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Connecting environmental systems analysis to manufacturing technology: A catalogue of the world's steel and aluminium components

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ABSTRACT

In pursuit of greenhouse gas emissions reductions, the environmental systems community has developed material flow analyses to describe the transformation of resources into goods, while the manufacturing technology community has developed innovations that can affect the production of individual components. However, these two communities have remained disconnected, because neither is able to relate their insights to their point of common interest: the global production of components. For the first time, this paper connects global analyses of the use of steel and aluminium to the production of components, classified by the metal forming processes which shape them. The results demonstrate the proportions of steel and aluminium used in ten distinct component groups, at global level, and for the major product groups which drive demand for these two metals. This helps both to prioritise requirements for innovation in design and manufacturing and to evaluate of the emissions potential of such innovations.

1. Introduction

Supply-side technologies such as carbon capture and storage, hydrogen electrolysis, negative emissions technologies and nuclear power, are deploying too slowly to meet climate mitigation goals. For example, in anticipating future emissions-free supplies of steel (which, with aluminium, is one of the two metals that dominate global metals emissions), Watari et al. (2023) anticipate a 35–42 % shortage of supply by 2050. As a result, demand-side interventions will receive increasing priority, and in turn this will drive new interest in environmental systems analysis. However, there is currently a disconnect between system-wide analysis of the use of these two metals and the development of technical interventions that might reduce demand.

For twenty years, Material Flow Analysis (MFA) (Streeck et al., 2023) has been applied to characterise the stocks (G. Liu and Müller, 2013; Pauliuk et al., 2012) and flows (Wang et al., 2007) of steel (J.M. Cullen et al., 2012) and aluminium (J.M. Cullen and Allwood, 2013; G. Liu and Müller, 2013; G. Liu and Müller, 2013) production and use (Maung et al., 2017), at global, regional (Dworak and Fellner, 2021; Hua et al., 2022) or national (Zhu et al., 2019; H. Yang et al., 2023) scales. This crucial work illuminates the scale of material use, so helps to direct attention towards key processes and end-use products. This has motivated new approaches to system-wide process control (Billy et al., 2022), and the design of recycling systems (Pauliuk et al., 2013; Modaresi and Müller, 2012; Nuss et al., 2014). However, while MFA is essential to determining the responsibility of different products for material use and hence for production emissions, it is insufficiently granular to prioritise the innovations in component design or production technology that would support continued service delivery with greatly reduced material input.

In contrast to the top-down insights of MFA, innovators in manufacturing and design, have sought bottom-up means to deliver "more sustainable" products. Such innovations include, for example, additive manufacturing techniques (Ford and Despeisse, 2016), sustainable grinding (Singh et al., 2020), environmentally friendly lubrication (Hörner, 2002), recycling by solid-bonding (Wan et al., 2017), innovations in materials science (Daehn et al., 2022) and overarching goals such as "light-weighting" (Lewis et al., 2019). However, while analysis of these interventions can demonstrate relative improvements over today's methods (Hagedorn et al., 2022), their proponents are rarely able to demonstrate how their proposed changes might scale up to have a global impact. Similar to work on behaviour change and climate mitigation that focuses largely on the relative improvements that individuals can make in their domestic setting, such approaches have

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proved “too reductive, individualistic, linear, deliberative and blind to [the scale of] environmental impact” (Whitmarsh et al., 2021).

There is a void between top-down environmental systems analysis and the bottom-up interventions that might be developed by innovators in design and manufacturing, which is currently filled with woolly aspirations expressed with religious fervour, such as “circular economy” (Allwood, 2014; Kirchherr et al., 2017), “regenerative design” (Cole, 2012), “eco-efficiency” (Hauschild, 2015) or “cradle to cradle” (Toxopeus et al., 2015). But the abstractions of these philosophies have to date proved insufficient to deliver meaningful, implementable, scalable change. As a result, manufacturing research motivated by environmental concerns lacks direction and scale, while environmental systems analysis is unable to identify the specific interventions that would deliver substantial change.

Some important technical innovations have demonstrated that value can be delivered with less material, by intelligent manufacturing. The development of tailor-rolled blanks is an excellent example, in which changed control methods, allow rolling of variable-thickness strip metal, to deliver increased stiffness where it is most needed, while saving material elsewhere (Kopp et al., 2005). Elsewhere, developments in computer-controlled tube-bending have reached significant commercial scale, creating new geometric forms with less material input (Murata and Kuboki, 2015; Becker et al., 2014), and the new process of transversal compression drawing uses moveable blank-holders to reduce losses in sheet-metal forming (Briesenick and Liewald, 2024). These innovations demonstrate that new material efficiencies can be achieved, provided manufacturing technologists are motivated with clear evidence of the benefit their work might bring.

In recent work, we have been fortunate to identify an intervention that bridges top-down and bottom-up approaches. Motivated by the high fraction of sheet steel and aluminium that is cut off in downstream automotive manufacturing (J.M. Cullen et al., 2012; J.M. Cullen and Allwood, 2013), we conducted detailed supply chain analysis to establish that the largest source of scrap is the trimming required after flat sheet blanks have been shaped during deep-drawing (Horton and Allwood, 2017). Taking inspiration from the techniques of Origami, we invented a new process, “folding-shearing” that, by obviating the requirement for blank-holding around the product perimeter, reduces the need for trimming (J.M. Allwood et al., 2019; Cleaver et al., 2022). For representative automotive sheet metal parts, this leads to a 30 % reduction in embodied emissions and a 20 % cost saving, and the company DeepForm Ltd is now commercialising the process as a drop-in replacement for conventional tooling in automotive press lines.

The key to finding this innovation was to relate the top-down priorities of MFA to a particular component type and its process chain. So, in order to accelerate and broaden the search for related innovations, for the first time, in this paper we aim to characterise global use of steel and aluminium in a catalogue of representative components and their associated process chains.

2. Methods

To build our catalogue, we follow three steps of analysis. Firstly, we review and reconcile top-down analyses of global use of steel and aluminium in products. Secondly, we specify a classification of representative component geometries, through a review of previous work in the area. Thirdly, we attribute the top-down analysis of metal use in products to the catalogue of components through detailed investigation of product designs, in order to estimate the global mass of metal used in each form of component. In order to simplify our language, we use the word ‘steel’ as a proxy for all ferrous metal, including both cast iron and stainless steel, justifying our choice by the relatively small mass of these alloys. We summarise the method here, and in the thirteen tables of the Supplementary Information file, demonstrate precisely how we manipulated the data we’ve drawn on, to create the paper’s main results.

2.1. Estimating global use of steel and aluminium in products

The global trade associations for steel and aluminium offer only sparse information on the use of their metals in different applications, divided between four major categories as construction, vehicles, industrial equipment and metal goods. Previous academic analyses have further sub-divided these categories for particular years and regions. For steel, two global analyses explore the data for 2008, (Cooper et al., 2012; Cullen et al., 2012), with one for Chinese consumption in 2018 (H. Yang et al., 2023) and one for US consumption in 2017 (Reck et al., 2024). These analyses all report data for consumption, or final use of steel, after yield losses in production have been taken away from initial liquid metal production. The most recent figures for global production, reported as fractions of liquid metal use, and which are divided into fewer categories, are for 2023 (World Steel (2024)Total production of crude steel: World total 2023). The proportions of these different analyses of the use of steel are presented for comparison in table S1 in the supplementary information. For categories that are reported in all three global analyses, the proportions vary by no more than ±3 % even though the data spans over 15 years.

For aluminium, only two relevant analyses have been found, both for global consumption in 2007, (Cooper and Allwood, 2012; Cullen and Allwood, 2013). The most recent figures for total global aluminium production are also for 2023 (International Aluminium (2024) Primary Aluminium production statistics 2024) but are not disaggregated at all. The proportions of the two more detailed analyses are presented in table S2 in the supplementary information, showing variation of no more than 1 % although this is unsurprising, as both analyses are for the same year and performed within the same research group.

The analysis of proportions of use of the two metals is summarised in table S3. For each metal, Cullen et al. (J.M. Cullen et al., 2012; J.M. Cullen and Allwood, 2013) estimate the yield ratio of final goods delivered from liquid metal produced, as 69 % for steel and that for aluminium as 56 %. These ratios are used to convert 2023 liquid metal production into an estimate of final metal use, and the proportions from the same two papers are used to estimate the final use of the two metals in 2023, disaggregated into ten major applications each.

For the categories of metal use in vehicles and metal goods, it is possible to add more detail to this breakdown, with a bottom-up analysis based on product sales. The Supplementary Information of (Cullen et al., 2012) gives preliminary details of the product composition of the entries in these two categories, which were used as a basis for finding total global production of a key products. A wide range of other sources, mainly design studies or life-cycle analyses, were used to validate the earlier estimates by calculating the product of global sales volumes with the average mass of each product and the fraction of steel and aluminium within this mass. The resulting bottom-up analysis is reported in table S4 and used to disaggregate the 2023 final metal use data of table S3. The additional sources of data were: for car sales (OICA 2023) and composition (Buschow, 2001; Lutsey, 2010); for truck composition (Cruz and I, 2020); for aeroplane sales (JADC 2022) and composition (Jr et al., 2011); for rolling stock sales (A. Statista 2024) and composition (Jones et al., 2017); for ship sales (BRS group 2023), mass (Hiremath et al., 2015) and composition (Hou, 2011); for food and drink can sales (360 Research Reports 2023) and mass (https://www.metalpackagingeurope.org/article/can-logistics-lighter-greener-and-more-efficient#); for foil (https://www.alcircle.com/-specialreport/315/aluminium-foil) and shipping container sales (https://www.ft.com/content/2c3747de-7827-–471e-99a0-af554cb3b4e8 2022); for domestic cookers and ovens sales (Statista 2024) and mass (D. Landi et al., 2019) and for the mass of all other domestic appliances (Truttmann and Rechberger, 2006).

This bottom-up approach increases the resolution of final metal use from 10 to 20 categories, albeit at the cost of some uncertainty. Table S4 shows that at the more aggregated level (i.e. for total use in the two categories of vehicles and metal goods) the bottom-up and top-down approaches are within ±4 % for steel and ±12 % for aluminium. At finer levels, the variation is greater, particularly for aluminium. However, this may reflect different definitions of categories (does the category "cars" include "light vans" or not?) or the inclusion of large "other" categories in the analysis of metal goods.

Combining the top-down and bottom-up analyses, Table 1 presents our estimate of the proportions of final use of the two metals in twenty product categories. The numbers in the table refer to the fraction of final use of metal in products after the yield losses have been removed. This simplifies communication, as the product fractions add to 100 %, but is potentially misleading as the embodied emissions from metal mainly arise from liquid not final metal production. Some sub-divided product categories (such as ships or rolling stock) have been aggregated.

Table 1 is a higher-resolution product breakdown than previously published, with only 12 % of final use of both metals unallocated in the final row. Despite the uncertainty behind these numbers, the table gives clear priority to the major product types to be investigated in this paper. If it is possible to identify the major component types used to produce these products, we can reasonably assume that they are representative of the use of the two metals in general.

2.2. *Classification of steel and aluminium component types*

For 40 years, many attempts have been made to classify component geometries according to shape. An early approach (Sachs and Voegeli, 1966) aimed to support the selection of manufacturing methods for a given part shape and, as illustrated in Fig. 1, subdivides sheet-metal structures into components according to geometrical features that relate to the capacity of sheet metal forming processes.

A similar more recent approach (Šugár et al., 2011) applies Group Technology (Mitrofanov, 1960) to classify sheet metal parts into families based on various attributes including manufacturing processes. This system divides sheet forming processes into four groups: shearing (cutting), drawing, bending and metal spinning. In later work, a set of rules was proposed to decompose parts into manufacturing features (Baptista et al., 2019), to facilitate design for manufacturing, which could lead to a classification system. This has yet to be completed but relates to the

Table 1
Consolidated estimate of the fraction of final steel and aluminium used in products.

	Steel	Aluminium
Final metal used in products	100 %	100 %
Construction	**55 %**	**22 %**
Buildings	33 %	20 %
Infrastructure	22 %	2 %
Vehicles	**13 %**	**32 %**
Cars	5 %	16 %
Light commercial vans	4 %	14 %
Trucks and buses	2 %	2 %
Airplanes	0 %	0.3 %
Trains	0 %	0.2 %
Ships	1 %	0.1 %
Other vehicles	1 %	0 %
Industrial equipment	**16 %**	**19 %**
Mechanical	13 %	6 %
Electrical	3 %	12 %
Metal goods	**16 %**	**27 %**
Packaging total	*2 %*	*14 %*
Food and drink cans	1 %	5 %
Shipping containers	1 %	0 %
Foil and other	0 %	8 %
Domestic appliances total	*2 %*	*2 %*
Cookers and ovens	1.0 %	0.4 %
Refrigerators and freezers	0.5 %	0.4 %
Washing machines	0.5 %	0.5 %
Dishwashing machines	0.2 %	0.1 %
Air conditioners	0.1 %	0.1 %
Other metal goods	*12 %*	*12 %*

approach of the German standard DIN8580 (DIN 8580 2003) which classifies manufacturing processes, and the shapes they can produce, based on the predominant stress state in the part as it is formed. As a result, for example, metal forming processes where through-thickness stresses are negligible are classified as sheet forming processes, while those enforcing a three-dimensional stress state are termed bulk forming.

Recent developments in part classification have aimed to support component reuse, for example with a systematic classification of sheet metal parts to allow search and retrieval of similar parts and reuse of existing part designs and process plans (Greska et al., 1997). Such approaches aim to reduce the number of part variants and increase the efficiency of design and manufacturing, for example with an automated system initially developed to classify bent and embossed features in sheet metal parts (Gupta and Gurumoorthy, 2013) and subsequently developed to include generic features (Gupta et al., 2017) as an aid to reusing existing designs.

A useful precedent for the requirements of this paper is Ashby's classification which links processes to the shapes and tolerances they can deliver (Ashby, 2011). The design of this classification is shown in Fig. 2, showing the overall approach, but without detail of each shape class.

For this study a classification is developed from Figs. 1 and 2, to span the component geometries that can be created by high-throughput manufacturing technologies. The variety of such geometries is potentially infinite, as downstream manufacturing processes adjust the initial form, by forming, or the subtraction or addition of metal. However, while CNC cutting machines can cut virtually any geometry out of a suitable blank, the predominant industrial approaches used to mass produce high-volume components, are based on high-throughput metal forming. The classification developed for this paper and shown in Fig. 3 therefore relates closely to these forming processes. For example, three-dimensional components are likely to be made by forging or casting, prismatic components by rolling, extrusion or drawing, and sheet components are made by bending, stamping or deep drawing. Each component may have many further geometrical details but is classified by its predominant feature.

The classification of sheet and plate components in Fig. 3 arises from the mechanics of forming processes: in bent features the only plastic strain is along the line of the bend; in stretched features the part perimeter is largely unchanged, so shaping the part leads to thinning; in deep-drawn parts, there is little change in thickness as material is drawn into the part from the perimeter of the blank. Most of the processes in the classification of Fig. 3 depend primarily on a large force acting along one axis across the part. For forming shell geometries from flat sheets, the classification separates stretching-embossing processes from deep-drawing, because the first depends on "crash-forming" with the part perimeter unrestrained, while the latter uses a blank-holder to control material flow while navigating the two failure modes of tearing or wrinkling. The classification assumes that most sections (the stiff beams of steel-framed construction) are made by hot rolling. Lighter sections may also be made by roll-forming, which is a form of bending process, albeit in the analysis that follows it can be difficult to distinguish which sections are made by which form of process.

2.3. *Estimating the mass of steel and aluminium in components*

Armed with the classification of Fig. 3, the remaining work of the methodology is to estimate how much of the steel and aluminium in the major products reported in table 1 is in the form of each component type.

Two previous analyses provide sufficient detail on the use of steel and aluminium in **construction** to relate the total use of the two metals in table 1 to the catalogue of Fig. 3 directly. Cullen et al. (2012) and Cullen and Allwood (2013) relate the global production of liquid steel and aluminium respectively to the intermediate products of the metals industries, which for construction largely define their role as

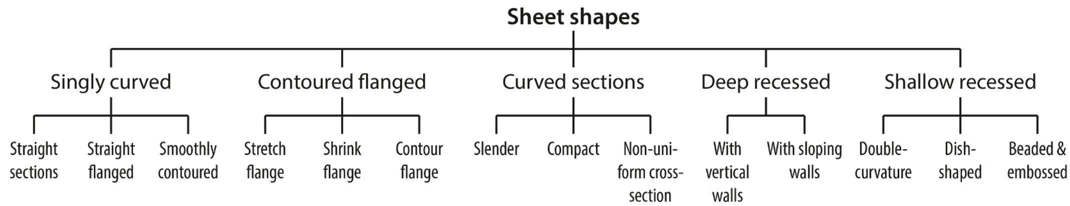

Fig. 1. An early classification of sheet metal components.

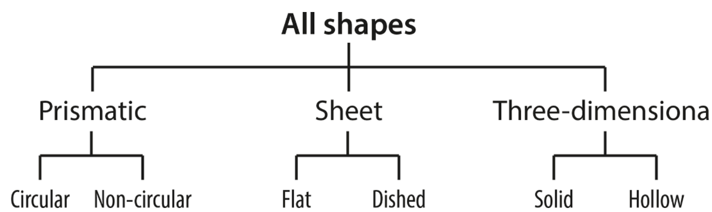

Fig. 2. Component shape classification linked to processes (adapted from [70]).

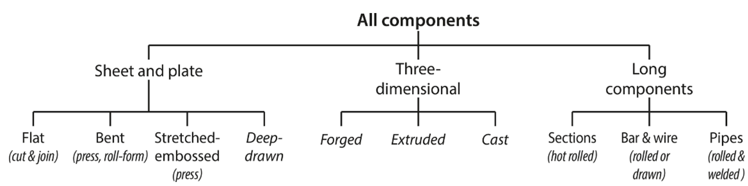

Fig. 3. Proposed component classification (*with forming processes in italics*).

components: hot rolled sections, reinforcing-bar or plates rolled and welded into pipe need no further analysis to be entered in the catalogue of Fig. 3. This is confirmed by a detailed analysis of the flow of steel into the construction sector (Moynihan and Allwood, 2012), in both the UK and globally in 2006, which details the range of components in both buildings and infrastructure and gives further detail of material use in different commercial building types. The numbers from these three papers are used to assemble table S5, which details the breakdown of steel and aluminium use in both buildings and infrastructure and shows how the different uses in construction relate to the catalogue. No comparator analysis has been found for aluminium use in construction, but the relative consistency with (Cullen et al., 2012) and (Cooper and Allwood, 2012) for the use of steel, gives some confidence that this breakdown may be accurate to around ±10 %.

Vehicles. *Cars and light vans*, which are generally viewed as having similar composition, dominate the vehicles category. Only two studies have attempted to categorise component types by material and mass and these are summarised in table S6 for three representative cars. Within the table, cars from 1995 (Sullivan et al., 2010) and 2011 (Sato and Nakata, 2020) are analysed in studies aiming to identify the embodied energy/emissions of a specific mass-market car. The data are cross checked against the proportions of steel and aluminium (Davies, 2012), with the aggregated mass fraction of component types from a study of light-weighting options (Stodolsky et al., 1995), and an LCA study (Weiss et al., 2000). However, in recognition of changing trends in both the material composition and size of cars, the most recent vehicle, is taken as representative in allocating the use of steel and aluminium in cars and light vans to components, although it retains a large undifferentiated category of "stamping" encompassing all components made from sheet materials.

Unlike cars and light vans, *trucks and buses* are built on a heavy chassis frame, typically welded from plate steel. A detailed analysis of a 40-tonne articulated truck (weighing 15 tonnes with 25t load capacity) specifies the typical mass composition of vehicle systems and is reported in table S7, with total material masses for steel and aluminium used as a check (Hill et al., 2015). Percentage material composition of these systems have been estimated to match the reported material mass, from which table S7 estimates the likely entries in the component catalogue. The formed sheet components in the cabin can be assumed to follow the same proportions as in table S7. As the total weight of a bus analysed in the same source is similar to that for the truck, it will be assumed that buses have a similar composition.

The distribution of aluminium in *aircraft* quoted from the Chinese non-ferrous metals fabrication industry association (Zhou et al., 2021) is 60 % extruded (for ribs, stringers and fittings), 28 % rolled (for skin-panels, which are largely bent prismatically), 7 % forged and 5 % cast for more complex structural elements.

A comparative analysis of materials used in four metro *train* vehicles in 2009 (Carruthers et al., 2009) reveals that 41 % of the train mass is in the bogies (forged from steel) and 24 % in the body shell (largely formed by bending sheet aluminium). All other components have much smaller mass contribution and use a diversity of materials, but as only the use of aluminium appears in table 1, analysis is sufficient to allocate it to the catalogue of Fig. 3.

The component composition of *ships* is deduced from a comprehensive review (Jain et al., 2016) of nine studies of ship-breaking, which aim to inform decisions about the use of materials harvested from end-of-life ships. The review reports that 85 % of the weight of a large ship is in the stiffened plates that form the hull, comprising flat or near flat cut-plates welded to stiffening long sections. As ships use just 1 % of the mass of all steel in table 2, all other components will be ignored, and using an informal estimate from diagrams of ship cross-sections (Eyres, 2001), it will be assumed that 80 % of the mass of steel in a ship is in plates and 20 % in long sections. The use of aluminium in cruise ship superstructures is assumed to be in the form of welded flat plates.

As "other vehicles" includes those used in agriculture and military applications, they will be assumed to have the same component composition as trucks.

Industrial equipment. This sector of metal use is the least researched, remaining frustratingly opaque, even in the face of sectoral

Table 2
Catalogue of the world's steel and aluminium components.

	Catalogue - steel										Catalogue - aluminium								Product proportions		2023 use by product (Mt)	
																			Steel	Alum.	Steel	Alum.
Proportions of final metal used in each product, by component (rounded by nearest %, or 0.1 % for proportions less than 0.5 %)	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	100 %	100 %	1309	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 %**	**212**	**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 %				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				

trade analysis (Jiang et al., 2023). Analysis of trade data in the PRODCOM database (Eurostat 2024) reinforced by statistical analysis (Statista 2022) confirms that it largely comprises "General purpose machinery" (52 % of the total, including manufacture of steam, gas, wind and hydraulic turbines, pumps, compressors, taps, valves, bearings and transmission equipment, furnaces and burners, lifting and handling equipment and non-domestic cooling and ventilation equipment) and "Industrial Processing machinery" (34 % of the total, including specialist machines and applications to aid the manufacturing processes in a range of diverse sectors: for example, special purpose machinery for mining and quarrying, metallurgy, food and beverages processing, textiles and clothing pro- duction, paper and paperboard production, or construction). However, one previous analysis (D.R. Cooper and Allwood, 2012) has attempted to disaggregate industrial electrical equipment into components, with a granularity appropriate to this paper. This leads to table S9, with sufficient detail to translate the total global use of steel and aluminium in Table 1 into the categories of the proposed component catalogue of Fig. 3.

Metal goods. The literature of Life Cycle Analysis (LCA) provides a rich source of data on the composition of metal goods, aiming to support product optimisation and recycling strategies, albeit often with more detail on material specification than geometry or manufacturing pathways. Several analyses of aluminium beverage cans (A. Detzel and Mönckert, 2009; Metal Packaging Europe 2022) confirm that 78 % of the material is in the deep-drawn body of the can, while the remaining 22 % forms the closure (comprising top and ring pull) which is largely embossed from flat sheet. Cooking foil needs no further analysis as it is used directly after cutting, and while no LCAs of shipping containers have been found, structural engineers have considered re-purposing them for housing, providing detail on geometry, including the thickness of the corrugated side materials (Giriunas et al., 2012), and the cross-sections of the channel-sections which provide the structural frame (Ntumi, 2018) which is sufficient to divide the mass between sections and bent plates.

Among the domestic appliances, a detailed life cycle inventory summarised in table S11 describes the use of materials and their forms in gas ovens (Statista 2024). A less-detailed inventory of the make-up of refrigerators (R. Xiao et al., 2015) separates the materials between the sheet steel used to form the cabinet, and metal used in compressors and "accessories", with no further detail, but an eco-design study (European Commission 2016) suggests that the compressors are an assembly of cast iron or steel components with extruded aluminium, and the accessories of either metal are assumed to be pressed from sheet. A similar study by the same group provides the material composition of washing machines by main modules (Yuan et al., 2016), leaving open the form in which metal is used in "electronic components", but a second LCA study by a different group (Alejandre et al., 2022) clarifies that this is largely related to cast metal. The second of these studies also provides a compositional analysis of dish-washers, allowing the same assumption about the use of cast metals. This is supported by a study which divides the use of steel between stainless and galvanised components (Porras et al., 2020). Assuming that the stainless components are largely the internal panels in contact with water, which are all shaped to support water flow, we assume these are deep-drawn, while the galvanised sheet is used for the external box, made largely by embossing, as with the other appliances above. Finally, two LCA studies of domestic air conditioners (Li, 2015; Karkour et al., 2021) divide the material composition to include stainless steel, steel, cast iron and aluminium, without component descriptions, so it is assumed that the steel is all used as embossed sheet, and the aluminium as extruded pipes and fins for heat exchange.

This analysis of metal goods leads to the allocations of metal to components summarised in table S10.

The category of "other metal goods" accounts for 12 % of the final use of both metals, and further disaggregation of this group has defeated us. It certainly includes aluminium lithographic plate (0.5Mt in 2008) and the use of aluminium for deoxidising steel production (1.3Mt in 2008) (Cooper and Allwood, 2012), but neither these, nor the use of steel in powder form (~1 Mt in 2015) (J.M. Azevedo et al., 2018), are substantial fractions. Until further data is collected, and in recognition of the diversity of applications in this "other" category, we therefore assume that the component breakdown is the average of all other applications of the two metals.

Tables S5-S10 and the above text now provides the data required to assemble the main results of the paper. Further manipulation of the main result to allow construction of the two new Sankey diagrams in the Results section is described in tables S12 and S13.

3. Results

The catalogue of components is presented in table 2, which is the result of combining the product analysis in table 1, with the detailed analysis of components in tables S5-S10.

The entries in the main part of the table are the percentages of final metal used for each major product in table 1 (rows) and the component forms of Fig. 3 (columns) split by steel and aluminium. The row sums show the percentage of all metal used by each product, equal to those in table 1, and are scaled by the reported final use of the two metals in 2023. The column sums give the percentage of all metal used for each component form, and the estimated mass of each component type produced in 2023.

Fig. 4 presents the same data (the column sums as proportions) as a bar chart.

The lengths of the bars in the figure demonstrate wide variation of metal use across the components, showing for example the importance of extruded aluminium and the bars and wires made in steel, and the relative unimportance of forging or stretch-embossing. The fact that so much sheet metal, of both types, is simply cut and joined, or cut and bent to shape, is a significant revelation, given the lack of attention that these processes receive compared to the intensive research efforts spent on deep-drawing.

To draw out the full benefit of the new catalogue and the analysis in the paper, Figs. 5 and 6 are Sankey diagrams to show the transformation of the intermediate products of the metals industry via component manufacturing processes and into final goods. The diagrams have been scaled by 2008 data, and in both cases, the left side matches identically the equivalent stage of Cullen et al.'s earlier analyses (J.M. Cullen et al., 2012; J.M. Cullen and Allwood, 2013), so enthusiastic users could print out our new diagrams and the earlier versions, and stick them together!

In both cases, the right-hand side of the diagram, from components to products, is drawn directly from the proportions of table 2 scaled by 2008 final consumption. The left side is the solution of a "sudoku" puzzle, allocating the intermediate products to component production, according to the natural feedstocks of each process. The details of this allocation are given in section 10 of the Supplementary Information and includes the small "balancing terms" illustrated in the two figures, which reflect changes in product design since 2008 and our uncertainty about the component composition of the "other products" categories in table 1.

Comparing the two new figures with their precursors, our combination of bottom-up and top-down analysis has allowed greater resolution in final products, for example demonstrating the high importance of shipping containers, and the low relative importance of aircraft manufacture.

However, the main value of the new figures is to give new priority to the search for innovations that reduce metal demand in future. The scale of component production summarised in Fig. 4 is already indicative of where attention is required, but Figs. 5 and 6 also reveal the product chains, from material producer through manufacturing to product design where more attention is likely to yield most reward. An obvious priority for both metals is to explore in detail how sheet metal is used in construction and whether new design methods or production technologies could deliver equivalent value with much less metal. The large

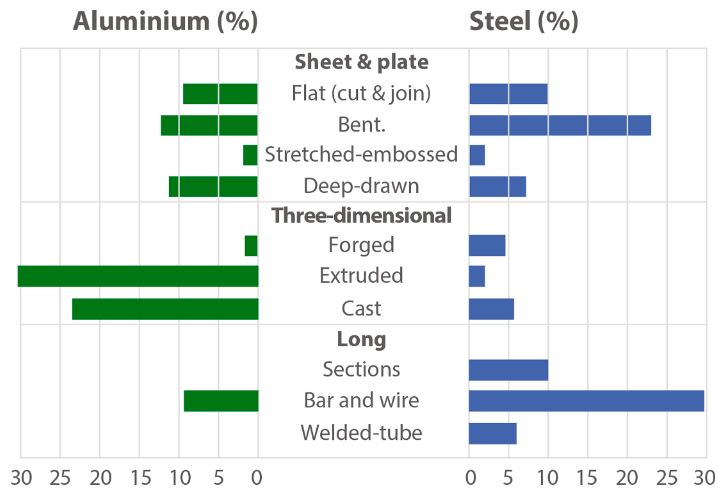

Fig. 4. The proportions of the world's use of steel and aluminium by component.

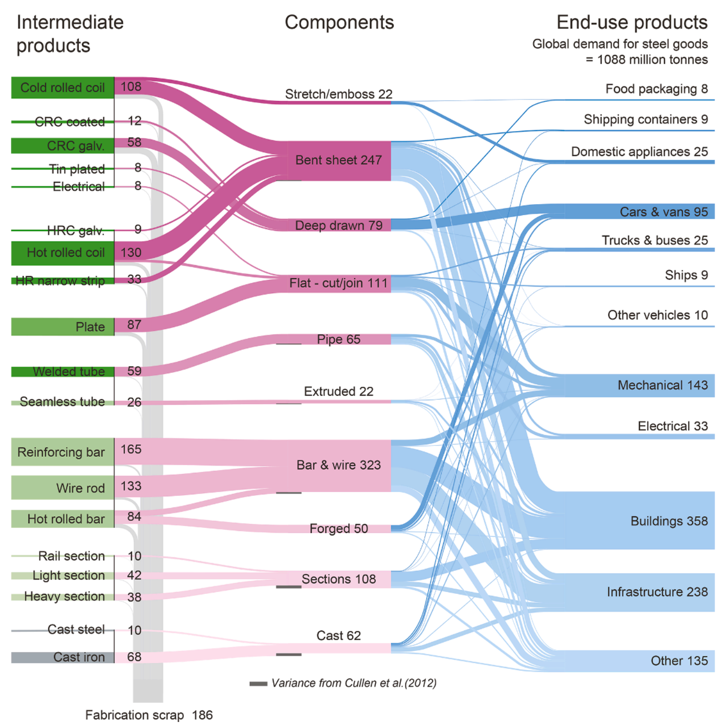

Fig. 5. A Sankey diagram showing the flow of intermediate steel products through component manufacture and into final products.

fraction of aluminium processed by extrusion equally merits attention, as few applications really require constant-cross-section elements. Similarly, beyond the use of reinforcing bars in construction, further exploration into the drivers of substantial additional requirements for bars may reveal new opportunities for material efficiency. For both materials, the category of industrial application is the most opaque, and future research could usefully aim to identify what this large driver of demand for both metals really entails.

4. Discussion

For the first time, Fig. 4 allows a translation between the insights of the environmental systems community and those working on innovations in design and manufacturing. For example, knowing that two thirds of all aluminium is used in bent, deep-drawn or extruded components clearly targets the search for innovations to reduce total material demand. Equally, the absence of powder metal processes from the figure saves any further exploration of the role of additive manufacturing as a contributor to climate mitigation. The requirement for innovation is focused entirely on the most long-established high-throughput processes, and must aim to adapt those processes rather than hope to replace them with novel, but lower throughput, approaches.

By far the most significant application of steel is in construction, and from table 2, the key components are reinforcing bars, bent sheet and plate, and hot rolled sections. Yet, a title search of the complete annals of the International Academy of Production Engineering (CIRP) since its founding in 1951 suggests that no paper has ever been published focused on the developments of manufacturing technology to support construction. The applications that most matter have been overlooked by those who could attempt to intervene, because previously they have been given insufficient attention. Equally, the dominant application of aluminium is in cars and light vans, motivated partly by the automotive

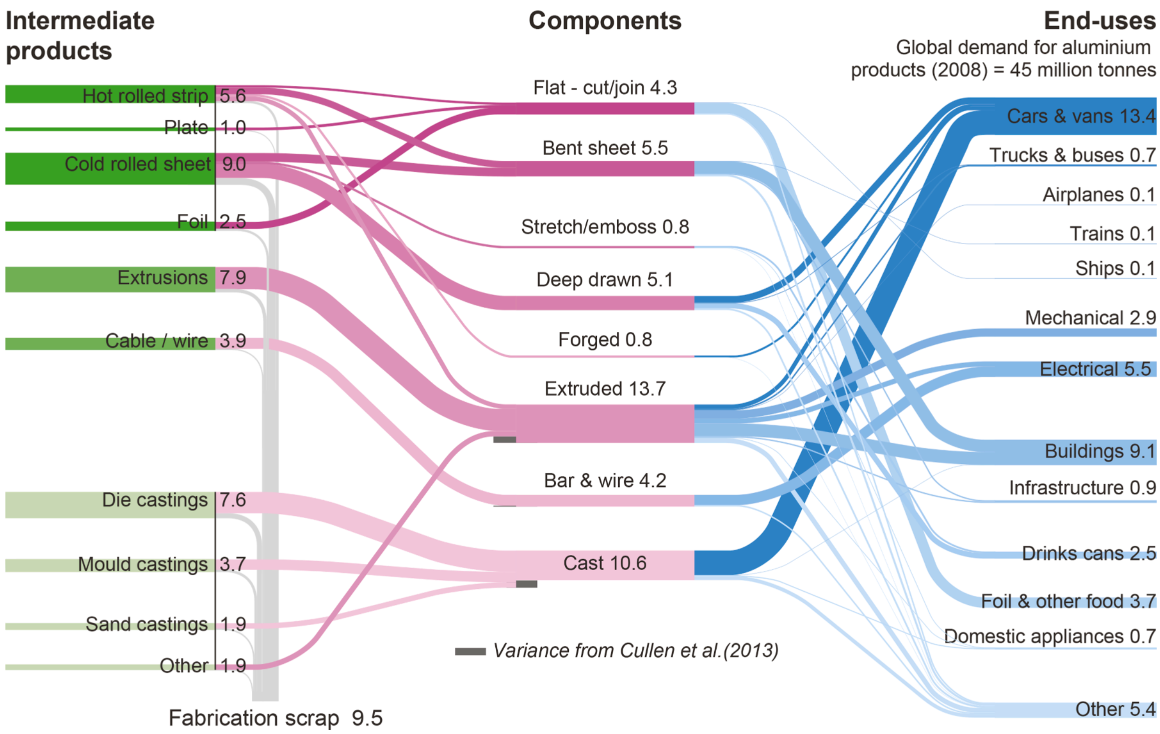

Fig. 6. A Sankey diagram showing the flow of intermediate aluminium products through component manufacture and into final products.

industries long trumpeted push for "light-weighting." Yet cars are in fact still becoming heavier (A. Hula et al., 2023), because they are becoming larger, so manufacturing innovators can push not just for material selection, but also to promote smaller more materially efficient designs and production processes, requiring as much attention on customer preferences as on manufacturing technology. While domestic appliances have been the focus of much sociological work on behavioural change, the table reveals that they are not a high priority product, and despite their much discussed "fly-to-buy ratio" (Hodonou et al., 2019), neither are aeroplanes.

Table 2 further prioritises the innovation requirements within each product type. For ship building and the construction of mechanical equipment, for example, the priority is to make better use of flat plate. While laser-cutting and welding thick plates provides a convenient route to stiffness for massive structures, other approaches such as space-frame structures (Kociecki and Adeli, 2015), could deliver this stiffness with much less material. Meanwhile, the priority for domestic appliances is to reduce the use of stretched-embossed steel sheet. For example, could appliance stiffness requirements be reduced by dynamic compensation for vibration (Spelta et al., 2009), or could the outer case of the appliance be formed with a material with lower embodied emissions (Ashby, 2012)?

The numbers in table 2 are estimates subject to significant uncertainty. The data required to create the table are not collected by any agency, so must be estimated, inferred and extrapolated. Tables S1 and S2 show that variations of around $\pm$2–3 % in estimates of proportions of metal use at the larger category level (construction, vehicles etc.) which rise to more like $\pm$10 % for specific products. This level of uncertainty is consistent with a paper using Bayesian methods to estimate material flows (Lupton and Allwood, 2018) and a very detailed report of updates to the steel analysis (Harvey, 2022). Table S4 which compares top-down and bottom-up analyses of metal use in the vehicle, appliances and packaging sectors shows variation up to $\pm$50 % in the estimates, and in the absence of any other basis for assessing the uncertainty of table 2, this would be a sensible figure for the overall uncertainty of the numbers in table 2. Further effort might reduce this uncertainty in the global analysis but might generate little new insight about the actions motivated by this paper: the catalogue of table 2 already demonstrates the priority component forms and processes. Designers can now use this priority list to begin a more detailed examination of particular product or component types, as demonstrated for car-body parts in [33], in order to target their search for effective interventions.

The analysis gives no insight into the material losses of machining, by which final components are cut out of intermediate products produced by the processes of Fig. 3. Particularly when bars are used as the feedstock for machining, these losses are high, and greater characterisation of them may motivate innovations in metal forming to reach "nearer net shape." To date, such innovations have been held back by the higher cost of machining time relative to materials, but as public and regulatory pressure to reduce emissions increases, the ratio of these costs will change.

The existence of the catalogue now creates the starting point for a more detailed study on material efficiency: how well are these components made and used relative to the demands made of them in service. Manufacturing yields have been assumed in this analysis, which has focused on final metal use, but if they are characterised in more detail and combined with the insight of table 2, this will direct attention towards the greatest opportunity for avoiding manufacturing scrap.

A key consequence of the analysis of the paper is to direct the attention of the manufacturing innovation community towards processes with high throughput. To illustrate this, Fig. 7 contrasts the throughput of the ten processes associated with the catalogue developed in this paper, with that of three recent innovations in metals-processing technology (production rates found in the literature for Wire EDM (Gutowski et al., 2007), Incremental sheet forming (Allwood et al., 2005) and powder processes (J.M. Azevedo et al., 2018).)

The message of the figure is absolutely clear: if manufacturing technologists wish to contribute meaningfully to reducing the demand for metal in anticipation to a rapid contraction in supply as zero-emissions goals become law, they must focus on delivering "drop-in" solutions for existing processes. Innovations in the tooling and control of these processes, as evident in the examples described in the introduction to this paper, could have an important impact at scale. Novel material combinations, and new micro-scale production will not.

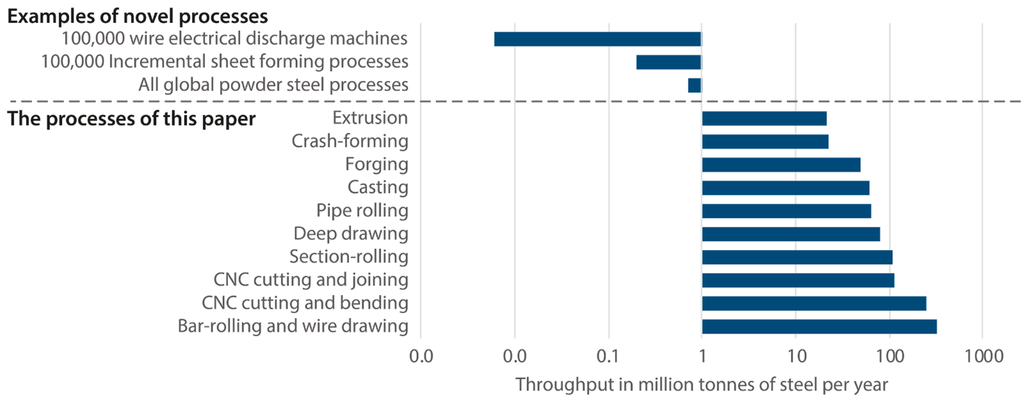

Fig. 7. Throughput of various manufacturing processes compared.

In the 1980′s a movement aiming to address part of the motivation of this paper began, under the banner of "near-net shape forming." (N.A. Waterman, 1982; Altan and Miller, 1990) The goal of innovations in this space was to avoid any scrap at all in the production chain from liquid metal to final part, so inevitably this focused primarily on casting and forging. (Kudo, 1990) Some innovations in the area began, and have continued particularly in the area of cold-forging, where a secondary benefit of near net shape forging is improved wear-resistance. However, all innovations in the space run against the "magic triangle" of manufacturing, which is to aim at minimum cost and lead time with perfect quality. Unfortunately, the financial benefit of material saving is quickly eliminated with any increase in cycle time, and even capital purchases are hard to justify if they are linked to disruptions to existing production habits.

This difficulty is reflected in the fact that we have known for more than a decade that construction is the dominant user of metal. Several innovations have been proposed, including new design tools to avoid over-specification (Gauch et al., 2022), new techniques for making variable section beams (Carruth and Allwood, 2012), and new approaches to commercialising steel re-use (Dunant et al., 2018). However, they have as yet achieved little commercial scale, as steel is made in such high volumes that it has a low price compared to the costs of the labour needed to use it well.

In the short term, this imbalance between labour and metal costs further reinforces the importance of innovations to tooling and control in existing processes, which can be adopted rapidly and with low risk or cost. In the medium term, it is likely that the prices of new metal will rise as emissions constraints bite (L. Gast and Allwood, 2023), in which case the forms of innovation stimulated by this paper will find greater market pull, with the goal of making better use of less metal.

Finally, the catalogue motivates a change in approach from the metallurgical/materials science communities. Where, for recent decades, these groups have pursued material innovation (new compositions and alloys) as the solution to all problems, now they could explore whether, at global scale, the properties of metals are being used effectively in service (evidence suggests that, at lease in steel-framed construction, they are substantially over-specified (Moynihan and Allwood, 2014; Dunant et al., 2018)), and if not, to pursue a closer integration of their material insights with those of product and process designers (J.M. Allwood and Raabe, 2024).

5. Conclusions

Previously, the environmental systems community knew about the use of metal in intermediate and final product groups, which informs responsibility but not change. Now we can report metal use by component, so can prioritise the design and manufacturing interventions that will make most difference. Rather than attempting to "add on" environmental concern to other research activities, future researchers can now design their activities to target the right impact – making better use of less metal, while also "calling out" interventions (such as additive powder processes) that can have negligible impact at scale. The results have high uncertainty, but the overall distribution of metal between component/process types gives clear guidance, and future studies focusing on particular component forms and processes may be able to add resolution.

Supporting information: The Supporting Information comprises thirteen tables S1-S13 all referenced in the main text, and has brief text to define the sources and manipulation required to create the result reported in Table 2.

CRediT authorship contribution statement

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

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Julian Allwood reports financial support was provided by Engineering and Physical Sciences Research Council. Omer Music reports financial support was provided by Engineering and Physical Sciences Research Council. Julian Allwood reports a relationship with DeepForm Ltd that includes: board membership and equity or stocks. Omer Music reports a relationship with DeepForm Ltd that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107949.

Data availability

All data used in the analysis is in the paper or SI

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