel which is machined from plate, with loss of around 90% of the plate. Mass reduction is so important in determining the fuel efficiency of aeroplanes that the cost of this loss is not important to final customers, even though it leads to an embodied energy of over 2,200 GJ per tonne.

As with steel, a change in recycled content of the original liquid metal will shift the graphs up or down, but will not change the relative impact of yield losses.



Aluminium energy / yield graph

Cumulative energy versus cumulative yield for aluminium case study products

The causes of yield loss

We found two different sources of yield losses in our case studies. Planned yield losses occur in normal operation, for example:

- Leaving behind a "skeleton" when cutting circles from rectangular plate as perfect tessellation is not possible
- Trimming the side of metal coil between rolling processes to leave a straight edge and to prevent crack propagation
- Removing a layer of metal oxide either mechanically (e.g. scalping), or chemically (e.g. pickling)
- Machining complex geometries from regular shaped stock.

Measuring these planned losses is straightforward as they are determined by design. In contrast, unplanned losses related to quality cannot be anticipated and may change significantly over time. They include:

- Producing poor quality parts due to equipment faults or material defects
- Damaging material or products during handling
- Creating waste when starting and stopping equipment

As unplanned losses are an indicator of efficiency, they are commercially sensitive and we found few companies willing to reveal them. Also, for all our case study parts, yield loss was dominated by planned losses.

How can we reduce planned yield losses?

Our case studies revealed three processes as the main generators of planned yield loss: blanking and trimming (after stamping) of sheet metal and machining of plates and bars. These processes are required because the intermediate stock products created in the first stage of the supply chain are the wrong geometry for the second stage. To reduce these losses, we could develop new processes, operate existing processes more effectively or change component designs. This gives rise to many opportunities for innovation:

- The ongoing development of 'net-shape casting' processes aims to produce intermediate stock closer to required shapes. This appears to be a major opportunity for reducing yield losses, but is currently inhibited by a lack of economies of scale, and the difficulty of controlling material properties as effectively as in existing processes.

- In current blanking processes, a clean cut round the perimeter of the blank can only be achieved if a sacrificial 'skeleton' of material outside the perimeter is discarded. Innovation might eliminate this requirement.
- Except in can-making, stamping and drawing processes require an over-size blank which is gripped during forming, and then trimmed and discarded. Novel processes could aim to obviate this trim.
- Current machining processes convert all unwanted material into small chips, but innovative cutting processes might allow separation of larger pieces of material for other uses.
- The efficiency of tessellation in cutting out parts from stock improves as the number of parts increases. New business models, with stage one metals companies providing blanks to many customers from a restricted stock range, might allow significant increases in tessellation efficiency.
- Component designs could be modified to increase tessellation, and hence reduced planned yield losses.

Examples of recent or current process innovations to reduce planned yield losses include:

- Continuous casting of steel to reduce planned yield losses compared to discrete ingot casting
- Re-melting aluminium in an inert atmosphere to reduce oxidation losses
- Intelligent casting to producer customer-specific widths of coiled strip
- Adjusting blank geometry to allow better tessellation
- Controlling the rolling process to reduce the requirement for trimming due to earring after aluminium can manufacture
- Developing new alloys to allow use of thinner gauge material in can-making, so reducing the mass (but not the fraction) of planned yield losses

The effect of yield on embodied energy and carbon

Table 4 predicts the savings in liquid metal, and therefore in embodied energy, that could be achieved for each case study component, if all yield losses were eliminated. Using the global Sankey diagrams from earlier, we can scale up this estimate: assuming all of the yield losses downstream of liquid metal production can be eliminated, the total demand for liquid steel will reduce by 26% and the total demand for liquid aluminium will reduce by 41%.

However, the metal that we have described as 'yield loss' is, of course, not really lost – but, as shown in the Sankey diagrams, is recycled by melting. Therefore reducing yield losses does not affect demand for primary metal made from ore, but reduces demand for metal made by recycling at the same rate that it reduces the supply of metal for recycling. The benefit of yield improvements is thus to reduce demand for energy in recycling processes.

Case Study Product	Reduction in cumulative embodied energy (%)
Steel I-beam	8
Aluminium beverage can	33
Aluminium car door panel	51
Steel car door panel	51
Aluminium wing skin panel	92

Table 4—Theoretical embodied energy savings for processes with 100% yield

Avoiding yield losses in all steel manufacturing therefore saves 11% of energy associated with global steel production, and about 10% of CO_2 emissions. For aluminium, even though the saving in mass is higher than for steel, the energy saving is just 4%. This small number is due to the greater difference in energy requirements for making aluminium from ore as opposed to scrap.

It is difficult to predict a realistic target figure for future yield losses, but clearly there are many options to make significant changes. We have drawn attention to several specific opportunities to develop improved manufacturing processes. In addition, as with our earlier discussion on lightweight design, we recognise the potential for yield improvement through collaboration along the supply chain, particularly in ensuring that component designers are aware of the impact of their choices on total yield.

	Steel	Aluminium
Current liquid metal demand	1400 Mt	76 Mt
Current metal content in products	1040 Mt	45 Mt
Liquid metal reduction potential	360 Mt 26%	31 Mt 41%

Table 5—Potential reduction in demand for liquid metal through yield improvements

	Steel	Aluminium
Current energy used (liquid metal production)	17 EJ	6.5 EJ
Energy reduction potential	2 EJ 11%	0.24 EJ 4%
Current CO_2 emissions (liquid metal production)	1400 Mt CO_2	340 Mt CO_2
CO_2 reduction potential	150 Mt CO_2 10%	13 Mt CO_2 4%

Table 6—Potential reduction in energy and CO_2 emissions through yield improvements

Material Substitution

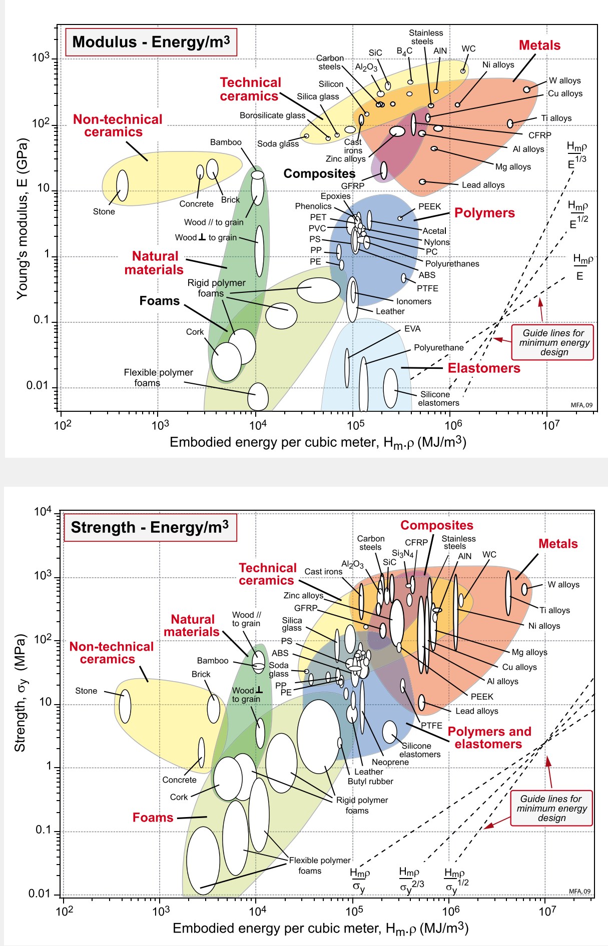
We choose materials to meet design requirements, typically minimum stiffness or strength. To meet any given set of design requirements we may opt for a lower mass of a stiffer/stronger material, for example using carbon fibre or magnesium to replace steel or aluminium. However, we should step back and consider the bigger picture; would these substitutions give an overall energy saving?

To answer this question, the balance of strength/stiffness properties to the embodied energy used in processing the material may be compared graphically on Ashby diagrams[5]. Using performance indices that are based on the design requirements, guidelines of constant energy are plotted. Materials with a better performance index, lying above or to the left of the guideline through the current material, will provide the same service (strength or stiffness) with a lower embodied energy.

In static, structural applications, steel provides the required service of strength or stiffness at a relatively low embodied energy but there are natural materials that may be possible substitutes, for example stone in compression and wood in tension. These may be viable in some situations such as small buildings, but generally the ease of manufacture, recyclability, consistent properties, and the compact nature of a steel design make it a more attractive option. Apart from wood and stone, there are no other substitutes for steel with equivalent performance and reduced embodied energy. Although often discussed in this context, composites have higher embodied energy than steel.

If use-phase energy is dependent on mass, or when other properties such as corrosion resistance are important, the situation is not as clear. Aluminium is often preferred to steel, as it has good strength to weight properties, is recyclable, has well established fabrication processes, and has good corrosion performance. In this case, composite materials may provide solutions with lower total emissions than aluminium, and may be preferred if higher manufacturing costs can be offset by energy savings in operation.

When all the details are considered, it seems we have already chosen our key materials wisely, and only limited energy savings in specific applications may be made through materials substitution.



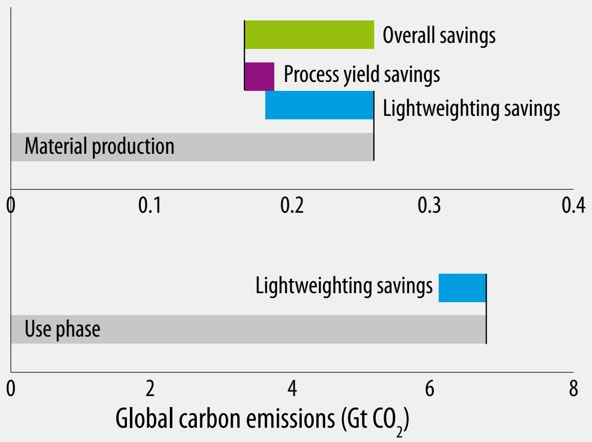
Materials selection options through comparing performance and embodied energy: stiffness against embodied energy (top); strength against embodied energy (bottom)

Estimating emissions savings for cars made with less liquid metal

We've predicted the possible scale of emissions savings from lightweight design and avoiding yield losses, so can now estimate a total benefit. However, for cars, where fuel consumption is strongly dependent on mass, we can also anticipate the emissions saving in-service from having lighter cars. We'll assume that the car remains the same, except for application of our two strategies, and that as is currently typical, 70% of the car is made from steel and aluminium[6]. We can therefore hope to save 15–30% of 70% of its mass by efficient design. To translate this into a saving in fuel use, we can use a standard simple estimate that a 10% saving in vehicle mass gives a 5% saving in fuel consumption[7]. So our predicted saving in fuel consumption is 5–10%.

The figure illustrates how the emissions savings from using less liquid metal add up for the car, both in production and in use. In production, most of the benefit comes from lightweight design rather than from yield improvement, and the total emissions saving in material production is roughly equal to the saving due to reduced fuel consumption. These figures are illustrative only—and it is likely that pursuit of lighter weight vehicles will drive wider changes to car design than component optimisation. However, for liquid metal producers, these figures clearly show that a drive for more fuel-efficient vehicles will also translate into a reduced demand for liquid metal.

Calculation details can be found in the working paper: *The global emissions case for lightweight design and process yield improvements.*[W9]



Graph of carbon emissions savings for the car, as a result of pursuing lightweighting and process yields improvements. (Note the two strategies when applied together are multiplicative and therefore the savings overlap for material production).

The economic case for using less metal

Product lightweighting and yield improvement have the potential to deliver financial savings through reduced material costs, reduced use phase costs and decreased exposure to carbon taxes. This section looks at how big these incentives are, how sensitive they are to a carbon price and why and why not opportunities for product lightweighting and yield improvement have been exploited in the manufacture of three products: a beverage can, a car and a train.

The aluminium beverage can

The beverage can industry has seen aggressive lightweighting resulting in a 35% reduction in material requirement over the last 30 years. Historic and ongoing efforts to lightweight products and improve yield have been motivated by the need to reduce material costs which account for approximately two thirds of production costs (exchange rate dependent). The standardised nature of the product and its automated production process means that any material saving solutions can be widely applied allowing the burden of R&D expenditure to be spread across a high volume of sales—the European market is estimated at over 50 billion beverage cans[8].

Contracts typically link can price to input material price and, even where this link is not explicit, any reduction in can weight is transparent to the buyer and so can be negotiated over. Although these contracting practices insulate the can-maker from volatility in the primary metals market (reducing hedging costs) they mean that material cost savings from lightweighting must be shared with customers. By contrast the benefits of yield improvements are invisible to the buyer and so are accrued entirely to the can-maker. Whilst can lightweighting enhances competitiveness (itself important for utilisation and so margins), yield improvement adds to margins directly.

In the analysis, the incentives for lightweighting and yield improvement of the beverage can are driven entirely by the price of aluminium can body stock. Additional potential benefits include reduced producer responsibility costs (see policy review) and logistical saving. Although these logistical savings are expected to be minor for can transportation, a study into down-gauging of food can-ends found significant logistics cost savings in can-end transportation as 18% more can-ends could be transported per pallet load following a 0.03 mm reduction in gauge[9].

The can-making industry has actively exploited opportunities to reduce material costs, exploring strategies that can be financed through existing funds to renew tooling e.g. reducing skeleton waste through novel stamping methods, as well as investing in significant capital assets e.g. necking technology to reduce can base and end size. Can lightweighting is limited by network externalities along the supply chain; capital-intensive filling and vending operations are reluctant to run lighter cans that require operational change and/or capital expenditure.

The car

There has been an upward trend in kerbweight of UK vehicles over the last 40 years as typified by the average small family car, which has increased in weight by 5–10% with each model change, resulting in a 35–75% cumulative increase in weight since the 1970s. Despite this overall weight increase, the industry has put great emphasis on weight reduction of the car body. The use of high strength steels, for example, is estimated to have reduced vehicle weight by 5% over the period[10]. Rather than passing the resultant weight saving on to consumers as fuel savings, the industry has opted to add features, increase vehicle size and improve performance in order to win customers. These improvements are estimated to account for three quarters of the weight increase observed (15% due to improved comfort, 13% due to adding features, 17% due to improved performance e.g. better acceleration and handling, and 30% due to increased size[11]). The remaining increases in weight are attributed to safety, with most cars now achieving five stars in the European safety-rating scheme—Euro-NCAP.

These priorities chime with research into customer preferences for vehicle characteristics, that ranks fuel efficiency as ninth after characteristics such as performance, comfort, style and safety[12]. This research concludes that weight influences many vehicle attributes, but is not coveted by consumers in its own right. The premium paid for diesel over petrol vehicles shows that consumers do factor fuel efficiency into purchases, however, they may not be prepared to compromise other attributes in order to get similar fuel efficiency improvements through lightweighting. As a result, lightweighting is limited by its effect on other vehicle attributes that are favoured by consumers.

The analysis shows that the majority of the benefit of lightweighting of vehicles comes from use phase savings as a result of an assumed fuel efficiency saving of 0.13 l/100 km/100 kg weight saving[13]. Without strong customer preferences for fuel efficiency these savings will not be pursued in the absence of intervention. Legislation to limit tailpipe emissions from vehicles (discussed in the policy section) force car manufacturers to realise these use-phase savings irrespective of customer preference. The legislation aims to reduce emissions from the new car fleet to 130 g CO_2/km by 2015 and to 95 g CO_2/km by 2020.

Car manufacturers are willing to bear some additional costs in order to meet these standards and deliver enhanced fuel efficiency to customers. Analysis conducted for the European Commission to assess the cost of different options for enhanced carbon efficiency of vehicles, found that the three lightweighting options considered (5%, 15% and 30% reduction in weight of the body-in-white) presented above average costs per unit CO_2 with cheaper options offered by hybrid technologies and improvements in transmission[14]. This is in direct contrast to evidence presented by Tata Steel Automotive, which suggests that its VA/VE (Value Analysis/Value Engineering) technique—which aims to optimise material choice and design—can deliver concomitant cost and weight savings[15]. Information on the cost of abatement is highly commercially sensitive and it is likely that the true answer lies somewhere between the two. Whilst strategies that involve material substitution (e.g. substituting aluminium for steel in the body in white) are likely to be costly, other strategies must exist that save both costs and weight if only by reversing or kerbing the trend in additional features on vehicles.

The train

The UK rail industry managed to stem train weight increases in the 1980s and 1990s by using lighter weight materials (switching from steel to aluminium body shells), pursuing lightweight design for select components (see, for example, the box story on Bombardier's FLEXX Eco-Bogie, page 10), and applying integrated design principles by replacing body shells built on underframes with monocoque designs. From the 1990s onwards, however, upward pressure on train weight prevailed and vehicle masses rose in the range of 10–25% between late 1980 and early 2000 models[16]. This weight increase is attributed to: an emphasis on reliability which has seen increased built in redundancy e.g. a larger proportion of powered vehicles; improved access and onboard services e.g. air conditioning and information systems; demands for enhanced speed and control e.g. the addition of tilt systems and intelligent train systems; and, developments in safety such as the use of improved crash protection structures.

The railways offer an efficient means of transporting weight by land—in the analysis of the benefits of lightweighting, trains are found to emit five times less carbon in transporting 1 kg than is emitted by transporting the same kg by car. Nevertheless the more intense use of trains and the added benefit of reduced track maintenance costs, mean that the benefits of lightweighting trains are an order of magnitude greater than the benefits calculated for the other case studies (this, even when the 7 year franchise life, rather than the 30 train life is taken as the unit of analysis). On this basis we would expect great emphasis to be put on lightweighting of trains but instead we find that, in the recent past, lightweighting has carried low priority for the rail industry when procuring new trains. This seemingly incongruous finding is explained by the structure of the industry.

Following the privatisation of the industry, there are three means by which a train can be procured: (1) a Rolling Stock Company (ROSCO) can buy a train and lease it to a train operating company (TOC) that has won a franchise, the train then being available to lease to other TOCs at the end of the franchise period; (2) the TOC can buy the train outright but at the risk of being left with a redundant asset at the end of the franchise and, (3) the franchising authority (e.g. DfT) can procure the train and issue a franchise that demands its use.

Option (1) is the most commonplace and can reduce the priority given to lightweighting due to: a preference for versatile trains that maximize residual value; use phase benefits accruing to the operators over the franchise life only; and, rail access charges (the charges that transfer maintenance costs and electricity costs from Network Rail to TOCs) that do not fully pass on the benefits of weight saving. Finally, although the discounted benefit of saving one tonne in mass from a vehicle is measured in tens of thousands of pounds over the lifetime of a vehicle, this compares to whole life costs measured in millions of pounds. The potential savings are therefore so relatively small that the case for lightweighting is difficult to demonstrate in isolation. Lightweighting may well, however, be viable as an intrinsic part of other initiatives.

Recent work conducted by the Rail Safety and Standards Board on the benefits of lightweighting (used to inform this report) provides a benchmark for showing the use phase cost implications of weight[17]. In addition the McNulty Review on Value for Money on Railways may recommend addressing some of the distortions in the industry structure and may improve incentives for lightweighting by emphasizing whole-system, whole-life cost savings[18].

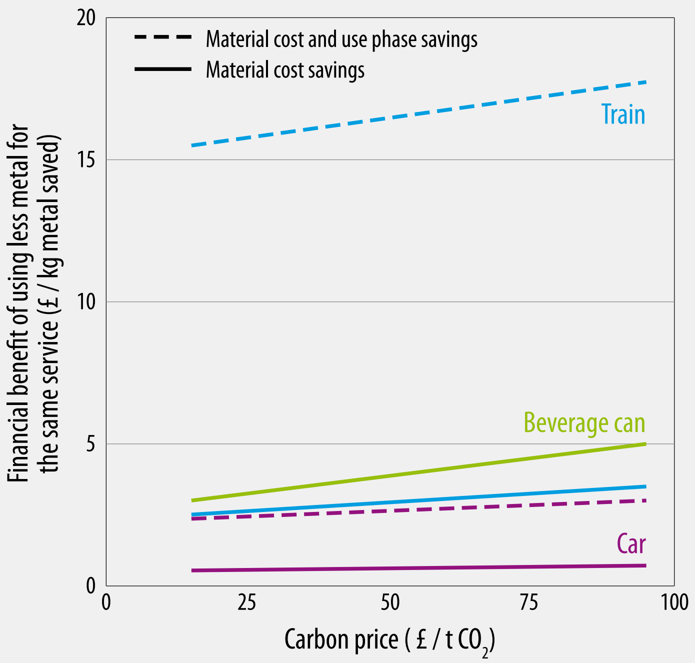
All data sources are listed in the WellMet2050 working paper: *Incentives for product lightweighting and yield improvement*[W10].

Key Insights

The willingness-to-pay analysis on the next page does not tell the full story—it is not just the magnitude of potential benefits that dictates the incentives for material efficiency, but the size of these benefits relative to other costs faced by the industry.

Although use phase benefits dominate in the transport industries considered, these appear to provide less motivation for lightweighting as they are only seen by the manufacturer indirectly and are clouded by other consumer preferences (in the case of the car) and distorted by the industry structure (in the case of the train).

Yield improvement and lightweighting can deliver cost savings aside from material cost savings e.g. inventory, handling and logistics savings. These savings are likely to be important in upstream forming industries where the material cost of process yield losses is effectively invisible due to internal material flows.



Graph of the material cost and use phase benefits of lightweighting and the effects of increasing the carbon price.

How big are the benefits of yield improvement and lightweighting?

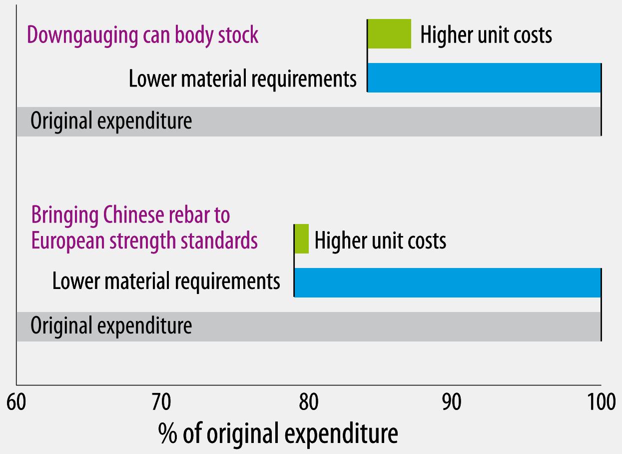
Product lightweighting can be achieved through material substitution; incumbent materials can be replaced with stronger, higher performance materials. The benefits of lightweighting and yield improvement have been calculated for each product taking into account material cost savings (assuming constant unit costs), use-phase energy cost savings and track maintenance costs savings (for trains only). In each case the intercept is determined by the unit material price and the weight sensitivity of discounted use-phase costs. The slope of the line shows sensitivity to the carbon price, with differences in slope caused by differences in the embodied energy in input materials and differences in the carbon intensity of use phase activities.

We can see that higher carbon prices cause higher material prices and increased use-phase weight-attributable costs, enhancing incentives for lightweighting and yield improvement. If consumers are assumed to perfectly factor use phase savings into their purchasing decisions, and if material cost reduction is assumed to be given equal weight across sectors, we would expect the greatest emphasis to be put on the lightweighting and yield improvement of trains and equal weight to be put on the lightweighting of cars and cans. The text above explores, sector by sector, the additional considerations that explain why these expectations are not met. The next section explains why the reality of the EUETS offers weaker incentives than those assumed here.

Implications for unit material costs

Product lightweighting can be achieved through material substitution; incumbent materials can be replaced with stronger, higher performance materials that reduce material requirement at the expense of higher unit material costs. The diagram distinguishes between the effect of reduced material requirement and the effect of increased unit material cost on total material expenditure for two case study strategies. The first explores the hypothetical scenario that the strength composition of Chinese annual rebar consumption (currently 60% 335 MPa, 40% 400 MPa) is increased to EU standard practice (100% 500 MPa). The second scenario explores how the material cost of producing 1000 cans is affected by a reduction in gauge from 0.34 mm to 0.27 mm. The graph shows that, despite higher unit costs caused by the addition of Ferrovanadium to enhance rebar strength and higher rolling charges to reduce gauge, the application of each of the strategies considered offers material cost savings as reductions in material requirement outweigh marginal increases in unit costs.

Whether or not these strategies can be cost effectively implemented will depend on the effect on other cost components e.g. it is thought that higher strength rebar is not currently being used in China due to a reluctance of local producers to invest in capital equipment for pre-straining, heat treatment and improved control.



Graph of the material cost and use phase benefits of lightweighting and the effects of increasing the carbon price.

Policy and liquid metal consumption

We have seen that both yield improvement and product lightweighting save embodied emissions in manufactured products, and that product lightweighting may have additional use phase emissions benefits. This section considers whether current UK government environmental policy offers adequate incentives for these emissions saving strategies.

Policy review

Product lightweighting is a crosscutting issue that links energy intensive industries with use-phase emissions and waste generation. Encouraging product lightweighting and yield improvement does not, therefore, sit conveniently within the objectives of a single government department. A review of existing government policy that may encourage these strategies (see policy boxes for details) has reached the following conclusions:

Existing policies that price emissions are ineffective at promoting yield improvement and lightweighting

In order to make decisions about lightweighting and yield improvement effectively, manufacturers must face consistent carbon prices so that they can factor in the cost of the externalities they cause both up and downstream. In reality there is no single price of emissions: the average Phase II EUA price has been €approximately £15/tCO_2; the CCL is levied at 0.47 p/kWh equating to an implied carbon price of £0.09/tCO_2[19]; the fuel duty is levied at £0.5819/L equating to an implied carbon price of £220/tCO_2 for the use of diesel in cars and £252/tCO_2[19] for the use of petrol. Furthermore there are multiple reasons why policies that price emissions from energy intensive industries (e.g. the steel and aluminium industry) do not result in prices of their outputs increasing in line with the emissions associated with the production of those outputs: tax revenues from the **Climate Change Levy (CCL)** are returned to businesses through cuts in National Insurance contributions; the majority of the CCL can be avoided by industries that negotiate Climate Change Agreements; fears over carbon leakage result in free allocation of EU ETS emissions permits. As a result of these measures, product manufacturers do not face input prices that duly reflect embodied emissions in their energy intensive inputs. Given the severity of the challenge to tackle climate change, material efficiency strategies such as yield improvement and lightweighting must be pursued independently of these policies.

The greater flexibility offered by modern building codes should be exploited through better communication between clients, designers and contractors

Building codes specify minimum quantities of steel and concrete in order to guard against building collapse and reduce accidents in construction. Modern, advanced codes allow the designer increased flexibility in material use by providing clauses that allow conservatism to be removed if better workmanship can be achieved or better information is known. One example is in Eurocode 2 (BS EN 1992–1–1:2004)**Annex A, which details reductions in partial safety factors that can be applied if reinforcing bars are placed more accurately. Using these reduced factors would decrease the amount of steel required. However such clauses are not widely exploited, instead default options are used. For non-safety-critical issues, such as deflection, recommended (not required) limits are specified by the codes. Performance in these categories can be negotiated with the client and less stringent criteria (that save metal) adopted if suitable. Again, this is not commonly done, leading to some buildings being over-specified. Increased communication between different designers, contractors and clients, with better awareness of other disciplines' and professions' requirements, would help to overcome this and put material only where necessary.

Due reward must be given to emissions savings from lightweighting of vehicles

The EC regulation 443/2009 sets fleet average emissions standards for vehicles at 130 g CO_2/km by 2015 and 95 CO_2/km by 2020. These standards are set for the average fleet mass with 4.57 g CO_2 added/subtracted for every 100 kg increase/decrease in kerbweight. As the target CO_2 varies by weight along this "limit line", car manufacturers are not duly reward for emissions savings achieved through weight reduction; where lightweighting occurs, the car manufacturer will simply face a more stringent emissions target. Performance relative to these targets is measured according to the testing standards set out in ECE Regulation 84. This static test, which is conducted on rollers, does not fully take into account the benefits of weight reduction. Certified CO_2 figures are calculated using categories that cover a 100 kg range of vehicle weights. This means that up to 100 kg in weight can be taken off cars at the top of a weight class, before any change in certified CO_2 is seen. These distortions must be addressed if vehicle manufacturers are to see lightweighting as a viable strategy for achieved emissions standards.

Measurement and reporting of embodied carbon should be encouraged to increase awareness of the opportunities for material efficiency

There have been some promising developments in the measurement and reporting of embodied carbon and material efficiency. The European environmental management system, EMAS requires participating companies to report mass flow of different materials used, and the European Committee for Standardisation is working on a standard (CEN–TC350) due for release in the next year which will provide the basis for measuring the integrated performance of buildings over the life cycle. Both examples include measures of the embodied energy in materials and can be used to identify opportunities to save material (and so reduce carbon emissions) through yield improvement and product lightweighting. This move, towards environmental reporting that reveals opportunities to save carbon across the whole life cycle, and results in actionable targets, should be encouraged and applied consistently across supply chains.

Emission reduction targets must take into account embodied energy

This report has highlighted the potential to reduce emissions from energy intensive industries (such as aluminium and steel), by improving material efficiency through yield improvement and lightweighting along the supply chain. Nevertheless environmental initiatives such as BREEAM and policies such as the emissions standards for vehicles fail to take into account embodied energy in their emissions assessments. As a result, these policies do little to discourage the realization of use-phase emissions savings at the expense of greater embodied emissions. By contrast the Australian buildings rating Green Star was revised last year to encourage dematerialisation of steel in structural applications. The Green Star rating awards points for example for the use of high strength steels and for the specification of rebar that is assembled off site using optimal (material saving) fabrication techniques. As opportunities to reduce use-phase emissions are exploited, the emission reduction opportunities offered by reducing embodied emissions become more prominent. Once consistent means of measuring embodied emissions have been established (see point (4)) targets must take these into account in order to provide consistent incentives for emissions reduction across the whole life cycle.

A full supply chain approach is required to systematically improve yield and to lightweight products

There are examples of successful supply chain initiatives that collect data on key performance indicators across the supply chain and set performance targets. The Eco-Reinforcement Responsible Sourcing Standard is part of the BRE standard for responsible sourcing of construction products (BES 6001) and puts emphasis on CO_2 reduction and waste minimization across the supply chain. In the grocery retail sector the WRAP Courtauld Commitment aims to improve resource efficiency and reduce emissions and wider environmental impacts by engaging the full supply chain. It is only by addressing the entire supply chain that the objective of "using less metal to deliver the same service" can be met. Such supply chain initiatives should be promoted in all metal using sectors with key performance indicators that report yield as a measure of material efficiency.

Policies that affect energy intensive input sectors:

The European Emissions Trading Scheme (EU ETS) is a cap-and-trade scheme. The current, second phase operates until 2012. The scheme applies to energy intensive sectors including the steel and aluminium sector. Facilities that exceed threshold output levels in these sectors are allocated allowances in the UK Allocation Plan. Permits must be bought in the carbon markets for emissions in excess of this initial allocation and operations can choose to abate to emissions levels below their allocation in order to sell permits. The European Commission is currently harmonising the allocation of free emissions allowances across countries, stipulating allowances be granted up to a benchmark set by the top 10% most efficient installations in each sector within the EU. Additional permits can be granted to industries at risk of carbon leakage.

The Climate Change Levy (CCL) is a tax on industrial and commercial non-renewable energy supplies. The current rates for 2010–2011 are 0.47 p / kWh for electricity. The levy is designed to be revenue neutral with the money raised returning to business through cuts in the rate of employers' National Insurance.

Climate Change Agreements (CCA) are negotiated between DECC and eligible energy intensive industries. A discount of up to 80% on the CCL is offered in return for agreed energy efficiency and carbon saving targets being met. The qualification criteria are that energy costs must account for at least 3% of production value and that the import penetration ratio, calculated at the sector level, must be at least 50%.

Policies that directly tackle manufacturer's input choice:

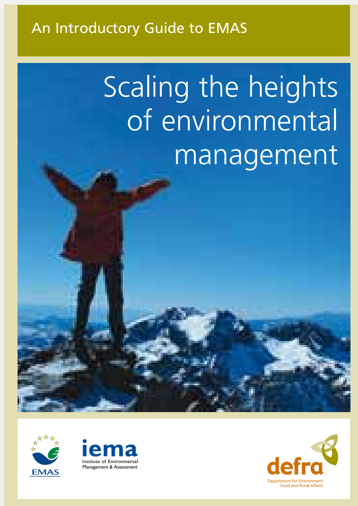
Packaging Essential Requirements Regulations apply to companies that make, fill, sell or handle packaging or packaging materials. They include a requirement to minimise packaging weight and volume subject to safety, hygiene and consumer acceptance. Companies must keep evidence of their compliance with this regulation and be prepared to supply this evidence to Trading Standards upon request. The European Standard **BS EN 13428:2004** specifies the assessment procedure to ensure that packaging weight and/or volume is at its feasible minimum.

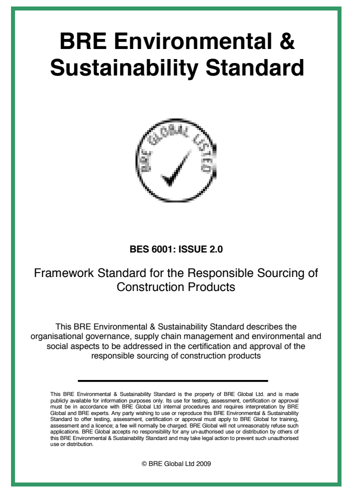
The **Producer Responsibility Obligations** apply to companies that handle more than 50 tonnes of packaging per year and have an annual turnover in excess of £2 million. Compliance is demonstrated through the purchase of Packaging Recovery Notes (PRNs) the price of which fluctuates throughout the year. Producer responsibility costs are in direct proportion to the weight of material placed on the market.

The **Eco-Management and Audit Scheme (EMAS)** and the European Standard **EN 16001** are voluntary tools that help companies evaluate, manage and improve their environmental performance. Material efficiency is included within EMAS as one of six core indicators, requiring organisations to report annual mass-flow of different materials used (excluding energy carriers and water). Organisations must provide justification that material efficiency is not relevant to their direct environmental impact in order to avoid reporting this indicator. EMAS accreditation can be set as a requirement for CCAs. Where this is the case, companies will receive a CCL rebate as a result of participating in EMAS.

The **BRE Responsible Sourcing Standard** BES 6001 provides a common benchmark for all construction products to demonstrate their responsible sourcing credentials

The **WRAP Courtauld Commitment** is a responsibility deal aimed at improving resource efficiency and reducing the carbon and wider environmental impact of the grocery retail sector. Signatories span the entire retail supply chain. One of its commitments is to reduce the carbon emissions associated with grocery packaging by 10% by reducing weight, increasing recycling rate and the recycled content of grocery packaging.





Policies that encourage a reduction in use phase emissions:

The **EU directive specifying emissions standards for new passenger vehicles** went into effect in April 2009. The directive demands fleet average vehicle emissions of 130 g CO_2/km. The target is being gradually phased in: it must be met by 65% of all new vehicles by 2012, 75% by 2013, 80% by 2014, and 100% by 2015. A target of 95 g CO_2/km is expected in 2020. Manufacturers pay a penalty for emissions in excess of the stated target. The directive specifies emissions limits for three weight classes (less than 1250 kg, 1250 kg to 1700 kg and more than 1700 kg) this has been extrapolated into a limit line with more stringent emissions targets for lighter vehicles in order to ensure that the fleet average target is achieved.

The **Fuel Duty** is a tax levied on motoring fuel and is currently charged at 58.19 p per litre for both diesel and unleaded petrol. Although the 2010 budget staggered the 3 p rise in the duty that was due for 2010 (due to the election), the former Chancellor remained committed to the fuel duty escalator that will see pump prices rise by inflation plus 1 p a litre, each year, between 2011 and 2014. The fuel duty is a lucrative source of revenue to the treasury and is not purely an environmental tax.

The **London Congestion Charge** is currently charged at £8 per weekday per vehicle to drive within the central London congestion charge zone. Hybrid, electric and alternative fuel cars are exempt from the charge. From January 2011 the charge will increase to £10 per day and the Greener Vehicle Discount (GDV) will be introduced. The GDV makes all Euro 5 standard petrol or diesel cars that emit less than 100 g CO_2/km exempt.

Voluntary eco-standards such as **BREEAM** give accreditation for the sustainability features of buildings. Building's are scored across a number of sustainability criteria. The materials category includes an assessment of the embodied life cycle impact of buildings but no specific targets are stated and the embodied energy in steel frames is typically ignored. Instead the emphasis is on use-phase savings. By contrast, the Australian Green Star rating system was revised in February 2010 in order to drive best practice steel production and fabrication and to encourage demanterialisation of steel in structural applications.

Actions and opportunities

We've seen in this report that we can significantly reduce the volume of liquid metal being cast to meet our current needs for metal service. We could reduce product weights by up to a third, and we could save a further quarter by avoiding manufacturing yield losses. This saving offers such a serious carbon abatement opportunity that it should be taken very seriously. Who could initiate change in this area?

Senior management throughout the supply chain of metals manufacturing companies could drive major change in liquid metal consumption:

- Many of the companies we visited had a poor understanding of their true yield performance, and even where data was known, we found managers could be reluctant to reveal it, even internally. Awareness and intelligent management of yield losses could be improved
- The liquid metals industry currently thinks of its products as the standard stock parts—sheets, plates, bars and rods—but these are intermediate products, not in the shape that their customers really require. There is significant opportunity for supply-chain collaboration to reduce total yield losses
- Although the objective of the Metal Diet is to reduce production of liquid metal, there is a major opportunity for liquid metals manufacturers to add value to their business by integrating downstream operations into their own activity, so converting all manufacturing 'new scrap' into 'home scrap' and thus internalising the motivation for yield improvement

Our **examination of policy** has shown that, under present policies, lightweighting and yield improvement will not be given due consideration across all steel and aluminium using sectors, despite the fact that these strategies represent substantial opportunity for emissions reductions. In order to address this imbalance government should:

- Recognise that material efficiency strategies (such as lightweighting and yield improvement) offer sizeable emissions savings but will not be encouraged by existing policies based on emissions pricing and so should be pursued independently
- Understand that due reward is not given to lightweighting in EU tailpipe emissions standards and that this legislation should be revised or that lightweighting of vehicles should be encouraged through other means
- Acknowledge that more must be done to encourage design teams in the construction sector to take advantage of the greater flexibility offered by modern building codes with respect to the lightweighting of buildings
- Foster better measurement and reporting of embodied carbon and create reporting standards where these do not exist
- Incorporate embodied carbon into emissions targets industries—such as the construction industry and the automotive industry—that are heavy users of emissions intensive metals
- Act as a coordinator to facilitate a supply chain approach to material efficiency, building on the success of the Courtauld commitment and supply chain initiatives in construction

In the definition of a **design specification**, arising from interaction between client/customer, designer, marketing, standards and other stakeholders, a significant impact on total metal requirements could be achieved by:

- Specification of lightweight design as a component of the earliest design/procurement brief
- Ensuring that design codes and load specifications accurately reflect the required in-service performance requirements
- Looking for alternative means to overcome design loads that arise before the final user service—for instance, where excess material is currently required to cope with construction, installation, production or distribution loads
- Applying life-cycle costing to capture full benefit of use-phase reductions and other co-benefits

Several of the studies in this report have shown opportunities for development of novel or improved **manufacturing technologies:**

- The process of blanking—cutting blanks from coils of strip metal—is among the most inefficient in the supply chain. Two opportunities to overcome this are to develop novel blanking processes to avoid the need for 'skeletons' between products, and to tessellate blanks more efficiently through intelligent and integrated optimisation over a wider product range
- Many sheet forming processes, particularly deep drawing, form final components but require significant excess material for blank-holding, which must be trimmed and scrapped. New processes could be developed to obviate this need
- The mismatch in geometry between intermediate products and final components might be reduced through a re-examination of the opportunities created by near-net-shape casting
- Unplanned losses of 1–2% are normal in many manufacturing operations, but these become significant for metal goods because the supply chain is long, with many sequential operations. Shorter supply chains, or better control could reduce them

To continue promoting and developing a **low metal diet,** the WellMet2050 team will:

- Work to raise awareness of the fact that in the energy intensive steel and aluminium sectors there is potentially a greater emission abatement opportunity from reducing liquid metal consumption than from energy efficiency in primary production
- Develop and demonstrate novel technologies for manufacturing nearer net shape, lightweight components
- Continue and expand our engagement with government to ensure that wider supply chain material efficiency becomes a core part of energy intensive industry policy making
- Develop specific case studies with consortium partners to demonstrate the metal saving opportunities possible through integration along the component supply chain
- Aim to provide a sound basis and guidance for setting future targets relating to embodied emissions in key product groups

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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

W1 Cullen J (2011) *Global flow of steel.* WellMet2050

W2 Cullen J (2011) *Global flow of aluminium.* WellMet2050

W3 Carruth M (2011) *Design optimization case study: food cans*

W4 Carruth M (2011) *Design optimization case study: deep sea linepipe*

W5 Carruth M (2011) *Design optimization case study: structural beams*

W6 Carruth M (2011) *Design optimization case study: car structures*

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W8 Milford R (2011) *The effects of yield losses on embodied CO_2 emissions in four case study metal products*

W9 Milford R (2011) *The global emissions case for lightweight design and process yield improvements*

W10 Patel S (2011) *The incentives for product lightweighting and yield improvement*

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