CIRP Annals - Manufacturing Technology 74 (2025) 895–919

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: https://www.editorialmanager.com/CIRP/default.aspx

Cut the scrap: Making more use of less metal

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ARTICLE INFO

Article history:
Available online 12 June 2025

Keywords:
Environment
Metal forming
Material efficiency

ABSTRACT

Action to cut emissions is likely to reduce production of the bulk metals. However, up to 80 % of steel and 90 % of aluminium made today are wasted in three forms of scrap: manufacturing scrap cut off in the supply chain, specification scrap from over-design and property scrap in which materials are under exploited. Innovations in product design and forming technology can reduce this scrap, but only if delivered in high-throughput processes, to overcome trade-offs with the economies of scale. The priority for innovation is to adapt tooling and controls in existing forming processes, not to attempt to replace them.

1. Introduction

It is now widely accepted that material efficiency is an essential component of industrial climate mitigation [25,116]. Cullen et al. [57,58] estimated that 31 % of global steel production and 39 % of aluminium production never provides service in a final product, but is cut off in the metals industries themselves, and in downstream component manufacture. Recent innovations such as the folding-shearing process [5,15,49] have demonstrated that well-targeted developments in production technology can have a significant impact in reducing total global volumes of this scrap, by innovation in component manufacture. One motivation for this paper is to explore developments that promise further reductions in manufacturing scrap and motivate new effort in the area. Manufacturing scrap is removed by cutting processes such as blanking, turning and milling, but arises from the limited geometrical capability of high-throughput forming processes, hence the focus of this paper is on forming technology. However, two further forms of scrap are equally important. Across many product groups, and most especially in commercial construction, many metal components are over-specified by design, and in service will never be loaded to their designed capacity. This motivates an equal search for opportunities to reduce *specification scrap*, in particular where the economies of scale in current production technologies inhibit production of better tailored component geometries. A third motivation is that in many components, metal is used well below the materials' limits of its strength, stiffness or other properties. This will be referred to as *property scrap*. The scope of the paper is to stimulate attention and review developments aiming to reduce all three of these forms of scrap.

Section 2 explores the extent to which zero-emissions production of the bulk metals can scale over the time by which climate mitigation must be implemented. The section points to a very high likelihood that supply will fall far short of demand, which prioritises action on the three forms of scrap. Section 3 characterises the sources of these three forms of scrap in a catalogue of representative component types. This leads to exploration in Section 4 of existing and emerging design and technology options to cut the scrap. However, as most such innovations run counter to existing customer, regulatory or economic incentives, Section 5 examines trade-offs between cutting the scrap and other goals in production. Section 6 concludes the paper with recommendations about the priorities for urgent innovation and longer-term research.

The paper's focus on these three forms of scrap is novel, but the motivation for reducing scrap sits in the context of many other approaches to reducing total metal demand. In order to draw attention to the opportunities for cutting the scrap, the paper does not attempt to survey opportunities for material substitution, product life-extension, repair and upgrade, re-use or recycling which are richly covered elsewhere for example [3,4,6,17,89,93,100,123,184,206,222]. The focus here is on cutting the scrap through innovations in design and forming technology.

2. Metal as a driver of global emissions

Global production of liquid metal drives a substantial fraction of all global greenhouse gas emissions. For most products, these 'upstream emissions' greatly exceed all impacts from downstream manufacturing so are the priority for metal-related research aiming to support zero-emissions production. The emissions intensity of liquid metal arises both from the chemistry of metal processing and from the combustion of fossil fuels to reach the required high process temperatures. But, as Fig. 1 demonstrates, it is the product of

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https://doi.org/10.1016/j.cirp.2025.04.013
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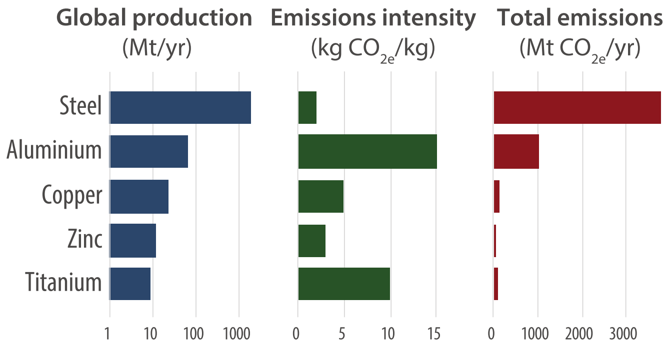

Fig. 1. Bar chart to show global production of the major metals, emissions intensity and total global emissions, in order to focus the priority of the paper on steel and aluminium. (Production data from [207], emissions data from [112,115,230]).

emissions intensity and scale that determines priorities for climate mitigation. While production of copper, zinc and titanium have higher emissions intensities than steel, the enormous scale of global demand for steel and aluminium prioritises these two metals above all others.

Global demand for steel and aluminium over the past century has grown strongly, as they are the foundation of so many products associated with economic development, in particular in products associated with construction, vehicles and industrial equipment. A country's demand reaches a peak during the most pronounced periods of economic growth, as for example in the rapid expansion of steel demand in China from 1990 to 2020. If economic growth in India and other developing nations were to follow a similar pattern, global steel demand would continue to grow, as illustrated in Fig. 2, with global aluminium demand growing similarly.

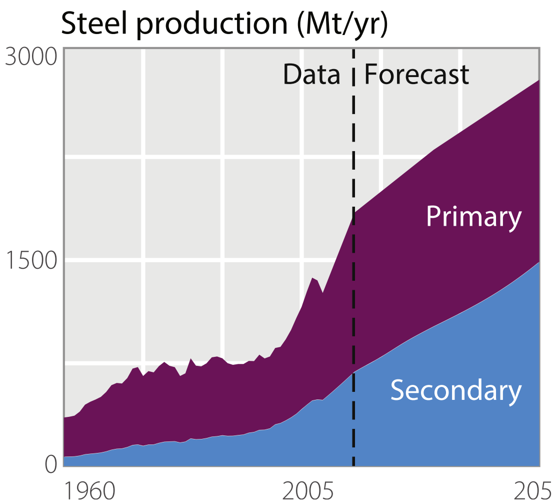

Fig. 2. Past and forecast global demand for steel assuming climate change is ignored. (Figure reproduced with permission from [6], with similar analysis in [214]. 'Primary' refers to production from ore, and 'Secondary' refers to production by recycling.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As well as showing forecast demand, the figure indicates the likely future supply of steel, split between production from iron ore and from recycled steel, assuming that climate concern has no influence on production. On average, steel-rich products last for 35−40 years, so with high collection rates, the supply of end-of-life steel lags total global output by a similar period. Steel is relatively easy to separate out of waste streams, because it is magnetic. Because of the energy benefit of recycling over primary production, steel has always been recovered and recycled at a high rate. Steel recycling dates back to earliest times, and the collection of end-of-life steel goods is so comprehensive that models based on the average lifespan of steel-intensive goods (for example [54,67]) can be used to forecast future scrap supply, and hence electric arc furnace steel production. As a result, Fig. 2 includes a prediction of future global steel recycling output, by shifting total global steel demand forwards by 35 years, the average lifespan of steel in service. Most future growth in total demand could be supplied by increasing global recycling, but if demand continues to grow as illustrated in the figure, primary steel production must continue at around today's levels until global stocks saturate and a 'closed-loop' is possible [139,163,173,213].

Fig. 2 assumes that demand for steel, and by analogy aluminium, will be unaffected by climate change. This is unlikely. Recent reports of the Intergovernmental Panel on Climate Change (IPCC) [117,118] attempt to quantify the risks of continued inaction, of which the greatest threat for humans is likely to be food insecurity. With continued inaction on climate, global average temperatures are likely to rise by a further 2 °C or more, which will reduce crop yields particularly near to the equator, creating a significant risk of global war over food shortages this century.

As a result, whether by proactive climate mitigation or in reaction to unmitigated warming, pathways of economic development will change and the forecast growth in steel output in Fig. 2 is unlikely.

In pursuit of international co-ordination of climate mitigation, the United Nations Framework Convention on Climate Change was agreed in 1992. However, despite extensive discussion, global greenhouse gas emissions have since risen by 50 %. In recent years, a growing number of countries have pledged, or made legally binding, a commitment to reach 'net zero' emissions in their own territories [69]. Rising awareness of the severity of the threat, is motivating new legal action to accelerate change, forcing re-valuations of financial investments, and motivating new customer behaviour all in pursuit of more rapid action to cut emissions.

The next section therefore reviews options to deliver a future supply of metal without emissions. Can new technological approaches deliver sufficient steel and aluminium to match the demand forecast of Fig. 2 with zero emissions by 2050?

2.1. *'Net zero' metal supply*

Fig. 3 presents the emissions intensity of primary Aluminium production compiled by the International Aluminium Institute.

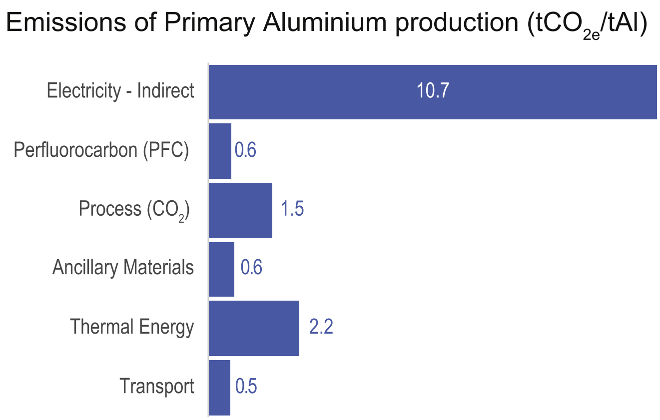

Fig. 3. Emissions of primary aluminium production [113].

Most emissions are associated with electricity generation, with the remainder arising from the consumption of graphite anodes and the use of sealing gases. Inert anodes (made from copper, nickel and iron and lasting up to thirty times longer than those of conventional graphite) have long been anticipated to address the first problem [174]. However, they have not been adopted widely, primarily because they lead to an increase of approximately 50 % in the electricity requirement of smelting. Despite this cost penalty, they may yet be deployed widely, particularly if all emissions are banned by health and safety regulation, but deployment will otherwise be slow.

The process of recycling aluminium involves melting and dilution, so itself releases no further emissions. However, it is difficult to separate alloying elements from molten aluminium. Unless end-of-life metal is sorted with much greater resolution than at present, it will remain difficult to recycle the purer wrought grades into wrought aluminium [82]. As a result, most aluminium recycling today is in reality 'down-cycling' into casting alloys [57]. Unless novel casting technologies are deployed to cope with higher silicon compositions [205] aluminium recycling will continue to require dilution with virgin material, thus process emissions to a process that could otherwise be emissions-free if powered by renewable electricity.

At best, by 2050, aluminium might be produced by either primary or secondary routes with zero emissions. As recycling requires much less electricity, it will be prioritised, motivating innovation in the control and separation of different alloys to increase quality. However, total output will be constrained by the industry's access to emissions-free electricity. As all other sectors seek to decarbonise, such electricity will become the primary energy for all economic activities and supply is likely to be short of demand. The consequences of this constraint will be explored below, after a survey of the options for 'net zero' steel production.

A hundred years of development has seen the global steel industry achieve astonishing improvements in energy efficiency, with best available technology now operating with energy inputs equal to just twice the chemical exergy in the bonds between iron and oxygen atoms in ore [6]. However, unlike the primary production of aluminium, the production of steel from ore depends on a reduction reaction, and when powered by coke as at present, this must necessarily lead to process emissions of carbon dioxide. As a result, global average primary production has an emissions intensity of around 2 tonnes of CO_2 per tonne of steel, and this figure cannot be reduced significantly with existing blast furnace technologies.

Because steel melts at a much higher temperature than aluminium, steel-recycling requires a more complex electric-arc furnace to create temperatures over 1500 °C and to burn off contaminants on scrap. However, the process is well established, and as its emissions are dominated by those of electricity generation, it could operate without emissions, provided pre-heating which is currently achieved by gas burners is electrified, and the consumption of carbon in anodes can be avoided.

For over two decades, the steel industry has looked for ways to produce primary steel without emissions, and this search has examined a wide range of options [48,212,223]. Two options receive most attention: applying carbon capture and storage technologies to blast furnaces or reducing iron ore using hydrogen.

Carbon Capture and Storage, which has been heavily marketed by the oil and gas industry (although they have not used any of their substantial recent profits to invest in it at scale [87]) requires two steps. Firstly, a pure stream of CO_2 must be separated from other exhaust gases, and this has been proved at many laboratories, although not scaled. Secondly, the resulting gas must be compressed and stored, and despite two decades of enthusiastic discussion, global capacity for such storage in 2024 has expanded to no more than 0.08 % of global greenhouse gas emissions [87]. Globally, only one small blast furnace has been linked to this technology, and the first public report on its performance, released in 2023 [14], demonstrates that in reality only 13.6 % of the emissions from steel production are captured and that seven years after it was inaugurated, the approach has not been replicated anywhere else. Furthermore, although the phrase 'Carbon Capture Utilisation and Storage' is used in marketing, global demand for carbon dioxide is so low (about 0.15 Gt CO_2/year mainly for making fertiliser [114]) that there is no significant opportunity for such utilisation to scale-up.

The second route to make steel from iron ore has therefore become the focus of the industry's hopes. Hydrogen reduction of iron ore eliminates the process emissions of conventional blast furnaces, and as the second stage of production occurs in a conventional electric arc furnace, apparently this opens a route to 'net zero' production [131]. This is attractive, has led to a demonstrator plant in Sweden [111], a high-growth company promoting the approach globally (H2 Green Steel) and it is now the focus of lobbying by the global trade association, World Steel [220].

Unlike natural gas, we do not have an abundant supply of hydrogen in nature. It must be manufactured, which could be achieved using carbon capture and storage, but the same problem of scale means this is unlikely. Instead, hope is being placed on 'green' hydrogen produced by electrolysis, which could be powered by emissions-free electricity.

Unfortunately, it takes a great deal of electricity to make hydrogen. As a result, hydrogen-reduced steel requires seven times more electricity per tonne of steel than recycling in a conventional electric arc furnace [111], and of today's global hydrogen production (largely used for the production of existing chemicals, despite the hopes of many other industries to use hydrogen for decarbonisation) just 0.3 % is made using emissions-free electricity [32, Fig. 6.] As a result, despite its technical promise, significant economic and deployment barriers limit the short-term feasibility of green hydrogen as a large-scale contributor to decarbonisation.

One final option to produce 'net zero' metals is to continue using existing emitting processes, but to 'negate' their climate impact by capturing an equivalent mass of carbon dioxide from the atmosphere using 'negative emissions technologies.' Despite their attraction to economic modellers, no such technology exists at scale today, and any implementation depends on both emissions-free electricity and carbon storage so can be discounted.

The result of this survey of technology options for producing the two metals without emissions is summarised in Figs. 4 and 5.

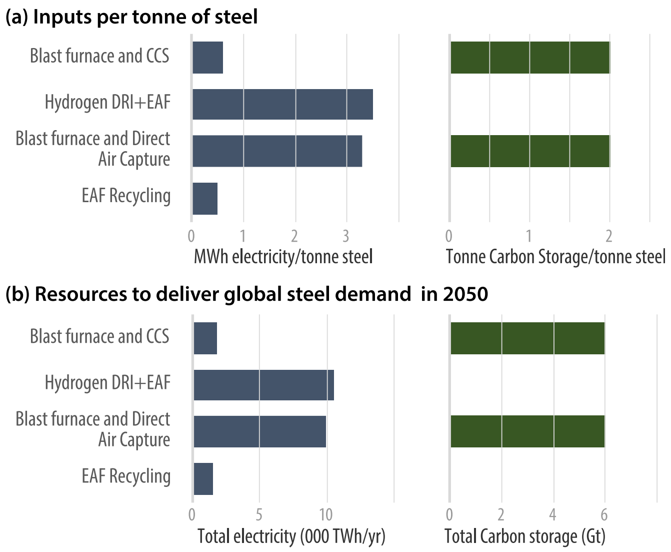

Fig. 4. The four major options for producing steel with zero emissions (a) showing input requirements per tonne of steel and (b) comparing demand for these inputs if steel demand grows according to the projection of Fig. 2. (Data from [126,132,137,221,225].).

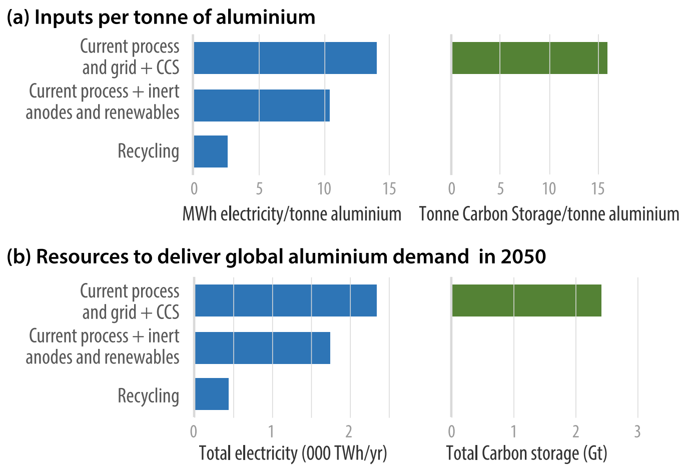

Fig. 5. Resources required to produce aluminium without emissions (a) intensity and (b) total resource required. (Data from [113,174]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

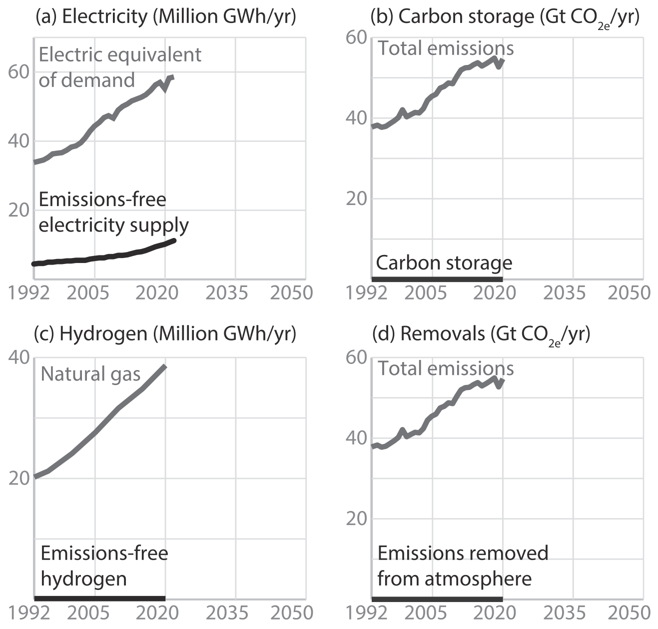

Fig. 6. Progress since 1992 in expanding the resources required to deliver climate mitigation. (adapted from [10] Fig. 8]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

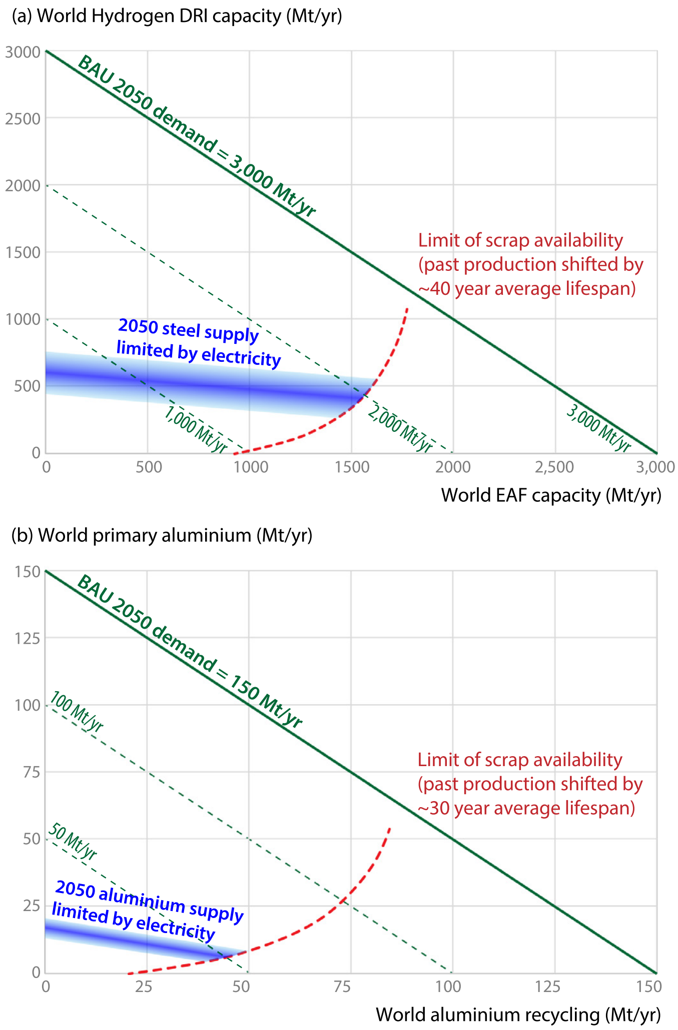

Fig. 7. Forecast zero-emissions supply of (a) steel and (b) aluminium constrained by access to emissions-free electricity and scrap, and trading off recycling with primary reduction. (Recreated from [11]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In response to these figures, it is tempting to believe that, given sufficient economic incentive, global supplies of emissions-free electricity and carbon storage could increase at a very high rate. Unfortunately, this is extremely unlikely. All past energy transitions, motivated by profit rather than the less commercial goal of eliminating unpriced emissions, have occurred at a linear, not exponential rate [168,192]. This is because, unlike commodity products such as mobile phones or clothing, energy infrastructure requires public consent in decisions on finance, location, access, environmental and community rights, safety and much more, all of which must be negotiated over a period of time. The total duration of large energy projects is at least double their construction time, and despite decades of optimism about the transition to a zero emissions future, there is no evidence of any non-linear growth in the required resources.

Fig. 6 shows that, since 198 countries signed the United Nations Framework Convention on Climate Change in 1992, emissions-free electricity supplies have grown, but energy demand is growing faster. Meanwhile carbon storage remains negligible, there is no significant supply of hydrogen, and no negative emissions technologies operate at any meaningful scale, so the only pathway to zero emissions is through use of emissions-free electricity.

The figure shows that supplies of emissions-free electricity have expanded at a relatively linear rate since 1960, with a small change of gradient around 2010 when wind power reached maturity (40 years after it was first commercialised.) Projecting forwards this suggests that by 2050 we may have 20–30 million GWh/year of emissions free electricity – perhaps a half of our total demand today (calculated by assuming that all energy-uses are electrified).

If the higher value of this forecast supply is shared across all emitting sectors, in proportion to their current emissions, the global steel industry can anticipate access to an additional 1.7–2.6 million GWh/yr by 2050, with the aluminium industry having around one tenth of that. If this is used firstly to power existing electric production with emissions-free electricity, and the rest is shared between new recycling capacity and new primary electrical production (using the conventional primary route with inert anodes for Aluminium, and for new steel, fuelling Direct Reduction of Iron with hydrogen made by electrolysis), Fig. 7 anticipates the likely production of the two metals in 2050.

Due to the electricity-intensity of hydrogen reduction for steel and of primary aluminium production, it is likely that both industries will prioritise recycling when faced with an energy constraint. However, the trade-off indicated in the figure will pivot on the quality of metal produced by the two routes. Recycling today is operated with only limited compositional control, and contamination of steel by copper in particular can lead to problems with hot shortening. This is a rich field for innovation, in managing the collection, separation and control of steel scrap [61], in purifying the steel melt [62], and in better sorting and separation of aluminium [56,156,174].

The evidence in this section has been presented at length to confirm that a substantial supply of steel and aluminium can be delivered by 2050 with zero emissions, but the supply will be well short of anticipated demand. This is due to constraints on the global supply of emissions-free electricity.

This analysis sets the agenda for the rest of the paper. How can developments in design and forming technology support the delivery of economic development and well-being while drawing on a much-reduced input of metal? The agenda has been set with reference to greenhouse gas emissions, but this focus on reducing demand also supports other environmental and political agendas, such as concern about criticality, resilience or air pollution which can also be ameliorated by reducing metal inputs [31,114].

2.2. Recycling and re-use to maximise the value of metal in history

Throughout human history, metals have been hard won from the Earth, their production requiring both fuel and controlled processing. The six metals that appear in the Bible (gold, silver, lead, tin, copper, and iron) were all produced and formed by specialist smiths named after their metal (goldsmiths, silversmiths etc.) who sought to create maximum benefit from their limited production. This led them to invent a wide range of craft-forming processes [34] with which they could produce jewellery, utensils, weapons and tools. Most metal was in the hands of a few rich people and drinking vessels (such as the gold cups of Ur [219]) were used to project power, the metal used extravagantly as an indicator of wealth. However, where the metal was used primarily for function, it would be combined with other materials (particularly wood for handles) to increase its application [59]. Many hand tools today continue to use wooden handles for their improved performance and the combination of metals with other materials remains familiar, for example in the use of steel reinforcing bars in concrete or in the use of tungsten carbide tips for cutting tools.

Early smiths used their metals in simple alloying combinations which facilitated recycling: a smith would know by inspection the content of a returned object, so could recycle it with confidence about the resulting properties, and such recycling has always been normal in the metal economy. Bentley et al. [30] reflect the difficulty of identifying whether archaeological objects are made of recycled or re-smelted iron or not but point to iron re-use in weapons welded of fragments (including the sword *Graisida* in the Icelandic *Gisla Saga*). They discuss stores of iron bars found in Syria and dated to ~700BC as evidence that re-shaping and welding old iron was common early practice. Woodward [218] similarly identifies re-use as the most likely form of recycling in pre-industrial times, pointing out that iron's longevity leads to an accumulation of stocks that could be reshaped, welded and repurposed more cheaply than the energy and time-intensive processes of making new iron in early blast furnaces.

Recycling has long been recognized as an energy-efficient metal production method. Recent advances, however, have introduced complexities, particularly in alloy control, highlighting trade-offs in modern recycling technologies. Recycling remains intrinsic to the metal economy today but recycling rates are lower than in earlier times, particularly for metals used fundamentally as alloying elements, or in electronics and magnets [89]. The energy benefit of recycling is such that all metals would be recycled in preference to new production, if their composition needed no adjustment. However, with the sophistication of scientific metallurgy, this has become difficult. In fact, for alloying metals used in low concentrations, price is now much less influential than the 'relative concentration ratio', as the determinant of recycling rates [75].

Apart from the use of precious metals as indicators of wealth, the early smiths understood how to deliver maximum value from their metal, thinking of value not just as price, but the extent of service that could be delivered for each kilogram of metal. The focus of this paper is on the bulk metals of steel and aluminium, and a key question will be about the efficiency of our use. Given a century's abundant supply of the two metals that has driven down their price to levels unimaginable to the early smiths, to what extent have we forgone their efficient thrift, and do we now use metal wastefully, without even noticing?

2.3. Opportunities for innovation in technology and business

The prices of commodity bulk metals remain low today, due to a combination of highly efficient production, global over-capacity and the absence of a cost or regulatory penalty on greenhouse gas emissions. As a result, end-users have little motivation to reduce their demand for new metal, particularly in countries with higher labour costs. For example, in the UK, commercial buildings constructed today, the horizontal sections of which dominate the mass of steel-framed buildings are typically over-specified by up to 100 %, even relative to already conservative safety codes [66,162]. This is because with steel prices around £600−800 per tonne, designers are primarily motivated to reduce expensive design time (charge rates for structural designers in the UK are typically around £600−800 per day) rather than reduce their demand for steel, particularly if their prices are set as a fixed percentage of total project cost. This motivation will naturally change when the supply constraint revealed in the previous section becomes apparent.

In parallel, the requirement that climate mitigation will lead to a reduction in the supply of the bulk metals runs counter to current political messaging and the lobbies of high-emitting incumbent industries.

Developing new approaches to reducing metal demand is a basis for exciting technological innovation and profitable business entrepreneurship. Many downstream sectors in construction and manufacturing are responding to customer pressure related to emissions with competitive pledges to reduce the embodied emissions of the products. This is demonstrated in the construction sector, for example where customers in the housing market are beginning to pay a green premium for lower embodied emissions homes [170], and in the pledges of the major automotive manufacturers [e.g., 120], who have followed on their commitment to electric powertrains by setting target dates for zero-emissions production of vehicles. In the absence of a sufficient supply of metal made without emissions, this motivates a search for approaches that can be deployed in the near term to reduce total metal inputs into production.

The innovation illustrated in Fig. 8 exemplifies this opportunity for profitable innovation. Motivated by the fact that automotive manufacturers on average discard as much sheet metal as they use when forming the body-in-white [106,107], the folding-shearing process, first revealed at the CIRP General Assembly in 2019, cuts the material utilisation of deep-drawing by around 30 % [5,15,57].

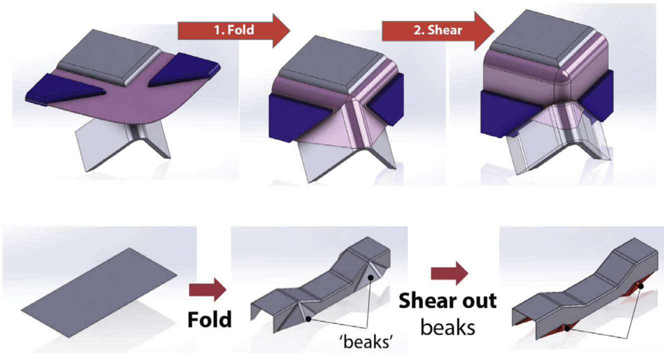

Fig. 8. The folding shearing process for forming deep-formed parts in sheet metal without use of a blank holder (adapted from [49]).

Most scrap created by the automotive industry does not occur after blanking but after deep-drawing. Flat sheet blanks are formed into the smooth curves of car components, by pressing between male and female dies. The perimeter of the blank must be gripped loosely in a blank-holder to avoid wrinkling, and material touched by the blank-holder is then trimmed off after forming. The innovation illustrated in Fig. 8 avoids the need for this blank-holder, by first forming the blank using origami-like folding to give it stiffness. The forming tools can then work against this internal stiffness to shape the part to final geometry, with minimum subsequent trim. The process is now being commercialised by Deep Form Limited, who have completed their first customer contracts and a first major venture-funding round.

Such opportunities for technical and commercial innovation, further elaborated in reports by the UK FIRES consortium [7,51] are furthermore gaining increasing recognition in national and international policy. The last two Assessment reports of the IPCC [25,74] have given specific attention to Material Efficiency, as a result of which, in their most recent assessment, the International Energy Agency [116] anticipates the greatest contribution to future industrial mitigation will come from reducing material demand. This is reinforced for example in the UK, with a new governmental division focused on Resource Efficiency and government recognition that new forms of innovation support will be required to support profitable entrepreneurship that reduces total resource demands.

By articulating the opportunity for such innovation in the use of steel and aluminium, this paper motivates a wider search for technical means to use less metal. Such innovations are both a defence against the inevitable supply shock that will occur as climate policies bite and reinforce nascent political and commercial interest in resource efficiency.

3. The space for innovation: Inefficiencies in metal use today

No agency exists to track the production and stock of metals in global use, so prioritising opportunities to reduce the three forms of scrap depends on reports, estimates and models assembled from multiple data sources. Fig. 9 is a first indicator of the priority applications where interventions that significantly reduce total global demand for the two metals will have most impact.

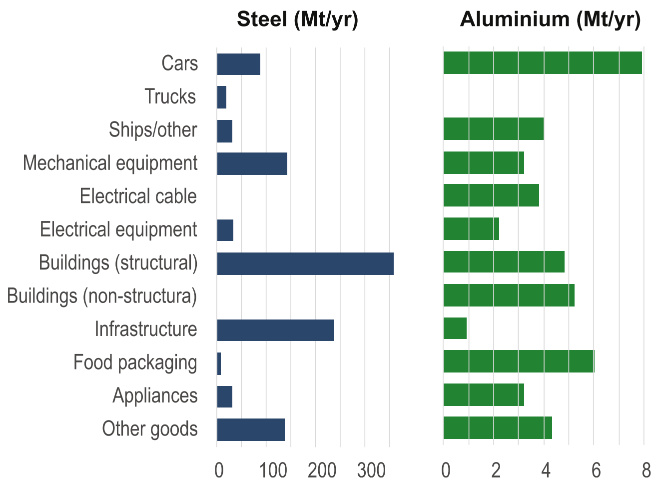

Fig. 9. End-use application sectors of global production of steel [58] and aluminium [57].

The figure clearly points to priority applications and exposes an artificial distinction between construction and manufacturing. All metal used in construction is subject to manufacturing effort (often called ‘fabrication’) between leaving the metals industry and entering service. The figure demonstrates that this is the highest priority sector for reducing demand, yet conventionally, manufacturing researchers give it little attention. For example, in its entire history, the International Academy of Production Engineering (CIRP) has never published a paper focused on the manufacturing of components for construction.

Fig. 9 points to priority sectors and indicates the economic activities responsible for metal demand. However, it points to products rather than components, so is insufficient for identifying opportunities for change in production processes and design.

In response, the rest of this section describes research completed during the preparation of this keynote paper to map the product categories of Fig. 9 into representative component types. This allows exploration of the sources and volumes of the three types of scrap introduced at the beginning of this paper, in the next three subsections, leading to results in Section 3.5 revealing the total scrap in current metal use. These results prioritise the opportunities for innovation in design and forming technologies that are the focus of the rest of the paper.

3.1. A catalogue of metal components

In order to identify the major component forms in which steel and aluminium are used, representative products were chosen for each of the end-use sectors in Fig. 9. Detailed designs/bills-of-materials were found for each, often in the literature of life-cycle analysis, as follows:

- Construction [57,58,161]
- Cars and light commercial vehicles [63,186,198,200,216]
- Trucks and buses [103]
- Airplanes [233]
- Trains [44]
- Ships [72,121]
- Industrial equipment. This sector is the least well understood. Two statistical sources estimate sector composition [71,197] but there is no published breakdown of product types, let alone components. Instead, an analysis of the component mix in end-of-life industrial goods, has been used as a proxy for better data [53].
- Cans for food and drink [64,152]
- Shipping containers [86,169]
- Cookers and ovens [133]
- Refrigerators and freezers [70,224]
- Washing machines [1,231]
- Dishwashing machines [176]
- Air conditioners [26,124,134]

Products for which no analysis could be found were treated as having the same breakdown as the most similar option in the above list. The results are therefore subject to substantial uncertainty, which is estimated at ±50 %, but could be higher.

Using these sources, major components were identified and classified by mass. The classification is subjective, but was largely determined by manufacturing route, for example differentiating sheet, forged and cast components, and within the sheet classification, separating component types by complexity, from flat through bent to stretched to deep-drawn. The three forms of long-product in the catalogue (Sections, Bar & Wire, Welded tube) may be delivered by various process routes, but have distinct supply chains and are clearly separable from each other.

The mass fraction of these components within the representative products, was then scaled by global production volumes, and reconciled to create for the first time a catalogue of the applications of steel and aluminium by component. This is summarised in Fig. 10, with full details of the analysis in the accompanying paper [166].

Fig. 11 presents the bottom row of Fig. 10 as a histogram to prioritise component forms by mass for the two materials.

The figure demonstrates that for steel, the four dominant component types are the sections and reinforcing bars of construction, and the simplest uses of sheet and plate, where metal is simply cut out and used flat, or bent to shape. These applications have attracted very little recent research attention, so are ripe for innovation. Aluminium is also used extensively in construction, in particular with bent sheets used in cladding and ducting, and extrusions used for window frames and curtain walls. However, the dominant applications of aluminium are in vehicle manufacture as sheet, and in equipment manufacture as extrusions and wires.

Armed with this new insight into global use of the two most emitting metals, it is now possible to explore and quantify creation of the three forms of scrap identified in Section 1.

3.2. Manufacturing scrap: Metal cut off along the supply chain

The evolution of scrap reduction practices spans historical insights and cutting-edge innovations. This subsection connects these developments, illustrating the continuity of efforts to minimize waste.

Manufacturers in the aerospace sector often refer to the ‘buy-to-fly’ ratio as a measure of how much of their purchased metal eventually takes off in an aircraft. This same measure applies to virtually all metal components, even cast ones, where runners and risers must be trimmed, even if the whole surface is not machined. And further back along the supply chain, within the primary metals industry itself, metal is trimmed of the edges of slabs and bars, or as part of early rolling processes, or when errors or delays in production lead to inadequate product quality.

Most manufacturing scrap is collected for recycling, so not lost. In later stages of the supply chain, or in batch-operated machining shops for example, the scrap is often not sorted carefully by alloy, so can only be downcycled to lower quality. In upstream operations (such as trimming coil edges during flat rolling) or high-volume downstream operations (such as blanking or trimming in automotive press lines) the manufacturing scrap may be sorted on collection, but

Proportions of final metal used in each product, by component (rounded by nearest %, or 0.1% for proportions less than 0.5%)	Catalogue - steel										Catalogue - aluminum								Product proportions		2023 use by product (Mt)	
	Flat - cut and joined	Bent sheet	Stretched-embossed	Deep-drawn	Forged	Extruded	Cast	Sections	Bar & wire	Pipe	Flat - cut and joined	Bent sheet	Stretched-embossed	Deep-drawn	Forged	Extruded	Cast	Bar & wire	Steel 100%	Alum. 100%	Steel 1309	Alum. 70.5
Construction																			**55%**	**22%**	**717**	**15.6**
Buildings	0.3%	12%			0.3%	1%	0.3%	6%	12%	1%		10%				10%	0.2%	0.1%	33%	20%	431	14.3
Infrastructure		4%				0.4%	2%	3%	11%	2%		1%				1%	0.0%	0.0%	22%	2%	286	1.3
Vehicles																			**13%**	**32%**	**167**	**22.4**
Cars				3%	1.4%		0.4%							3%	0.8%	1.8%	11%		5%	16%	64	11.3
Light commercial vans				2%	1.1%		0.3%							2%	0.7%	1.5%	9.0%		4%	14%	50	9.6
Trucks and buses	1%	0.2%		0.1%	0.8%	0.0%	0.4%							0.3%		1%			2%	2%	30	1.1
Airplanes												0.1%			0.0%	0.2%	0.0%		0%	0.3%	0	0.2
Trains					0.0%							0.2%							0%	0.2%	1	0.1
Ships	1%							0.2%			0.1%								1%	0.1%	11	0.1
Other vehicles	0.3%	0.1%		0.0%	0.3%	0.0%	0.2%							0.0%		0.0%			1%	0%	12	0.0
Industrial equipment																			**16%**	**19%**	**213**	**13.2**
Mechanical	5%	2%				0%	1%	0%	3%	2%						6%			13%	6%	172	4.6
Electrical	2%	1%							0%							4%		8%	3%	12%	40	8.6
Metal goods																			**16%**	**27%**	**213**	**19.3**
Packaging total																			*2%*	*14%*	20	9.6
Food and drink cans			0.2%	1%									1%	4%					1%	5%	*9*	*3.9*
Shipping containers		0.6%						0.2%											1%	0%	11	
Foil and other											8%								0%	8%	0	5.8
Domestic appliances total																			*2%*	*2%*	*30*	*1.2*
Cookers and ovens			1%				0.2%						0.3%			0.0%	0.1%		1.0%	0.4%	13	0.3
Refrigerators and freezers			0.2%				0.2%						0.1%			0.3%			0.5%	0.4%	6	0.3
Washing machines		0.0%	0.5%				0.0%										1%		0.5%	0.5%	7	0.4
Dishwashing machines			0.0%	0.2%													0.1%		0.2%	0.1%	3	0.1
Air conditioners		0.0%	0.1%				0.0%									0.1%			0.1%	0.1%	1	0.1
Other metal goods	1%	3%	0%	1%	0.6%	0.2%	1%	1%	4%	1%	1%	1%	0%	1%	0.2%	4%	2.8%	1%	*12%*	*12%*	*162*	*8.5*
Component proportions	10%	23%	2%	7%	5%	2%	6%	10%	30%	6%	9%	12%	2%	11%	2%	30%	23%	9%				
2023 use by component (Mt)	134	297	27	95	60	26	74	130	389	78	7	9	1	8	1	21	17	7				

Fig. 10. Catalogue of global steel and aluminium use by component type rounded to nearest 1 % (0.1 % for values less than 0.5 %) [166].

even if this is apparently a contribution to the goal of a 'circular economy' it would always save energy to avoid creating the scrap in the first place, than to recycle it [108]. As a result, all such manufacturing scrap cut off after first casting leads to increased embodied emissions in final components, as most emissions arise from the initial production of liquid metal, whether from ore or scrap.

Global estimates of manufacturing scrap in the metals industries, up to the delivery of standard intermediate products (bars, coils or sections for example) are given in [57,58] which also gives estimates for manufacturing and fabrication scrap in downstream supply chains.

To refine these downstream estimates, a series of case studies of part fabrication routes to estimate manufacturing scrap rates for each component were conducted [11]. The case studies built on expert reports, interviews and academic studies leading to supply chain analyses four of which are illustrated in Fig. 12, showing manufacturing scrap rates at every process stage.

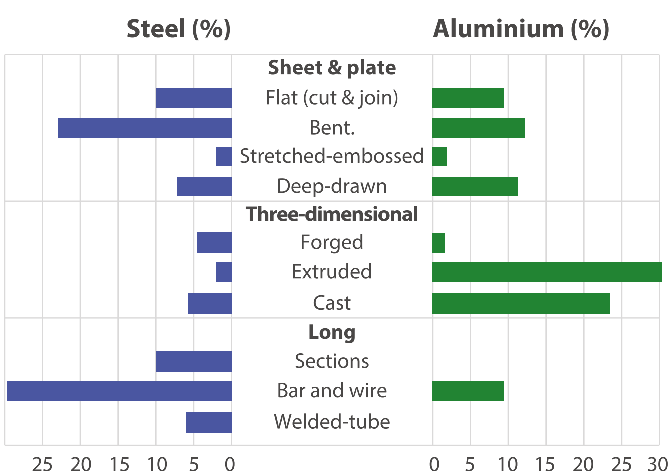

Fig. 11. Component catalogue of global steel and aluminium use and corresponding metal use (from [166]).

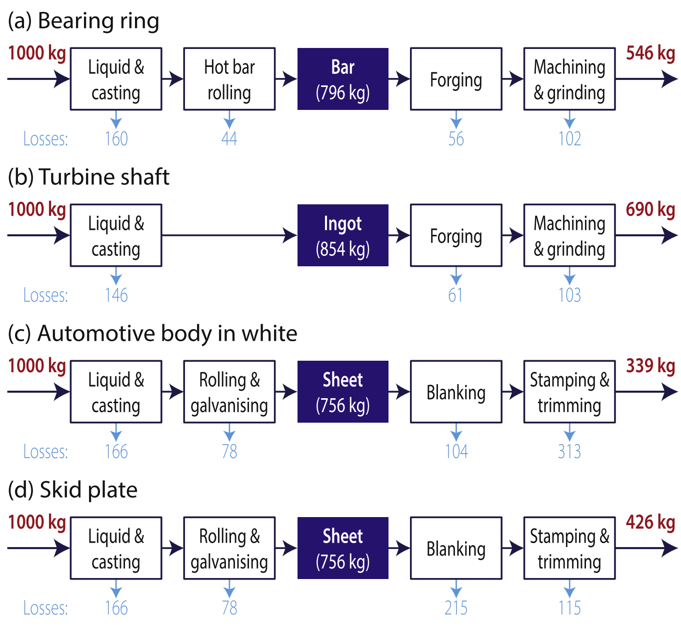

Fig. 12. Example supply-chain analyses of manufacturing scrap for (a) an outer ring of a bearing [211], (b) drive shaft of a wind turbine [217], (c) a case study automotive body in white [106] and (d) a skid plate [96]. The data has been normalised to a fixed input of one tonne of liquid metal.

The manufacturing scrap rates revealed by the study are summarised in Table 1.

Table 1
Manufacturing scrap rates for major processes (after [11]).

Process steps		**Steel**	**Aluminium**
Liquid	Ore/scrap to refined liquid metal	13 %	14 %
Casting	Slab/bloom/billet casting	4 %	9 %
	Foundry casting of products	34 %	33 %
Hot rolling	Section rolling	10 %	
	Rod and bar rolling	6 %	
	Plate rolling	10 %	15 %
	hot strip mill	5 %	15 %
Cold rolling/ welding	Seamless tube	8 %	
	Welded pipe	6 %	
	Cold rolling including coating	6 %	18 %
Cutting/ blanking	Cutting sections/rebar to length	5 %	
	Cutting bar or rod to shape	12 %	
	Cutting flat plate or blanking sheet	22 %	
	Cutting pipe to length	5 %	
Shaping	Stretch-embossing (crash forming)	10 %	
	Deep-drawing and trimming	28 %	
	Forging	24 %	
	Extrusion/drawing	24 %	
Machining	Cutting parts from bar and forgings	40 %	

The direct causes of these manufacturing scrap rates include:

- Casting defects, including porosity and internal stress.
- Removing free surfaces whose geometry or properties have been uncontrolled during thermomechanical processing.
- Removing material where insufficiently controlled temperature, strain or strain-rate histories has created variations in microstructure.
- Geometric inaccuracy or inadequate surface quality from net shape forming processes.
- Limits to formability, or high tooling costs, by which forming processes cannot deliver target geometries without machining.
- Problems of tessellation when dividing an intermediate stock product (such as a long section or coil of flat strip) into component blanks.
- Process imperfections and errors,
- Out of tolerance parts made during setup and switchover operations.

Apart from unintended process errors, most of this scrap is a function of the economies of scale, which lead to a trade-off between material, processing and labour costs.

Some scrap is a function of process limits, and this is illustrated in Fig. 13. During hot forming processes, the initial grain distribution of casting develops, with grains growing at elevated temperatures, and reducing with deformation. Due to the distribution of temperature

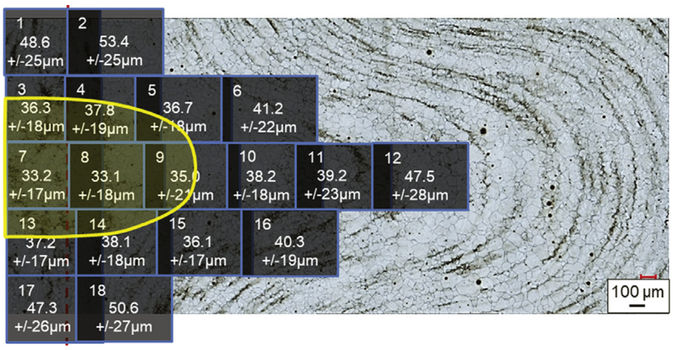

Fig. 13. Grain size variation today requires that only the inner envelope of this forged gear-wheel blank, has the required uniform microstructure, so the rest must be cut away as manufacturing scrap. In this case, product specifications required grain size < 35μm as indicated by the yellow border [21]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and strain rates across the geometry of three-dimensional workpieces, it is often impossible to deliver uniform properties across component sections, as required by high-performance applications, such as toothed gears.

If cost were no object, manufacturing scrap could largely be eliminated. However, in economic reality, the cost benefit of high-volume production mitigates towards averaged specification for intermediate goods. For example, few customers require uniform rectangular blanks of sheet metal, so purchasing long coils of constant width and thickness and then cutting them to shape is a compromise of cost against the waste of subsequent blanking and trimming, although variable width strip casting has been demonstrated [147]. As a result, due to the process downtime and relatively high labour costs implied by frequent switchovers between different parts, the supply chains for steel and aluminium components currently produce manufacturing scrap in order to save money.

One of the motivations cited by developers of additive manufacturing technologies is that they might reduce manufacturing scrap. However, producing powder typically leads to a substantial increase in energy input [19] and many approaches also have high manufacturing scrap, as the powder must be recycled by melting even if it has not been fused into a product. Typical material efficiency of powder based additive manufacturing processes is around 50 % at best, and although direct deposition or welding techniques may improve the yield from primary liquid metal to final component, the overall efficiency of this approach is not yet known [78]. Furthermore, these methods are unlikely to scale from the low-volume, small parts made today (<1 kg) to approach the global annual output of the steel industry (>1,800 million tonnes per year). As a result, while additive manufacturing has many other attractions (for example to make the tooling for metal forming [94] or for specific lightweight components in aerospace [33]) it is unlikely to have a significant impact on global rates of aluminium and steel manufacturing scrap.

Instead, the later sections of the paper will examine opportunities for innovation and development in forming technologies to lead to scalable reductions in manufacturing scrap. However, before reviewing those opportunities, the next two sections target the two other forms of scrap that motivate the paper.

3.3. *Specification scrap: Over-specified components and products*

Two studies have shown that the strength of steel-sections in a representative selection of commercial buildings in the UK is typically over-specified by a factor of two relative to the governing safety standards of the Eurocodes [66,162,196]. Interviews with the designers responsible for these buildings revealed two fundamental drivers of this specification scrap. Firstly, project costs are reduced when excess material use reduces labour requirements, for example in the design of joints, or in on-site management, or leads to price discounts for volume purchasing. Secondly designers specify excess material to cope with uncertainties, which may include uncertainty about peak loads, uncertain material specifications, uncertain on-site practices during construction, or the possibility that clients will change the design brief late in the project cycle. Cost saving and the response to uncertainty are the two fundamental drivers of specification scrap.

In the absence of co-ordinated analyses of specification scrap across global use of the two metals, a set of representative case-studies has been identified leading to the estimated ranges of over-specification reported in Table 2, which also references the source from which the estimate was made.

The estimates in the table, are subject to high uncertainty, and cannot differentiate steel from aluminium. However, they provide a first stimulus to recognise the existence of specification scrap and motivate action. This primarily requires reducing the uncertainties which motivate designers to use excess material as they seek to reduce total costs over product lifespans.

A limited literature (such as [52]) has examined the forms of uncertainty that drive this specification scrap suggesting that the main causes are:

Table 2
Estimated ranges of over-specification for each component considered in Fig. 11 (adapted from [11]).

Component type	Range of over-specific-ation	Case studies
Flat, cut and joined	1.1–2.5	Container ship FoS=1.3 for ultimate stress [157]
Bent sheet	1.1–2.5	FoS=1.4 for agricultural trailer [202]
Stretched/ embossed	1.1–2.5	*Assumed the same as flat or bent sheet.*
Deep-drawn	1.5–5.0	Chemical engineering evaporator [190]
Forged	1.5–3.0	Analyses of drive shafts [39,229].
Extruded	1.2–2.0	Curtain wall structure under wind load [18]
Cast	1.5–5.0	*Assumed 50 % higher than forgings.*
Sections	1.5–2.5	Steel-framed buildings [66,162], cantilevered tube [229].
Bar & wire	1.1–1.5	Currently recommended for re-bar in the UK [27]
Welded tube	2.0–3.0	Offshore structures FoS~2 [195], line pipe [175], FoS=3 crash-structures [40,159]

- variability in material properties or unreliable material characterisation.
- uncertainty about the loading that a product may experience during planned or unplanned use. This includes the possibility of stress localisation under concentrated loads.
- excess loading during crash or other unwanted events, or as determined by legacy regulations.
- requirements to meet higher loads during installation than in service, for example as occurs when J-lay sub-sea pipes are bent from vertical to horizontal during laying.
- uncertainty about design life and function, for example with road infrastructure designed today for two-hundred years, with no grounds for anticipating requirements so far ahead
- uncertain manufacturing or construction accuracy.
- uncertainty about client requests for late design changes leading to built-in redundancy.
- excessive 'futureproofing' including the use of platform designs, in which redundancy is added to create future flexibility.
- 'garden-fencing' which aims to lock consumers into a specific product ecosystem, particularly through uniquely packaged consumables [85]

Over-specification driven by these causes may further become encoded in product standards, inhibiting moves towards greater material efficiency. An additional source of specification scrap occurs when consumer preferences and fashion trends created by marketing campaigns lead to product size increases beyond what is essential to deliver a product function. Average European cars now weigh more than twelve times the passengers inside them. This multiple is even higher in the USA, and Fig. 14 shows that weight increases in new cars sold in the USA since 1980 have largely eclipsed the benefits of improvements in energy efficiency.

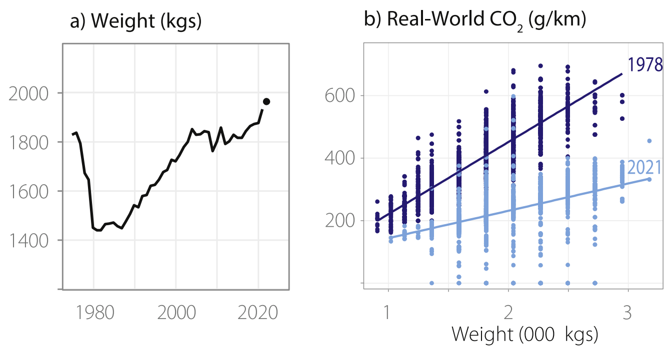

Fig. 14. Example of specification scrap from consumer preferences: (a) average weight of new vehicles in the USA fell during the 1979 oil crisis but has since risen 50 % so (b) improvements in energy efficiency have largely been absorbed by increased vehicle size [110].

The quantification of this last form of specification scrap depends on a qualitative judgement about what size of car is 'essential.' It is justified in this context because the shortage of metal supply forecast in the previous section will drive up prices and therefore motivate a rapid switch to smaller vehicles. With that motivation, today's larger vehicles will be seen as carrying significant volumes of specification scrap.

3.4. *Property scrap: under-exploited metal properties*

For a century, metallurgists have sought innovations aiming to increase the yield stress of metals, yet many of the designs listed in table 1 are limited by stiffness not strength. As a result, the strength capacity of most components is under-exploited, and in the language of this paper, this is an example of *property scrap*. Goldsmiths throughout history have been aware that their metal is primarily important because of its appearance, so have developed techniques for gilding, plating and veneering to coat the surfaces of cheaper metal, which provide strength and stiffness, leaving their precious gold to do only what it does best, to shine. As future supplies of energy-intensive steel and aluminium become restricted, managers of the supply chains of metal-intensive goods will similarly seek opportunities to exploit the properties of metal more fully, with modified design or material combinations selected in order to deliver less critical functions.

The fact that property scrap exists and is substantial is obvious when considering a simply supported beam loaded uniformly. The bending moment is at its maximum value only at mid-span, so everywhere else, the beam has excess moment capacity. But additionally, the longitudinal stress in the beam is at a maximum only at the furthest distances from the neutral axis, at upper and lower surfaces. Almost all the metal in the beam is loaded well below its yield capacity, and for a typical design, in excess of 50 % of the mass of the beam is property scrap – it could have been avoided by a different design which converted external loading to internal stress more efficiently.

Fig. 15 illustrates four more detailed case studies of property scrap. The red shading indicates the relatively small fraction of three components where, at the limit of service loading, the metal's limiting property is exploited fully. All the material not coloured red, is underexploited, so contributes to property scrap.

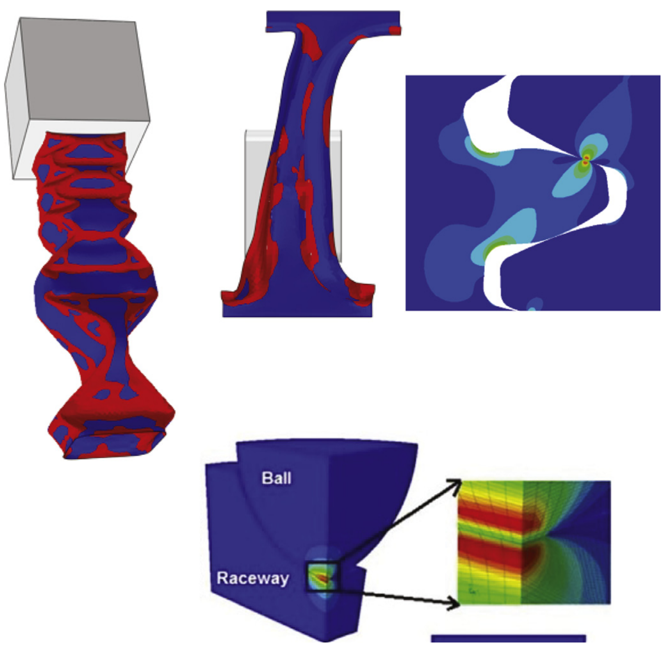

Fig. 15. Property scrap in components under service loads demonstrated by the blue (under-exploited) regions in contrast to the red (fully-exploited) regions for (a) a crashbox (53 %) (b) a B-pillar (77 %) (c) a gear wheel (68 %) and (d) a roller bearing (86 %). (Adapted from [11]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The examples of Fig. 15 are illustrative. Many components will be subject to multiple loading cases, for example with the B-pillar in Fig. 15b required to provide stiffness in normal driving, and energy absorption during front, side and non-perpendicular crash impacts. However, except in the case of wires or rods loaded in uniaxial tension and limited solely by strength (this is largely the case for reinforcing bars in composite concrete construction, which are a rare example of metal components designed with very low property scrap) it is very difficult to design metal components with full property exploitation.

Building on component case studies of the type illustrated in Fig. 15 and using finite element analysis to predict the stresses, strains and strain rates occurring during loading, Table 3 provides an estimate of property scrap rates across the catalogue of ten component types examined in this paper.

Table 3
vol fraction of the under-exploited properties of steel and/or aluminium components subject to their design loads (adapted from [11]).

Component type	Estimated property scrap	Range (%)	Case studies
Flat, cut and joined	60	40–80	Representative of components loaded largely in bending
Bent sheet	60	40–80	Mainly sections/corrugations in bending
Stretched/ embossed	90	60–95	Based on finite element analysis of case-study part
Deep-drawn	60	50–80	Based on finite element analysis of case-study part
Forged	50	30–80	Based on finite element analysis of case-study part & model of shaft in torsion
Extruded	60	40–80	Mainly loaded in bending
Cast	50	30–80	Same as forged
Sections	60	40–80	Analytical model of bending
Bar & wire	20	10–50	Largely loaded uniaxially
Welded tube	60	40–80	Mainly loaded in bending

The estimates in the table suggest that the only components which would avoid property scrap would be those loaded uniformly and statically throughout their volume. In contrast, property scrap is created when:

- a component is loaded in bending, in which case only the material furthest from the neutral axis can be exploited up to the limit of its strength. This implies that property scrap is inevitable for sheet or shell-like components apart from pressure vessels.
- buckling occurs (as in a crash structure) in which case deformation is localised to small regions.
- loading is localised, acting over only a fraction of a component surface, causing internal stress distribution.
- loading is dynamic in which case the capacity of most properties is exploited only at peak load.

The focus of the discussion above has largely been on the properties of yield stress, ductility and stiffness. In fact metal has many other properties which could be exploited to some extent in different applications. Two previous keynote papers have described the origins of these properties and options to control them [8,203], and potentially one means to reduce property scrap as discussed in [8] would be to tailor properties across a component, to match loading conditions. However, it is unlikely that this would have a significant impact on the energy or emissions of component production, which are more strongly influenced by upstream production of metal from ore, than by downstream processes of property adjustment.

3.5. Under-exploitation of metal

The results of sections 3.2-3.4 can now be combined to estimate the overall efficiency of the use of steel and aluminium today. For each component type in the catalogue of Fig. 11, Fig. 16 (adapted from the results given in [11]) brings together the estimates of tables 1–3 to calculate an estimate of the volume fraction of each type of scrap. The product of these three inefficiencies leads to an overall figure for the fraction of liquid metal that is under-exploited due to scrap in manufacturing, specification and properties. For example, using the data in Fig. 10, tables 1, 2 and 3, reveals that 60Mt of steel was delivered in forged components in 2023. With an average yield of 31 %, this required production of 194 Mt of liquid steel, leading to 134 Mt of manufacturing scrap. With an average over-specification of factor 2 and property scrap of 50 %, this leads to 15 Mt of essential use. The data of Fig. 16 is subject to the high levels of uncertainty indicated in tables 1–3, and the mid-range values are used to create a graphical representation of scrap in Fig. 17.

In the bottom row of Fig. 16, the scrap fraction for each component provides an overall estimate that approximately 80 % of steel and 90 % of aluminium is scrap, according to the definitions of this paper. This is the target for reducing metal demand to meet the shortfall revealed by Fig. 7, and can be approached with changed component design and forming processes.

Figs. 16 and 17 are highly motivating. Section 2 has reviewed the options to produce new steel and aluminium in a near-term zero-emissions future and demonstrated that the supply will be far short of demand if emissions are cut at the rate required to achieve climate safety. If production technologists and product designers do not respond, this will lead to a loss of economic welfare and restraint on economic development.

In contrast, the results of Figs. 16 and 17 suggest that because the bulk metals have been produced at such scale and with such cost-efficiency, our use of them has expanded over the past century with a

	Steel										Aluminium									
	2023 use		Manufacturing scrap		Specification scrap		Property scrap		Essential use		2023 use		Manufacturing scrap		Specification scrap		Property scrap		Essential use	
All masses in Mt/yr	liquid	*final*	Mass	%	Mass	%	Mass	%	Mass	%	liquid	*final*	Mass	%	Mass	%	Mass	%	Mass	%
Flat - cut and joined	231	134	97	*42*	43	*19*	55	*24*	36	*15*	13.4	6.8	6.6	*49*	2.2	*17*	2.8	*21*	1.8	*14*
Bent sheet	540	297	243	*45*	96	*18*	121	*22*	79	*15*	21.4	9.0	12.4	*58*	2.9	*14*	3.7	*17*	2.4	*11*
Stretched-embossed	55	27	28	*51*	20	*36*	5	*9*	2	*3*	2.6	1.0	1.6	*62*	0.7	*28*	0.2	*7*	0.1	*3*
Deep-drawn	244	95	149	*61*	56	*23*	26	*11*	13	*5*	26.7	8.0	18.7	*70*	4.7	*18*	2.2	*8*	1.1	*4*
Forged	194	60	134	*69*	23	*12*	23	*12*	15	*8*										
Extruded	38	26	12	*31*	8	*22*	11	*28*	7	*18*	40.4	21.0	19.4	*48*	6.8	*17*	8.6	*21*	5.6	*14*
Cast	130	74	56	*43*	38	*29*	24	*18*	12	*10*	29.3	17.0	12.3	*42*	8.7	*30*	5.5	*19*	2.8	*10*
Sections	183	130	53	*29*	52	*29*	48	*26*	30	*16*										
Bar & wire	526	389	137	*26*	9	*2*	109	*21*	271	*51*	12.9	6.7	6.2	*48*	0.2	*1*	1.9	*15*	4.7	*36*
Pipe	111	78	33	*30*	42	*38*	23	*21*	12	*11*										
Totals / *average*	2251	1310	941	*42*	389	*17*	445	*20*	476	*21*	147	70	77	*53*	26	*18*	25	*17*	18	*13*

Fig. 16. Global steel and aluminium scrap for the catalogue of components, for each form of scrap separately, and then aggregated (adapted from [11]).

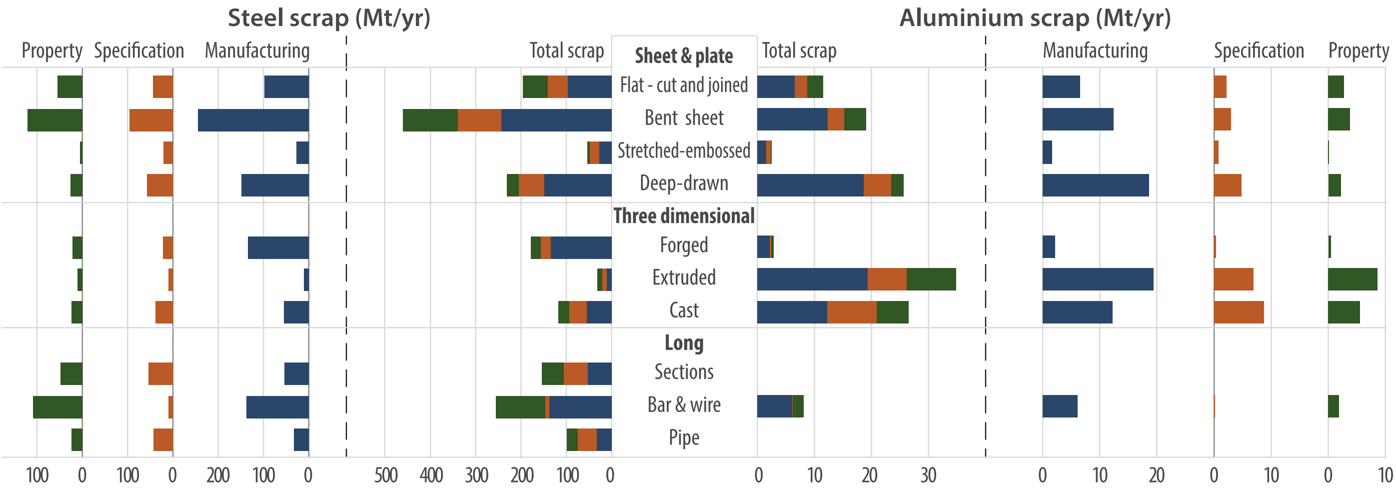

Fig. 17. Summary of the three forms of scrap for (a) steel and (b) aluminium. (n.b uncertainty for specification and property scrap at least ±50 %).

careless wastefulness of surprising scale. It is academic and impossible to ask what total fraction of the high volumes of scrap revealed in the figure could be avoided. Instead, the clear conclusion of this section is that manufacturing researchers can make an urgent and vital contribution to global action on climate change by targeting the three forms of scrap and exploiting the opportunities for technical and business innovation motivated by the figure. The next section of the paper aims to inform the search for these opportunities.

4. Design and manufacturing innovation to cut the scrap

Established design methods can be applied to target all three forms of scrap, without requiring innovation in production processes. In some cases, this may only require giving higher priority to efficient material use over other business considerations, or it may be linked to innovative production processes. However, the target of this paper is to reduce global demand for the two bulk metals, so even if a process such as additive manufacturing might allow material optimisation for a single component, this will have negligible impact on global demand due to the slow throughput of such novel processes. Therefore, having surveyed the opportunities for optimal design in sub-Section 4.1, Sections 4.2-4.4 in turn examine opportunities for cutting the three forms of scrap with high-throughput bulk-forming processes.

4.1. Optimal design methods to cut scrap

Michell [20,154] established the subject of optimal design by publishing his famous design rules for minimum mass pin-jointed trusses. He encoded these rules in analytical equations based on orthogonal intersections of tension and compression members. The resulting designs are theoretically perfect, but unrealisable as, in the limit, they require an infinite number of infinitely thin members. Discrete approaches have subsequently been developed by Prager and others, and exploration of Michell truss designs are still providing new insights into structural optimisation [19,98].

Michell's analytical method can be applied only to a limited set of geometries, boundary conditions and loading scenarios, so interest in optimal design studies has turned towards numerical algorithms.

The ensuing field of structural optimisation combines mechanics, variational calculus and mathematical programming to optimise material use or other performance objectives [29]. The resulting algorithms can be classified broadly into the three types of Fig. 18, focused on sizing of known elements of a structure, variation of an assumed shape, or topology optimisation within a defined domain.

Software to deliver such optimisation has matured over 40 years and is now used to determine efficient topologies and sizing for diverse applications, material systems and loading conditions. In the classical problem, boundary conditions and loading are defined for a body occupying a given domain. In an iterative procedure, material is

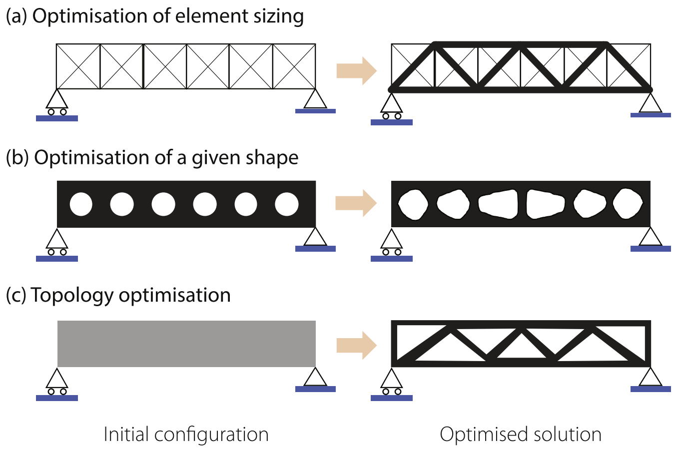

Fig. 18. Three approaches to truss optimisation (adapted from [29]).

placed or removed from locations within the domain until a sufficiently optimal structure is identified – typically by examining design variations in FEA (see example in Fig. 19). Multifunctional structures can also be optimised by defining suitable objective functions. More recently, machine learning has been used to reduce the computational effort normally required for topology optimisation [109,171] and to expand the range of design options through Generative Design [187].

Manufacturing of products designed with such software requires significant geometrical process flexibility so has been approached

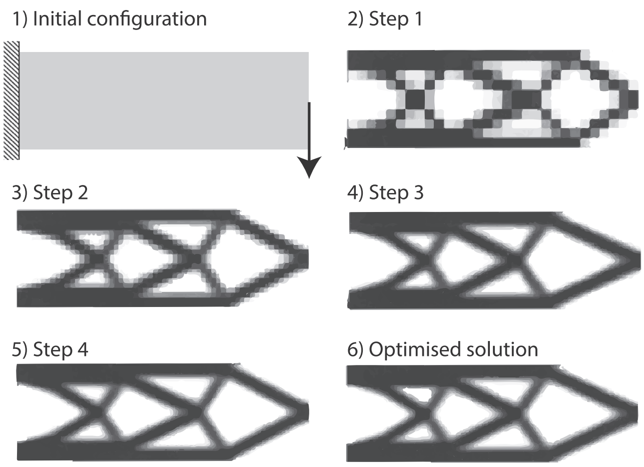

Fig. 19. Topological optimisation for a cantilever problem with increasing domain resolution (adapted from [29]).

largely with computer-controlled subtractive or additive manufacturing processes. The algorithms of optimisation are not inherently tied to specific manufacturing processes, but in recent years some work has focused on incorporating manufacturing constraints into design/optimisation software. [187] reviews applications of topology optimisation for sheet metal manufacturing in automotive applications. Commercial software is available to connect design generation and optimisation to manufacturability, for example nTopology and Altair Engineering focus on manufacturability for Additive processes.

Additive processes offer important advantages in specific application areas, for example with geometries that cannot be made by other means (e.g. heat exchangers employing minimal surfaces [68], functionally graded materials [232] or in-situ alloy creation [160]). However, these benefits from flexibility are offset by their low yield ratios (where un-sintered powder cannot all be re-used, for example) and very low throughputs. Compared to the 1800Mt of steel produced annually, total global consumption of steel powder for additive manufacturing is around 0.0002 Mt/yr and the process requires greater energy inputs than conventional bulk forming processes due to atomisation and the low melting-efficiency of lasers [19]. In addition, parts made by additive manufacturing usually require post-processing to remove support structures, surface quality is limited, material properties are difficult to control, residual stresses may be problematic, and the dimensional scale of parts is constrained. Some attempts have been made to combine the flexibility of additive manufacturing with the throughput of conventional forming technologies. Synergies between AM and forming, including hybrid additive manufacturing with forging or rolling [146,151], pressing additively manufactured sandwich sheets [182] or combining wire-arc additive manufacturing with forging [22]. However, as yet, no approach has been developed with high throughput.

The goal of saving material at global scale cannot therefore be approached through application of design optimisation software alone, as the resulting designs cannot be made with sufficient speed and quality. However, optimality can be approached within the constraints of high-volume manufacturing.

Applying similar logic at smaller scale, new mechanical metamaterials can be designed for production at high volumes, while delivering similar benefits as optimised trusses. Lattice structures have been at the centre of interest in this area and can be exploited to enable and control new bulk-material properties such as mechanical cloaking, negative Poisson ratios, chirality, and extreme sound dissipation [55]. Researchers often develop such structures using additive methods, for fast prototyping and geometrical flexibility. But some designs can be developed for production by forming and joining. One example is the use of expanded metal made by perforating conventional sheet metal then deforming by bending and twisting to create lattices (see Fig. 20. [193,210]). Such expanded metal has been employed in a range of lightweighting applications such as Periodic Cellular Metal structures to produce low cost heatsinks [228]. Blocks of material are sheared repeatedly to created thin fins which are not sliced off but deformed with the same tool to create parallel rows perpendicular to the block surface through a net-shape process.

The fact that optimal designs can be calculated efficiently, but produced only in low volume processes, points to a significant opportunity for innovation in manufacturing technology, in particular in high throughput forming processes.

4.2. Cutting manufacturing scrap

The term 'near net-shape forming' became popular in the 1980s to describe a range of research and innovation efforts aiming to produce parts without scrap. Potentially, this might apply to direct casting of parts, for example by injection moulding. However, this approach has had limited applicability for metals, due to the difficulty of controlling microstructure without hot-deformation, and even when it can apply (for example for magnesium alloys), the environmental cost may be high due to the need for high-impact sealing gases [24]. The first paper with the term 'net-shape forming' in the title, written in 1982, therefore sets the agenda for this activity, and focused on forging and powder processes [215]. As the author understood it, 'net shape forming' was focused on processes that could deliver final components from liquid metal without any waste at all, seeking advantages in both waste avoidance, and improved property control, in particular of wear surfaces: if gear teeth could be made directly by forging, with a final cold stage, this would create finer grain structures at surfaces for better wear resistance than can be achieved with machining and heat treatment. A decade later, in addition to a CIRP keynote [13], Professor Kudo summarised what had been learnt [130]. Continuing the ideal target of avoiding any loss from liquid to part, his focus was on forging, which provides all the examples in the paper. He concludes that due to the many sources of imprecision in forging processes including variations in feedstock material and geometry, improper lubrication, deflection, wear and expansion of tools, press deflection, damage during ejection and imperfect process control, some machining and grinding will be required after forging. While his paper set the agenda for the next three decades of work on cold forging in particular, the commercial reality of his conclusion is stark: if despite attention on net-shape forging, a machining stage is required, it will often be cheaper to forge less perfect intermediate shapes, and benefit from the high geometric precision of machining and grinding to deliver final parts.

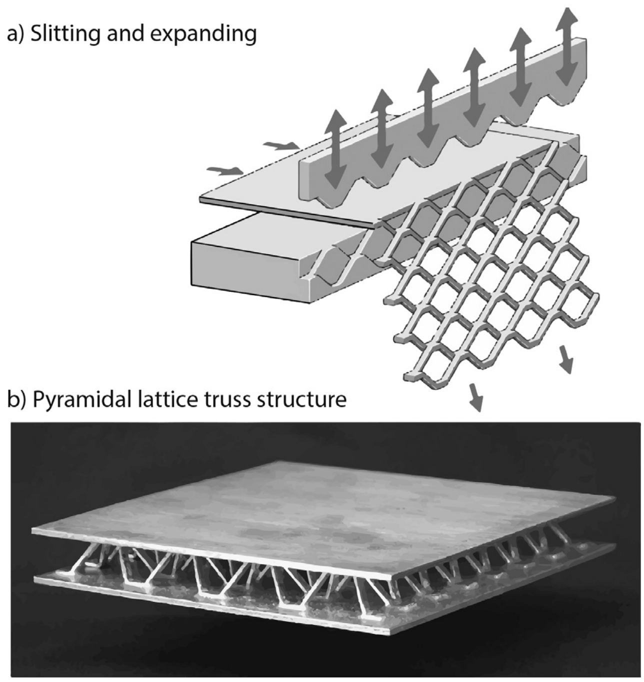

Fig. 20. Expanded metal created by perforating and flattening sheet used to make a sandwich panel [210].

The term 'near net shape' has subsequently had less attention in the metal forming community, although it continues to be a driver for work on powder processes and more recently plasma spraying [64]. However, limiting the focus of attention in 'net shape forming' to process chains that can convert liquid metal to final parts without any loss, denies attention to the dominant sources of manufacturing scrap revealed by Fig. 17. Figs. 16 and 17 reveal that 40 % of all global steel production and 59 % of aluminium is cut off during manufacturing, between casting and product delivery. Despite sheet and plate applications making up just 45 % of final use of steel, they lead to 61 % of manufacturing scrap. The same figures for aluminium are 63 % of final use and 76 % of manufacturing scrap. The clear focus for cutting manufacturing scrap, by mass, is these sheet and plate applications.

Even if this scrap cannot be eliminated entirely to reach the goals of the 'net shape' movement, to what extent can it be reduced?

Fig. 21 takes data from Fig. 16, including estimates of uncertainty, to give priority to the search for reducing scrap. As the mass of manufacturing scrap is the product of the values on the two axes, the

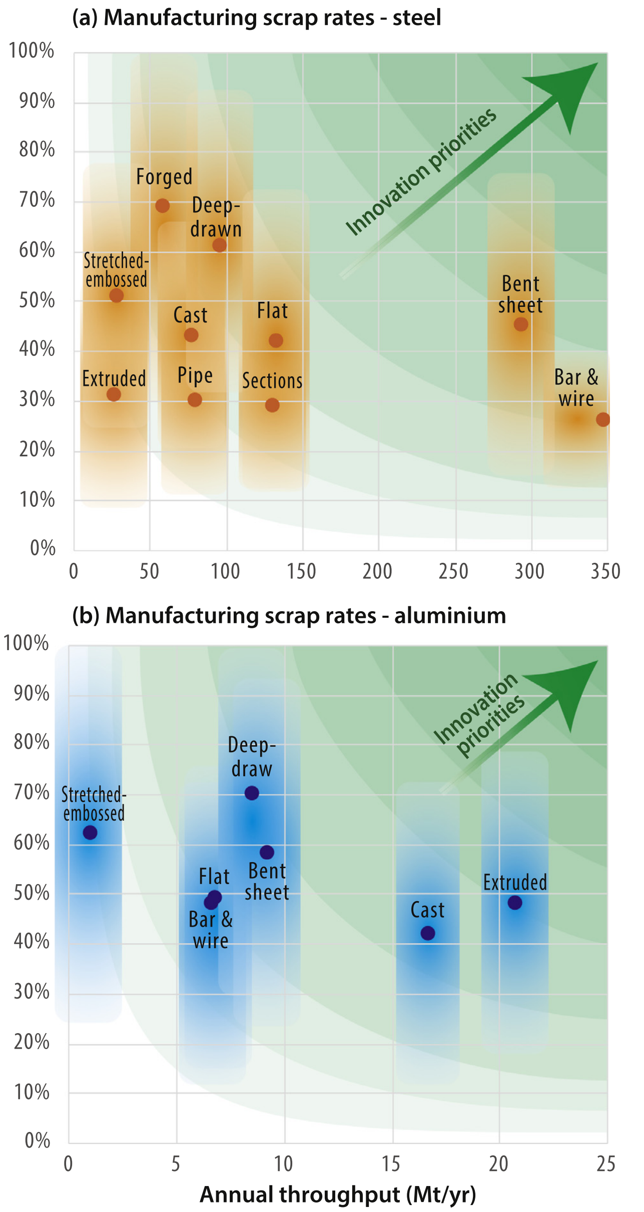

Fig. 21. Manufacturing scrap rates plotted against production rates for (a) the components of the catalogue in Section 3 and (b) the process chains by which they are made today and those discussed in this section.

priority is for components nearer to the top right of each plot, which clearly directs attention towards sheet, plate and long components, rather than the three-dimensional components that were the focus of the first wave of interest in net-shape forming.

Fig. 22, building on the case-studies of Fig. 12 and using data from table 1, Fig. 16 and [57,58], further prioritises the search for innovation between the production of intermediate stock goods, cutting or blanking workpieces, forming processes and trimming and machining. It shows that for both metals, the highest source of scrap is within the primary metals industry itself, although manufacturers have little influence over this. However, downstream, the major losses occur in trimming formed sheets and machining bars, billets and forgings. Any savings here will be amplified upstream.

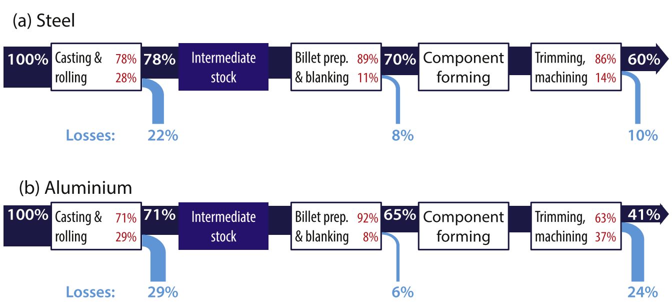

Fig. 22. Origins of manufacturing scrap by process stage.

Figs. 21 and 22 motivate a fresh look at net-shape forming, with the goal of targeting high-volume manufacturing scrap. There is space for substantial new research effort in this area, but already work has begun to explore the scope for improvement.

The second of the three forms of losses shown in Fig. 22 arises from cutting irregular shapes from long constant-width rolled strip or plate, to form flat components for joining, or the blanks for bending, stretching, embossing or deep-drawing. The well-known cutting-stock problem, equally familiar to the clothing, textiles and paper sectors, has attracted attention for decades as mathematicians have sought new algorithms to achieve improved tessellation. However, this is not the only solution. A different approach is to redesign workpieces for better tessellation and then modify downstream forming processes to deliver the same required part from a different blank. An attempt to reshape tessellating hexagonal blanks into circular disks prior to can-making demonstrated limited improvement [43], but silversmiths through the centuries have combined forming and joining to allow optimal use of their precious sheet metal [102] and this approach can be applied equally to ships or yellow-vehicles made of flat plate, where the joints between components can be designed for material efficiency as much as for the convenience of assembly [226]. A quite different approach to avoiding blanking scrap is illustrated in Fig. 23 to overcome the blanking scrap inherent to producing flat washers from sheet metal [185]. The process illustrated instead delivers washers with no waste at all, by a first step of lateral extrusion from a circular bar, following by piercing by a punch of the same diameter as the bar. Other smaller flat components could similarly be manufactured without waste from bar not sheet stock.

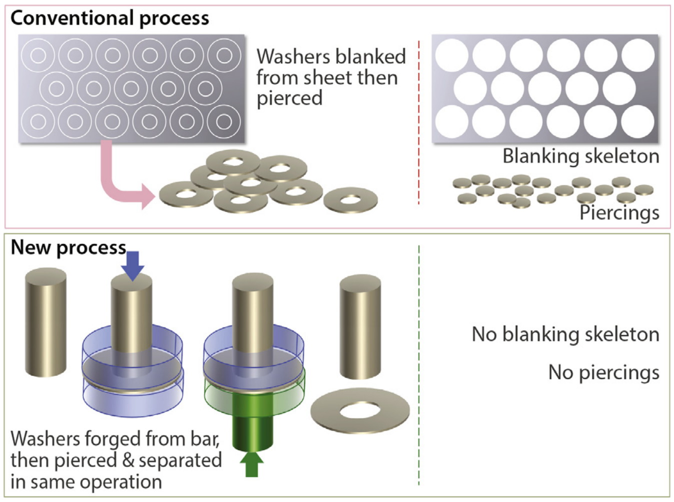

Fig. 23. Innovation to make washers without scrap [185].

After blanking, sheet material may be bent to final form, stretched, embossed, or deep-drawn. Any of these processes may subsequently require piercing, for example to remove interior areas for windows in car doors, or for aesthetic reasons in mounting appliances or other consumer goods. This creates an opportunity for material saving through intelligent nesting of different shaped blanks in the same feedstock [76] or could be approached by new forms of bending process, to create efficient frames or perimeters from thin strips [165,191] without the losses of piercing.

Deep-drawing is a particularly wasteful process, due to the requirement for a perimeter to the part to be held in a blank-holder to control material flow and avoid the failures of tearing or wrinkling. This additional perimeter must be cut off after forming, and the scrap may be amplified by requirements for 'addendum surfaces' which transform complex geometries into the more domed shapes that fit process operating windows. A substantial body of work (e.g., [167]) has aimed to reduce this excess material by combining finite element process analyses with optimisation algorithms. The folding-shearing innovation mentioned above aims to obviate much of this excess material, by folding the flat workpiece prior to forming [5,15,49]. An alternative approach, illustrated in Fig. 24 for an automotive front S-rail, is the novel process of Transversal Compression Drawing. It relies on stress superposition at the boundary of the workpiece via controlled motion of the blank holder to control material flow. In addition to a reduction in blank size, the authors report a reduction in springback and frictional losses [36].

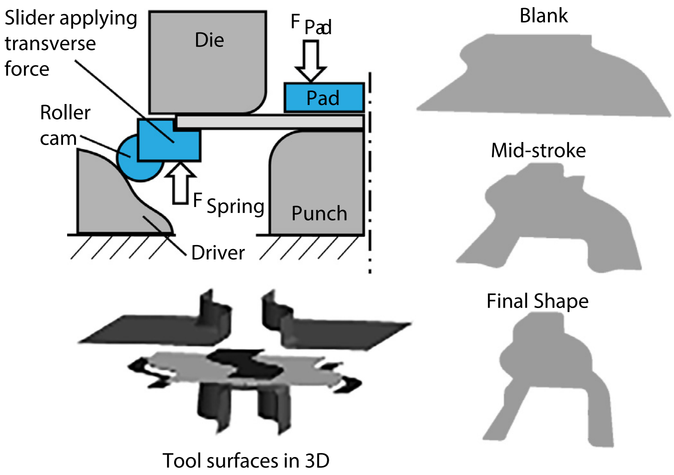

Fig. 24. The transversal compression drawing [36].

The beams, pipes, wires and bars that make up the category of long-products are generally produced continuously and cut to length with great efficiency. However, strictly continuous production can only be connected to continuous casting, which is economical only for indefinite production of an unvarying product. More normally, continuous production is interrupted due to the finite size of cast ingots and the head and tail of such finite production is typically scrapped, due to the difficulty of product tessellation and product quality control. In strip-rolling, this can be addressed by welding the tail of one coil to the head of the next, to reduce process interruptions [127]. A recent innovation has been to pursue similar continuity in the much shorter batches of aluminium extrusion [83].

For three-dimensional components, the idea targeted by Kudo [130] of avoiding any scrap from casting to part, has led not only to interest in powder and wire additive processes, but also to casting parts directly. At present, due to the difficulty of controlling microstructure without thermo-mechanical processing, only magnesium parts have been cast directly, and at significant environmental cost due to the primary production process [60]. An alternative approach, aiming to save material in sheet-blanking, is to cast variable width sheets [147] but this has been demonstrated at laboratory scale only.

Alternatively, materially efficient production of three-dimensional parts could combine novel approaches to billet formation with new forging processes. One such approach is to cast hollow parts and then apply the benefits of flexible forging to control not just geometry but also internal microstructure, in order to reduce the material wastage implied by the grain size variation in Fig. 13 [179,217]. A different method would be to form the billet by a different process, for example by wire additive manufacture, so that the forging process can be targeted on component properties more than geometry [22].

Fig. 21 is clear about the priorities for innovation in forming technologies required to deliver material savings. The key is throughput. Computer controlled flexibility, which has proved so valuable in machining, cannot in metal forming deliver the scale of saving required to make a difference to global metal demand. The highest priorities for reducing steel demand are innovations in the most common processes. Sheet-bending, forming bar and wire, cutting flat components from plates and sheet, and manufacturing sections attract the least attention from the research community, yet are clearly the most important targets for innovation. For aluminium, these processes remain as important but are exceeded by deep-drawing and extrusion. The key to impact in cutting manufacturing scrap is scale, and that almost certainly suggests that the innovations that matter are those which adapt the tooling used in existing high-throughput processes, rather than the invention of new, but lower capacity, machines.

4.3. Cutting specification scrap

The two root causes of specification scrap identified in Section 3.3 were cost and uncertainty, and these motivate the search for technical interventions to reduce such scrap in future.

Over-specification can reduce costs when purchasing benefits from economies of scale, or when the labour costs of improved specification outweigh the material savings. For example, it may be cheaper to purchase a hundred structural beams of one size rather than buying a hundred different smaller beams, both because of the volume discount, and because design and management costs are reduced by repetition. Two approaches to reversing these unwanted economic incentives are to reduce the economies of scale through innovations in production flexibility, and to reduce the costs of design and management through use of software support tools.

More than three decades of innovation in metal forming, starting in Japan in the 1990s [12], has sought increased process flexibility, aiming to mirror the flexibility and commercial impact of computer-controlled machining centres. The motivations for these developments include reducing the costs of product variety, reducing the costs of tooling in conventional processes, and reducing material wastage [227]. This motivation has inspired creativity, in structured searches for novel process configurations [2,141], explorations of the performance and mechanics of specific novelties [119,122,149], learning from the design and operation of craft processes of the past [34,183] and developing new approaches to process control [8].

Several process innovations, such as three-dimensional roll-forming [138], incremental profile forming [91] and flexible ring rolling [50] have demonstrated the potential for such savings at laboratory scale, but commercial take-up has been limited. Only innovations in computer-controlled tube bending [26,84,164] have had significant impact. Despite cost-analyses showing that flexibility offers advantages for low batch-size production [9] in reality, the true cost of deployment, including changed management practices, skills and risks, have far exceeded the potential benefits of such processes. The target of reducing the cost advantage of over-specification is therefore unlikely to come from innovations in production technology, but to be approached by new software and systems.

Under time pressure, designers often default to approaching each new task by replicating as much as possible of previous solutions [209]. Software tools can therefore expand the range of options they can evaluate and have been developed to support the evaluation of early design schemes, the selection of materials and processes and for overall process planning.

In the first category, the Handbook of Environmentally Conscious Manufacturing contains a list of historic software that attempted to have an impact in this area in the 1990s but they all appear to have been short-lived projects [143]. More recently, the PANDA software [81] was developed, to enumerate all possible design schemes to meet the client brief for a new building within the constraints of the Eurocode safety regulations and plot an ‘efficient frontier’ of the resulting cost and embodied carbon of each option, as exemplified in Fig. 25.

Plots of this form can be used in early-stage discussions between client and design team, can help to avoid specification scrap before it becomes ‘locked-in’ by subsequent decisions and at best can lead to savings in both cost and emissions [80]. LCA software such as OpenLCA, similarly allows engineers to optimise for energy use or carbon emissions [23].

Secondly, while it is unlikely that the energy of material production can be reduced by ‘de-tuning’ product properties to match specifications, selecting materials and processes for specific components is

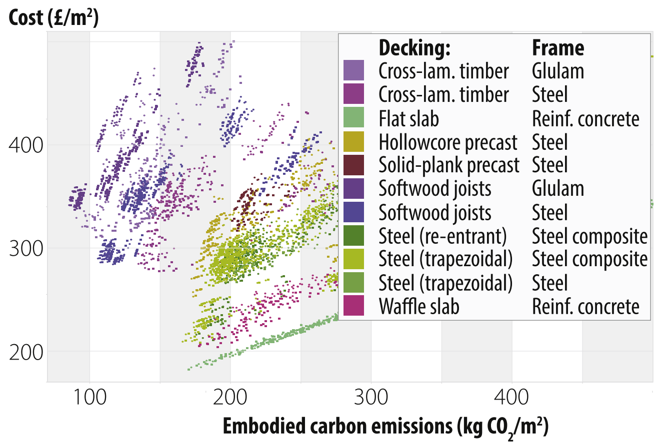

Fig. 25. Example ‘efficient frontier’ of building design [81]. Each point on the graph represents a different design scheme for the same building, coloured according to decking and frame choices, with a wide range of outcomes for building cost and embodied emissions as other design parameters (such as column spacing) change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

crucial to avoid over-specification. Ashby’s famous material selection charts, and associated methods, provide a rationale for this, including choosing the lower embodied emissions or energy material to meet given performance specifications [16]. Out of this he has developed tools for process selection [16], now expanded by others [201]. Researchers are now exploring options to automate these manual selection processes, for example using computational neural networks to classify and select sheet metal forming processes based on part geometry [95] or using fuzzy logic to evaluate and select a process change for near-net shape manufacture of a specified part from among all viable process combinations [144,145].

An interesting, and under explored variant of these approaches to material and process selection is instead to consider the design in reverse: given a material and set of process capabilities, what product design leads to the least manufacturing and specification scrap while meeting performance requirements? In effect, early blacksmiths took this approach to the design of the knife, fork and spoon familiar in today’s Western cutlery canteens. Supplied only with round bars of iron from the water-powered hammers that squeezed the slag from bloomery steel and equipped only with the anvil and hammers of the forge, the established our familiar forms of cutlery by hammering the blade, tines and bowl of the knife, fork and spoon from one end of the bar, leaving the rest as the handle. A similar approach has been attempted in a recent project to design a low-cost car with minimum specification scrap, using a structural frame made of tubes shaped by computer-controlled freeform bending [97].

Thirdly, extending the interest in material and process selection out to the complete production chain, long-standing efforts at computer supported process planning are being integrated with environmental concerns to deliver new software tools considering not just the management of a factory, but also the whole-life of products [189,207].

The other major cause of specification scrap is the uncertainty faced by designers, discussed in Section 3.3. Some of this can be addressed by different management practices, such as raising the costs to clients of late design changes, to avoid defensive practices leading to excess material use. A parallel approach is to adjust the design of the product to reduce load variations. Although it is difficult to find examples of this approach in the literature of manufactured products, it is familiar in structural engineering, for example when bridge or chimney designs are modified to reduce the oscillatory loading created by vortex-shedding [28] or when building designs are modified to survive the extreme loading of earthquakes [188]. Related approaches that might be applied to a wider range of products include the substitution of actuation for stiffness in machine design, or the use of sensors and control systems to reduce the likelihood and severity of crash impacts in vehicles. Structural Health Monitoring (SHM) employs sensors such as strain gauges [79] and acoustic or optical methods [92] to improve understanding of structural performance [73]. Most recently structural performance of infrastructure has been successfully measured with satellite imaging [155] and drones [125]. Ford Motor Co have used a real-time wireless sensor technology to control door seal gaps and reduce wind noise and water leaks [128]. In the aerospace sectors, similar monitoring is used to inform maintenance decisions [178].

With improved sensors and faster computation, Digital Twins of complex products and machines can be developed, allowing for better understanding and optimisation of components in practice. Examples have been reported in aerospace [135], manufacturing [77], and infrastructure [38]. In future, such Digital Twins may support attempts to reduce specification scrap by providing new insights on in-service requirements, maintenance, and failure.

Two other forms of uncertainty being addressed by recent innovations in civil engineering include the use of offsite manufacture, to reduce the use of over-specification to compensate for uncertain on-site control of fabrication [172], and the use of load-sensors to monitor live loads with the goal of reducing redundancy and anticipating problems in structural design.

In parallel to Fig. 21, Fig. 26 gives priority to the search for innovations to reduce specification scrap in the major uses of steel and

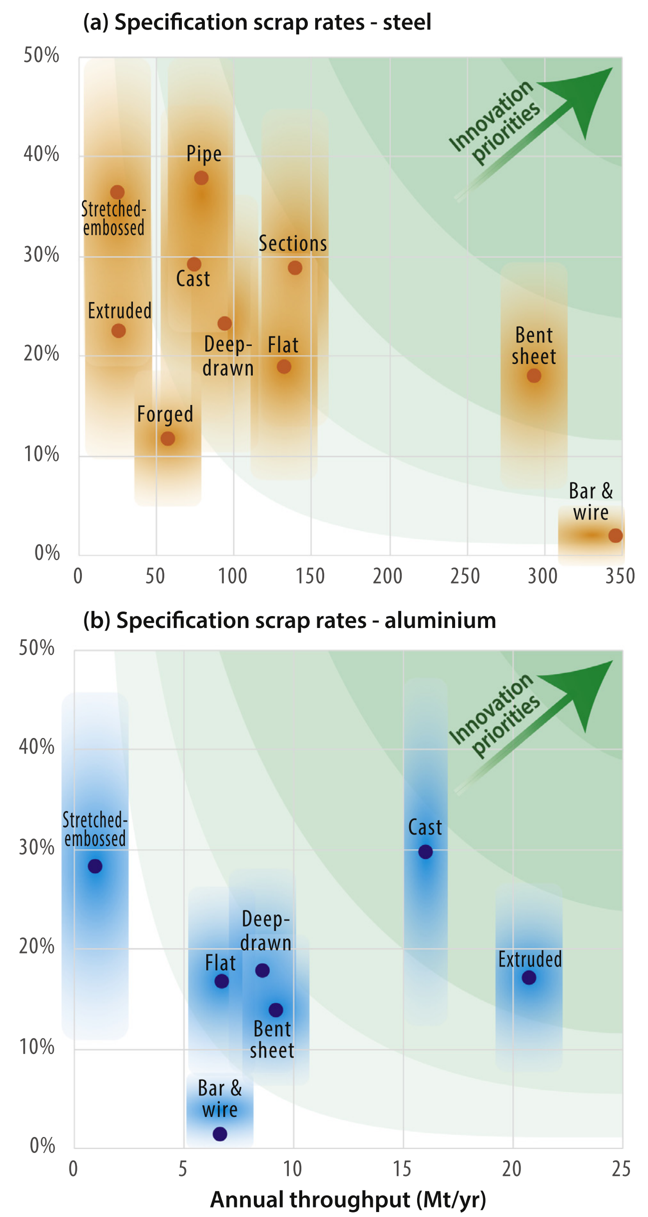

Fig. 26. Specification scrap rates plotted against production rates for (a) the components of the catalogue in Section 3 and (b) the process chains by which they are made today and those discussed in this section.

aluminium. For both metals, the greatest opportunities are for long-products, followed by those made from sheet and plate, and the survey of this section suggests that development of software tools to improve the match between product specification and manufacturing capability, and strategies to reduce the uncertainty of specification are likely to have most impact.

4.4. Cutting property scrap

The concept of ‘property scrap’ is new, first defined in this paper, so there is no direct literature addressing the problem with that title. However, in response to the evidence in Fig. 17 that metal’s powerful properties are being under-used in most applications, this section draws attention to innovations that aim to reduce scrap arising from under-exploitation of three properties: strength, ductility and grain size. It concludes by considering how changed approaches to design could reduce property scrap in future products.

In many applications, the target property of current designs is to deliver a certain level of stiffness, so fully exploiting the Young’s Modulus of metal, at the cost of failing to exploit its strength. Fig. 27a demonstrates this for the simply supported beam discussed in Section 3.4, which would typically be designed to deflect no more than a maximum value at mid-span under the maximum load. However, as the figure shows, if the beam cross-section is selected so that the stress in the beam just reaches yield in mid-span at the outer surfaces at this load, the stress state everywhere else in the beam will be well below this value. As a result, the beam demonstrates substantial property scrap, in failing to exploit the yield stress except at the two critical locations.

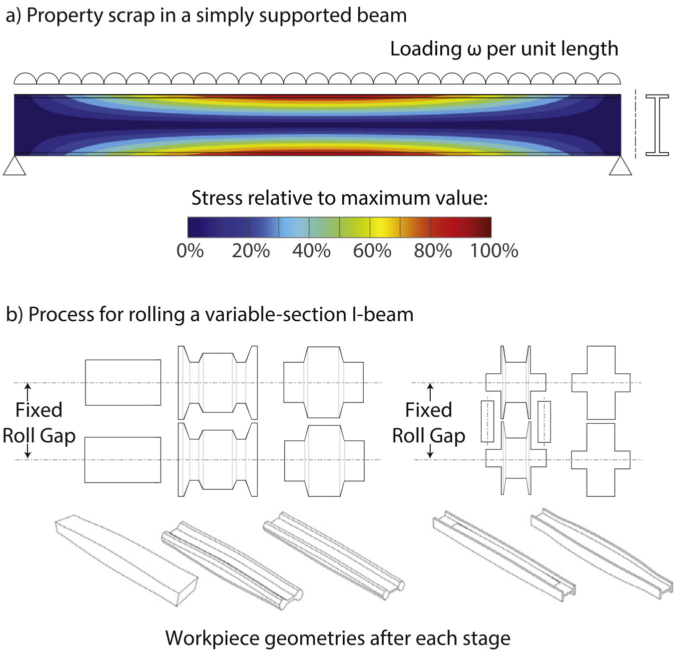

Fig. 27. (a) Property scrap in a simply-supported uniformly-loaded beam [11] and (b) a novel process proposed to manufacture I-beams with varying second moments of area (to track the bending moment distribution) [42].

A more efficient beam would have variable depth along its length, so that its second moment of area matched the bending moment created by loading. A process to roll such beams has been proposed and demonstrated at laboratory scale and is illustrated in Fig. 27b [42].

Variable section rolling as illustrated has attracted no commercial interest, but the same motivation has led to more pragmatic approaches using what are collectively known as tailored blanks. These include welded blanks, patchwork blanks, tailor-rolled and tailor heat treated blanks as illustrated in Fig. 28. (The properties of tailor-welded blanks are to some extent degraded by welding, so the two novel processes of longitudinal and lateral tailor rolling [104,129], provide a more robust solution.) The geometry and properties of such blanks can be tailored to some extent before final forming into a component. Due to their efficiency in reducing property scrap, tailored blanks have been adopted widely [148].

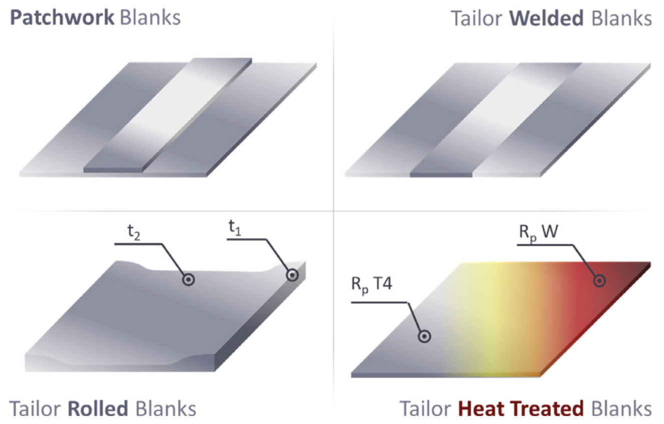

Fig. 28. Classification of tailored blanks [150]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Similar approaches to improving material utilisation can be taken in other applications by taking steps to ensure the best type of feedstock is used for a given application, before we consider the process itself. Metal foams, sandwich structures, corrugated sheets, metal composites and hybrid material systems are some of the options that can dramatically reduce the mass of material in the end product while maintaining sufficient stiffness. A recent innovation in this area is the use of selective embossing of sheets with a dimple pattern, both to increase the bending stiffness of the sheet by increasing its second moment of area, and to increase its strength through work hardening [37]. Alternatively, rather than forming ribs in flat sheets to increase their stiffness, they can be augmented with perpendicular stringers, either cut and welded to fit after sheet forming, or in a recent innovation, welded to the flat sheet and then formed in combination [90].

Crash structures, such as illustrated in Fig. 15a, exploit the property of material ductility, to absorb energy (convert it to heat) while doing irrecoverable plastic work. However, the figure illustrates that a typical crash box folds in a concertina pattern, so that although a fully plastic moment develops at the pleats of the fold, the flat faces between remain elastic. Such structures therefore exhibit a high degree of property scrap: the metal in the component could absorb more energy if more of the metal were to yield and strain. A process that achieves this effectively is tube-inversion [180,181] in which, as the tube is forced into a hemispherical die, it reverses into a larger diameter tube, with all the material having absorbed plastic work. Potentially, such a device could be arranged to be deformed in reversing cycles, to exploit the Bauschinger effect and the wide range of ductility demonstrated in the cyclic plane torsion test [204]. In a more familiar example, the history of weight reduction in drinks cans depends on technological developments to exploit more of the ductility in the body material, allowing ironing of extraordinarily thin walls [41,65].

The twin goals of forging processes are to deliver a target geometry while also delivering a predictable microstructure, and as illustrated in Fig. 13, the second of these goals is difficult, and many forgings must be machined extensively, to reach an inner core of material with predictable grain structures. Forging tools can be controlled to deliver predictable impulses of strain and strain-rate to workpieces, but the challenge for grain size management is the control of temperature: in large forgings, it takes significant time for heat to diffuse from the surface to the core, so it can be difficult to ensure homogenous grain structure. As a general principle, it is always easier to control the core temperature of thinner workpieces, and this has motivated work on forging hollow billets [217], and on applying flexible hot ring-rolling to near final shape workpieces [140].

Thus, although the name 'property scrap' is new, its existence has already motivated innovations, as a precedent for exploiting the breadth of opportunity revealed in this paper. Furthermore, in parallel with the above developments in processing technology, the goal of avoiding property scrap can also be approached by new design strategies that configure products and components to allow better exploitation. This is a new area, but the literature already suggests some first ideas for new design principles:

- *Avoid bending*. Loading in bending motivated the discussion above about increasing second moments of area, but property scrap will be minimised when components are loaded uniaxially (or within their plane.) This has always been a requirement for stone-masonry construction, leading to the concept of a 'line of thrust' which must remain within the material to ensure stability [101]. It has also motivated the study of 'tensegrity' structures formed entirely of members loaded in uniaxial compression, and tension members, often cables, which can be designed for minimum mass [45–47,88].
- *Aim at uniform loading*. Seeking designs that lead to more uniform loading of key components, both in time and space, not only helps with avoiding the specification scrap of the previous section, but also in tuning the component design to exploit its properties fully.
- *Combine materials to minimise property scrap*. BMW has demonstrated a car with a fabric exterior to question the need for metal to hold the car's paint in place, which equally motivated the use of plastic exterior panels by Citroen and in Smart cars. A more sophisticated idea about material combination is to aim at multi-property design, by combining materials. For example, various combinations of copper, steel and aluminium filaments were co-extruded in a copper-sheath to create multi-material cable with controllable density, strength and resistivity [208].

Even if one property is exploited efficiently, it is likely that others would be used only partially. This is an inevitable feature of any material selection, so in addition to the strategies implied by the bullets above, designers should aim to minimise property scrap for the properties that have been won at greatest energy cost. For example, the applications in table 3 do not exploit the electrical conductivity of steel and aluminium, so potentially could be made with non-conductive materials such as polymers or composites. However, delivering the stiffness requirements in the table would require a much greater mass of such materials, which might increase the total energy input. This argument suggests that there is scope to build on the materials selection work of Ashby [16] to target reduced property scrap across all material properties by combining component design, material selection and process choices with the goal of minimising the total emissions or energy of component production.

Fig. 29 reveals the scale of the opportunity for innovation in developing processes with reduced property scrap and prioritises aluminium extrusions, and steel bar, bent sheet and sections.

5. Incentives and trade-offs

In response to the urgent problem identified in Section 2, and the opportunity revealed by Section 3, Section 4 has shown that there are many options to 'cut the scrap.' However, these changes have not in general been implemented. This section therefore attempts to anticipate how innovations that reduce total material demand are traded-off against other goals of production.

Conventionally, manufacturing innovations aim to deliver improvements in the 'magic triangle' of cost, lead-time, and quality. Typically, no innovation will be considered that leads to a loss of quality, while any worsening of cost or lead-time could be considered only in response to strong market demand for the new benefits. In parallel, to date, environmental performance has generally been viewed by end-users as an 'and-also' requirement – one they expect manufacturers to deliver, without increasing prices. Reducing material demand may also challenge existing regulation, if for example safety requirements have been over-specified, or are applied to processes rather than products.

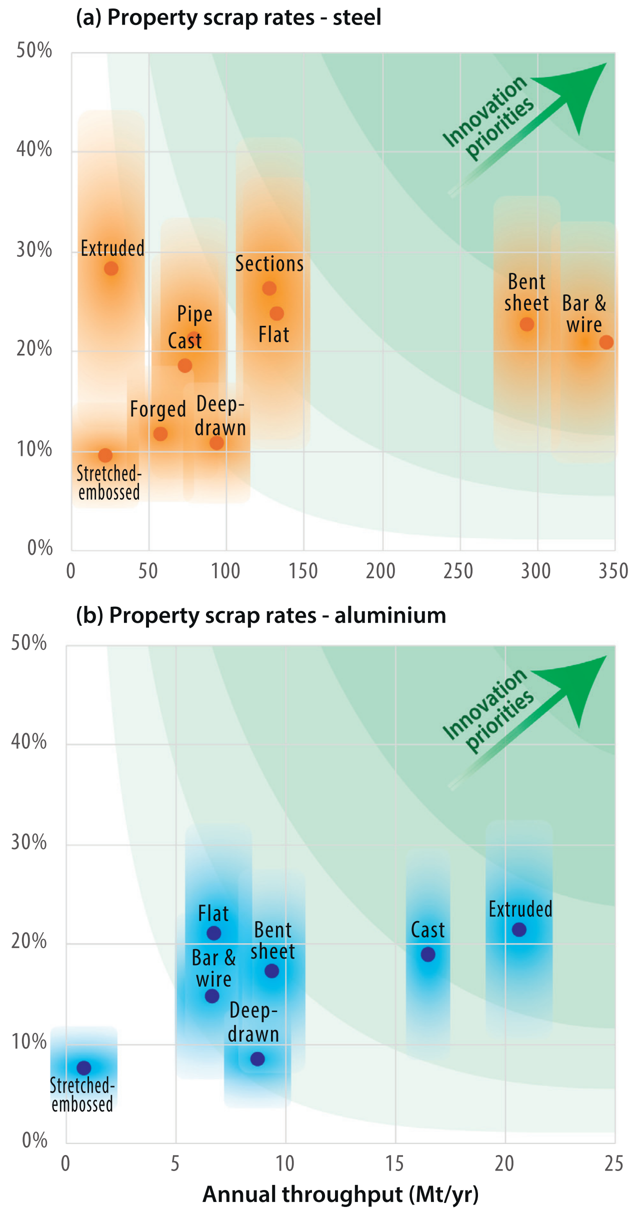

Fig. 29. Property scrap rates plotted against production rates for (a) the components of the catalogue in Section 3 and (b) the process chains by which they are made today and those discussed in this section.

The urgent goal of reducing total material demand may not always lead to benefits in the 'magic triangle', for users, or for all environmental metrics. This challenge is illustrated in the schematic of Fig. 30. Manufacturing companies have been optimizing at least three key performance dimensions: total unit cost (1), lead time (2), and quality (3). They have been striving for three zeros: zero dependence of cost on the produced quantity, i.e., operating at minimum unit cost where marginal costs are constant, zero lead time and zero defects; although these goals are not reachable, they indicate in which direction optimization takes place. Adding zero emissions (4) as fourth performance dimension is likely to create a traded-off with the other three dimensions, which may limit the viability of zero emission targets from a business perspective.

In response to Fig. 30, this section therefore aims to explore how the goal of reducing material demand is traded-off against other goals in production, and then looks forward to how these trade-offs might be resolved to allow a substantial change.

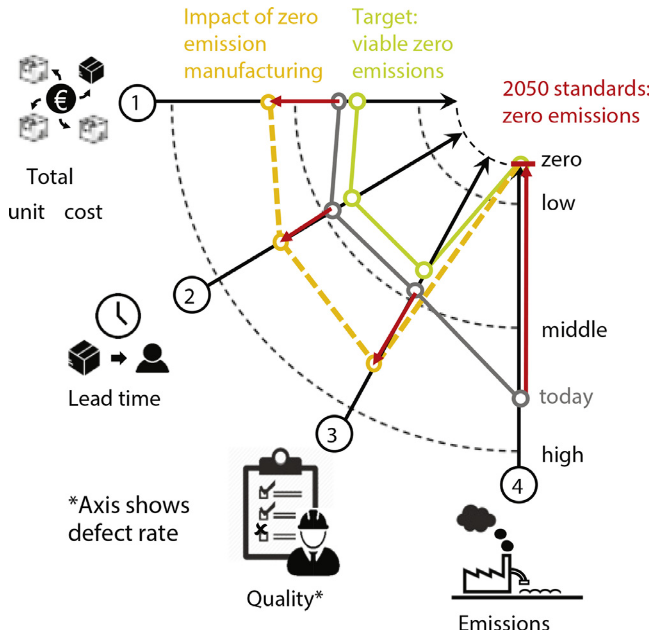

Fig. 30. Including zero emissions in the performance dimensions of production may worsen performance against the conventional goals of the 'magic triangle' of cost, lead time and quality.

5.1. Forms of trade-off with material demand reduction

The introduction has motivated exploration of three forms of trade-off between implementing material demand reductions and the goals of product design and manufacture, the business case, and other environmental impacts. These are now explored in turn.

Fig. 31 illustrates the influence of lot size and part complexity on the subdivision of manufacturing steps into forming (with no material loss) and cutting (with material loss). The diagram shows that for simple parts made in large lot sizes, forming is preferable to cutting. However, if part complexity increases, or lot sizes reduce or material costs fall, the process chain will favour cutting over forming, and manufacturing scrap rates will increase. Although the curves linking each pair of axes are schematic and indicate the trends only, they visualize the main factors that lead to a 'forming-to-cutting trade-off'.

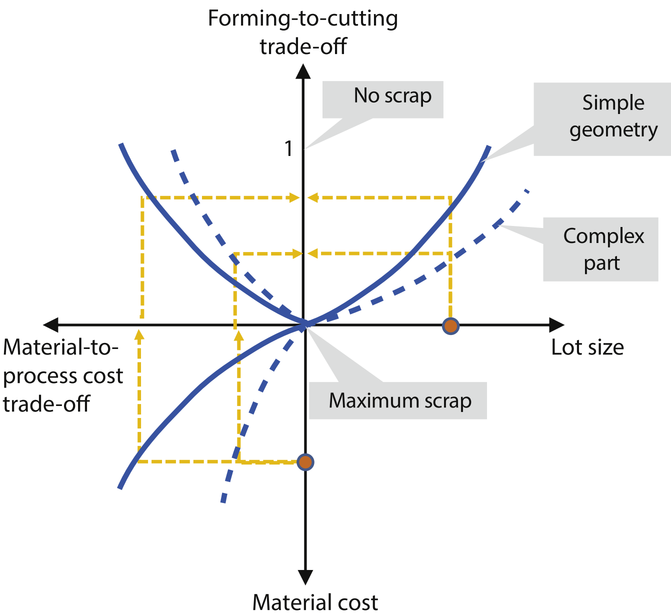

Fig. 31. Three linked curves to show how material cost and lot size influence the preference for forming or cutting depending on part complexity: increasing lot size or material cost or reducing component complexity leads to a preference for process combinations (the balance of forming to cutting) that reduce scrap rates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 32 illustrates the inherent trade-off between material yield and business case with an example showing the balance between net-shape forging and machining.

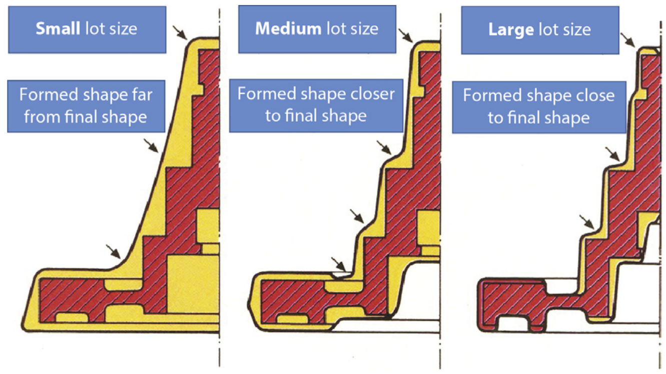

Fig. 32. Geometry produced by forging (yellow) vs. final geometry for three different lot size scenarios. Note that only large lot sizes allow for covering the cost of designing and manufacturing the dies for near net-shape forgings, while lower lot sizes are more economically produced by machining forgings that are far from the target geometry [99]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In addition, to the influence of part complexity on material utilisation, safety standards often necessitate design with excess capacity to maintain structural integrity under crash loading. As a result, for example, automotive sheet metal parts, use much more material and are substantially heavier than required for normal driving. This is also true to some extent for aeroplanes, to ensure safe landing after engine failure up to certain altitudes and surprisingly also for trains. Despite high control of train routes, the risk of impact remains, and as a result trains weigh substantially more than required to convey passengers at speed. This trade-off between design for normal and crash conditions is similar to trade-offs in construction, where buildings and bridges for example are designed for uncertain maximum loads which may be many times greater than the real loads experienced in service.

EcoDesign, which seeks to reduce environmental impacts through changed product design, has received a lot of academic attention [17], but has had limited aggregated impact, as it generally gives attention to minor adjustments in established designs, such as material selection. More challenging product design transformations are usually necessary to achieve meaningful change, and this requires considering the product's functionality. This often leads to trade-offs where customer preferences play a significant role. When conflicting environmental requirements exist, priorities must be established, and compromises made that balance various environmental concerns with the product's functionality [142]. While some green transformations lead to better products and business opportunities, conflicts between performance, economics, and environmental concerns persist. The paper puts forward the rather optimistic perspective that advancements in information and environmental knowledge will offer new opportunities for smarter compromises in design priorities but gives no evidence of applicable solutions.

For given designs, improvements must be sought along the manufacturing chain. The trade-off shown in Fig. 31 has its root in a fundamental limitation of forming processes, which is explored in Fig. 33.

The top right quadrant of the figure shows the trade-off between productivity and net shaping potential in forming. For maximum productivity, a single forming operation must be applied by stamping or forging, and this currently restricts the potential for materials saving to rather simple shapes. However, as shown in Fig. 31 and reflected in the bottom left quadrant of Fig. 33, higher part complexity will lead to a lower material yield.

The two charts reflecting these hypotheses are interconnected by two further charts that display the (nearly linear) relationships

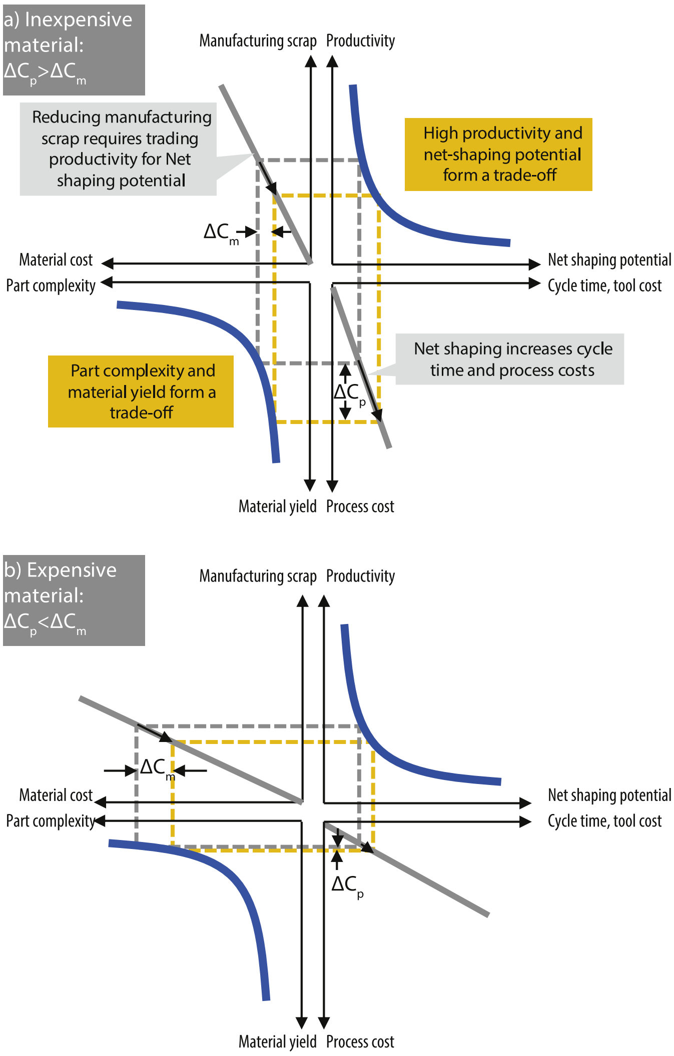

Fig. 33. Reducing manufacturing scrap in two scenarios. (a) For inexpensive materials, cost savings in material purchasing ΔC_m arising from use of more flexible nearer-net shape processes will not compensate for increased cycle times and associated increases in process cost ΔC_p. However, (b) for expensive materials, material cost savings ΔC_m are likely to be greater than increases in process cost ΔC_p.

between the manufacturing scrap rates and the cost of material purchasing per part (top left quadrant), and between cycle time and process cost per part (bottom right). Connecting the four charts with data for a given product design, manufacturing process chain and material choice leads to two points defining the process cost (bottom right) and material cost per part (top left), as well as predictions of the scrap rate and cycle times. Decreasing the material yield and hence material cost by ΔC_M will require trading productivity with net shaping potential, which will result in increased cycle times and process costs ΔC_P. For an inexpensive material, Fig. 33(a), the cost savings related to improving material yield may not justify the increased process costs. For a more expensive material, Fig. 33(b), the opposite applies, so improved material utilisation will be viable.

Product designs that cannot be made by forming alone must therefore face a trade-off between cost and material yield in the selection of manufacturing routes. For example, it may be difficult to manufacture structurally optimal shapes of the type reviewed in Section 4.1.

Fig. 34 illustrates the consequences of this incompatibility between productivity and flexibility when trading-off minimum weight design and manufacturing scrap. Sizing optimization can be employed to optimize the thickness distribution in a sheet component. Patchwork reinforcements can be used to stiffen and/or strengthen a component locally, but making the patches introduces additional scrap and the thickness distribution achieved with patches of constant thickness is still far from the theoretical minimum weight

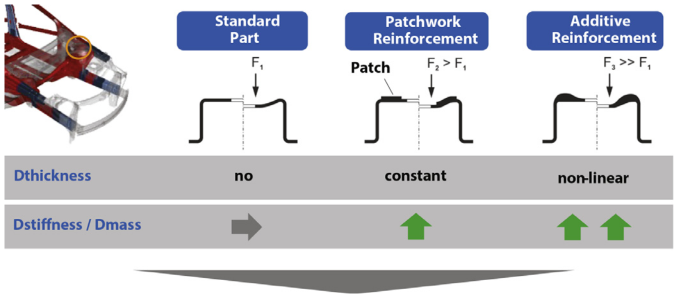

Fig. 34. Adding material locally (without cutting out patches) helps manufacture minimal weight designs but increases cost and lead time.

design. Reinforcements added by laser cladding, as shown on the right Fig. 34, allow for a more flexible distribution of material, but increase lead time, cost and quality risks. Clearly, such solutions are only viable for very expensive materials as indicated by Fig. 33(b).

While novel processes, flexible technologies or hybrid multi-material designs aim to resolve the incompatibility of productivity and net shaping potential, they tend to increase quality costs. These can be divided into control costs (prevention and appraisal) and failure costs [199], and both are typically increased by new lower-batch size interventions.

This trade-off is particularly challenging when introducing new forming technologies. Upstream, the economies of scale and reliable quality achieved by existing mass-production of generic intermediate products with high-throughput forming techniques, particularly rolling, are compelling. As a result, downstream the materially inefficient process of machining specific designs from generic cuboid blanks is attractive, despite the high manufacturing scrap it creates. Computer controlled machining is so efficient and can change so easily from one design to the next, that manufacturers generally prefer material waste to innovation.

Fig. 35 compares three routes to manufacturing a structural aerospace part with rib stiffeners in Ti6Al4V. Machining the part from a solid block ('hog-out machining') leads to the highest energy consumption. Forging a nearer-net shape intermediate is only slightly more efficient, as Ti6Al4V forgings depend on a minimum aspect ratio for the material to rise in the die cavity. Making the intermediate product with Wire-Arc Additive Manufacturing (WAAM) offers little benefit over the forging approach. However, if the rib is forged so that its width matches the target dimensions with minimal machining allowance, and its height is then increased to the target value by WAAM, the total material and energy input, can be reduced substantially [22], albeit this approach requires extensive investments to achieve qualification for use in the aerospace industry.

Section 4 demonstrated a wide range of options to reduce material demand. However, to date, with the exception of tailored blanks,

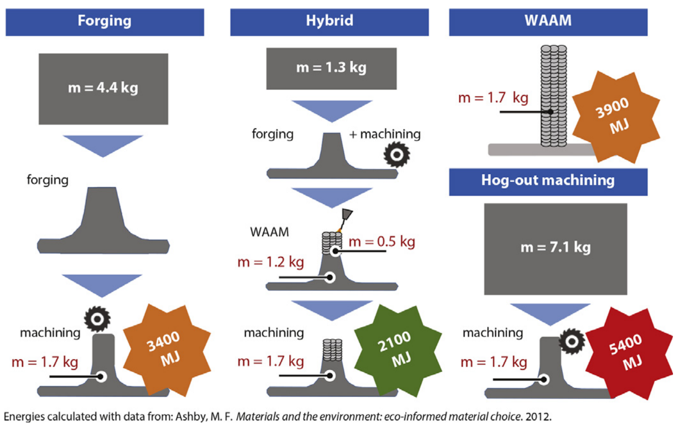

Fig. 35. Comparison of energy consumption for making a Ti6Al4V rib structure by hog-out machining, forging+machining, WAAM+machining and forging+WAAM +machining.

they have generally not been implemented, because the trade-off between implementation and the *business case* has not been compelling.

The discussion in this section so far has considered the direct costs of production. However, despite the opportunities for saving material reviewed earlier in the paper, the biggest barrier to implementation is probably the complex managerial risk of introducing new processes. Commodity production, which is the main focus of this paper due to its high demand for material, operates with high throughput and low margins, so managers are naturally reluctant to introduce innovations that might lead to any form of interruption. For example, the German automotive industry, has been very much concerned about stable, optimized supply chains that support build-to-order production [153]. The journey to deployment for material-saving innovations requires extensive buy-in across many functions in large manufacturing organisations, including a progression of tests and try-outs, before an enterprise-wide decision can be taken to adopt new approaches. Unless an innovation can be introduced without disruption to existing practices, it takes substantial time and effort to 'socialise' it among corporate decision makers prior to them committing to implementation, and the labour cost of this long process is high, unless the material savings promised are truly substantial.

Environmentally motivated interventions, which replace one input with another, may also have unintended consequences. For example, use of environmentally different lubricants to reduce health hazards for workers may lead to reduced machining times or loss of quality requiring additional rework elsewhere [35]. Alternatively, the rapid substation of CFC propellants in aerosols in the early 2000′s was highly effective in reducing ozone depletion but at the cost of greatly increasing greenhouse gas releases [177].

An important example of this form of trade-off occurs in decisions related to recycling. Where manufacturers have implemented target recycling rates as an environmental goal, for instance as promoted by marketing activities under the banner of 'circular economy', they may be motivated to increase blanking scrap or trim after deep-drawing. However, recycling is not of itself a benign activity and requires intense energy input and effort. Total energy demand is always reduced if scrap is avoided in the first place, so targets so targets should be set for both material utilization and scrap recovery in automotive manufacturing in order to reduce total material demand [108].

Similarly, the overall impact of recycling depends on the degree to which it maintains alloy integrity. 'Home scrap' in the aluminium industry, the trimmings of rolling and casting operations, are separated with precision and managed with great care, to allow reintroducing of the metal into a melt without further composition adjustment. However, for post-manufacturing or end-of-life scrap, the value of recycling depends on how 'compositionally forgiving' an alloy is [136]. Improving rates of recycling may not lead to reductions in total material demand if aluminium alloys are mixed and downgraded from high purity high value wrought compositions to lower grade casting alloys.

Particularly complex variants of this problem will become increasingly important as global steel production shifts rapidly towards electric arc furnace recycling. Steel recycling offers some opportunity for alloy control, but today's operators, value high-volume single-alloy sources of steel (most particularly from either manufacturing trimmings or from steel girders coming out of construction demolition) above all other inputs, because of their compositional simplicity. As recycling capacity increases, these sources will be in high-demand, and recyclers will turn to more diverse sources, motivating innovations in the collection and sorting of scrap, but potentially increasing the energy cost of processing it also.

The environmental benefit of reducing material input may also require a trade-off with the energy and other inputs to downstream production. This is exemplified by the progress of lightweight design in car body making which has led to a focus on developing materials with increasing strength levels. These became increasingly difficult to form, so the downstream industry has resorted to hot stamping as an alternative [158]. Hot stamping helps reduce material input due to high strength levels but may lead to an overall increase in embodied energy due to required heating. In addition, hot stamping processes operate without blank holders, this will limit the range of component geometries that can be produced, potentially limiting the opportunities to design efficient components while increasing the creation of trimming scrap.

Much has been written about trade-offs between the embodied and use-phase emissions of various products. While this can be important in particular applications, it is of less relevance when considering the large-scale applications of steel and aluminium. The use-phase energy/emissions of buildings, infrastructure, industrial equipment and vehicles for example are not increased as their material content is reduced, and in some cases (vehicles) reducing material content will directly correlate to reducing energy demands in use.

In the short term there may also be some environmental trade-offs with regulation, particularly if regulation designed for the past must be adapted to cover new practices, but this is a transient rather than long-term problem.

5.2. Resolving trade-offs

The previous section has confirmed that if cutting the scrap requires any decrease in production rates, loss of quality or increase in costs, then it is unlikely to be implemented at scale with today's economic incentives. That gives a clear steer to identifying pathways to implementation that can be effective.

Firstly, Figs. 21, 26 and 29 have given priority to the areas of most valuable improvement across the product catalogue, demonstrating in all cases that improvement must occur in high-throughput processes. This points strongly towards pursuit of interventions that involve adapting existing high-throughput processes, rather than inventing new ones. The most likely interventions are those involving new control strategies (as seen for tailor-rolled blanks [105,129]) or new tooling (as exemplified by folding-shearing [5,49]) both of which can be applied without disrupting throughput. In parallel, the survey of options for change in Section 4 has revealed several examples where designers can cut the scrap by making better use of the components produced by existing mass production processes. Reinforcing bars are used efficiently, due to the composite design of reinforced concrete, and other design ambitions such as focusing on uniaxial loading and avoiding stress concentrations can be implemented to have scalable impact.

Secondly, today's economic conditions are transient and will change as climate change accelerates. Eventually, politicians will have the public consent to act decisively, recognising that climate change is fundamentally a problem of health and safety, and like all such problems, they will respond with regulations that ban the harm, in this case emissions. Once emitting processes are banned, manufacturing and design will adjust to find the most cost-effective solutions among allowed alternatives, and cost comparisons with emitting options will be irrelevant. Before that occurs, willing clients can drive change in the economics of material consumption through paying a 'green premium' for products which have lower embodied emissions due to their requirement for less material input [170]. Customers are already demonstrating some such willingness, and it will grow particularly as client-facing organisations downstream compete for market attention by promoting their claims towards climate compatibility, which must be backed up by material saving.

Meanwhile, the normal practices of production management, exemplified by the Toyota Production System's focus on eliminating waste [194], can be applied with increasing attention on total material utilisation. Wide variations in the amount of scrap created by different automotive manufacturers while making the body-in-white, already suggest that some of them give higher priority to material utilisation, and simple changes in the metrics by which designs are assessed could be highly effective in motivating better communication between designers and manufacturing engineers about material waste [107]. Similar improvement processes could be used to make visible the uncertainties that drive over-specification and motivate efforts to reduce their impact. If 20 % of the features of a product typically account for 80 % of the value, there is likely to be significant scope to address over-specification in the other 80 % of features which will be given less attention [52].

Finally, even before public consent for biting regulations to ban emissions, new approaches in policy could enable more rapid deployment of innovations that reduce material demand. Conventionally, much government support for innovation has assumed that the innovation is a technology that will, in due course, become profitable so focuses on accelerating progression through the 'technology readiness levels.' For interventions that reduce material demand, different forms of funding that support market rather than technology development may be more valuable, and in many cases (such as large infrastructure projects) policymakers can have a significant influence through purchasing. With growing interest in Resource Efficiency in policy, governments may also take more interest in the stocks and flows of materials through their economy, to influence decisions about product longevity, recycling policies, and product standards. Small changes in existing regulations might for example lead to smaller road vehicles avoid excess material use in commercial construction and encourage better handling of post-use materials.

6. Opportunities and conclusions

Section 2 of this paper identified a substantial problem, that during the few remaining decades in which the world must eliminate greenhouse gas emissions, there will be a period of restraint, in which metal supply will be far short of demand. Section 3 has translated this problem into an opportunity, by demonstrating (with considerable uncertainty) that around 80 % of steel and 90 % of aluminium use today is actually 'scrap', created by waste in manufacturing, over-specification in design, or unexploited properties, much of this waste could be eliminated without loss of value to final users. This opportunity, summarised in Figs. 16, 17, 21, 26 and 29, defines the future research directions revealed in this paper: where much recent research in metal forming has targeted performance-enhancing innovations in the highest-value components made in low volumes, the substance of this paper motivates a higher-impact and more substantial opportunity for research aiming to cut the scrap. Section 4 surveyed interventions that suggest that it is possible to eliminate a substantial fraction of this scrap, and while Section 5.1 showed that action at sufficient scale is unlikely under current economic conditions, Section 5.2 has demonstrated that change is possible in both the short and long term. This leads to some clear guidance for managers and policy teams today, along with some clear direction for immediate priorities in research.

6.1. Practical advice for managers and policy makers today

The problem of material supply shortage is coming, and will be made apparent, once political rhetoric on climate action turns into commitment via meaningful carbon prices or emissions-reducing regulation. This action will cause rapid price rises for steel and aluminium supply, motivating a rapid shift to designs and manufacturing practices that deliver value with substantially less metal input. Such change is achievable and can be pursued immediately. This paper has prioritised this change for the bulk metals, but it will apply equally, for the same reasons, to all possible substitutes, including polymers, composites and timber.

A top priority for managers of customer or client-facing businesses is to map out the full material inputs to their products along the supply chain back to material supply, and then to attempt to parameterise the origins and scale of the three forms of scrap identified in this paper. Knowing the scale of this scrap allows immediate adjustment to the metrics that guide design and manufacturing teams, and will motivate suggestions for intervention, some of which will be immediately cost effective. Raising awareness of embodied emissions with customers will help them align choices with their own commitments to reducing emissions, and may rapidly lead to competitive advantage, where other offerings are delivered without similar care. Equally, clear metrics on scrap will motivate changed supplier contracts, for example to amplify the incentive for upstream change. The analysis of Section 5 explored the commercial challenge of implementation under current economic and regulatory conditions, but given the clear indicators revealed by Section 2, it is clear that this conditions will soon change. The immediate commercial priority revealed by this paper is therefore to prepare for imminent change in the cost and availability of familiar inputs.

The paper reveals a rich seam of opportunity for entrepreneurs, who can move faster than established supply chains, supplying information and insight into the origins of scrap, analysis and consultancy support on available options for change, and new business offerings that allow different modes of operation with much reduced scrap. Specifically, innovations in control and tooling for forming processes can be integrated into existing supply chains much more rapidly than entirely new process approaches. Such entrepreneurship is already developing, with several examples mentioned in this paper, and will grow.

Policy teams examining industrial emissions must face the consequences of the political impossibility of high and level global carbon prices and see different forms of intervention to drive change. In the longer term, this will require regulation that bans emitting processes and causes their closure. In the short term, governments can provide much clearer statistics on material supply and transformation and can work with sectors to identify the nearer to profit opportunities for change, which could be supported by modest subsidy or changed government procurement practices. Innovation funding can be adapted to support entrepreneurship focused on reducing the emissions of the way today's products are manufactured, in contrast to conventional entrepreneurship focused on delivery of new product features.

6.2. Research and innovation

For researchers concerned about climate change, this paper presents some clear directions. Firstly, the paper demonstrates that scale and speed of deployment is paramount. Research that promises emissions saving in a far distant future (such as new materials production processes), or which targets processes (such as additive manufacturing) which have negligible scale, is of little significance to the goal of emissions reduction. Instead, the priority is to modify today's high-throughput processes, in particular through developing new tooling and new control strategies for the bulk metal-forming processes that enable substantial reductions in total metal demand.

In parallel, there is a rich seam of opportunity to connect the activities of design with those of high-throughput manufacturing, to make better use of less metal in the components already produced today. This could combine modifications of Ashby selection methods, articulation of new design principles, or the construction of exemplars to demonstrate material input minimisation.

For any researcher who has the motivation to act, but is unsure where to start, the priority is to identify one or more high-volume components with features related to their existing expertise. The analysis of the three forms of scrap presented in this paper is the first of its kind and is at a high level and subject to very high uncertainty. Repeating this form of analysis in greater depth for specific high-volume components will point towards areas of opportunity that reduce manufacturing scrap, specification scrap, and property scrap. If these interventions can be scaled and delivered by familiar equipment with minor modifications, they will soon find eager customers and be the basis of a future climate compatible manufacturing system. In parallel, while steel and aluminium dominate global emissions from metal, the analytical approach and framework for innovation developed in this paper could equally be applied to other materials, with cement and plastic having the highest priority.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Julian M. Allwood: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Omer Music:** Writing – review & editing, Methodology, Formal analysis. **Evripides G. Loukaides:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Markus Bambach:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.

Acknowledgements

The work of JMA and OM on this paper was supported in part by EPSRC (Grant EP/S019111/1, UK FIRES). The work of EGL was supported in part by the Made Smarter Innovation: Centre for People-Led Digitalisation (EPSRC Grant EP/V062042/1).

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