

## Reusing Steel and Aluminum Components at End of Product Life

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### S Supporting Information

**ABSTRACT:** Reusing steel and aluminum components would reduce the need for new production, possibly creating significant savings in carbon emissions. Currently, there is no clearly defined set of strategies or barriers to enable assessment of appropriate component reuse; neither is it possible to predict future levels of reuse. This work presents a global assessment of the potential for reusing steel and aluminum components. A combination of top-down and bottom-up analyses is used to allocate the final destinations of current global steel and aluminum production to product types. A substantial catalogue has been compiled for these products characterizing key features of steel and aluminum components including design specifications, requirements in use, and current reuse patterns. To estimate the fraction of end-of-life metal components that could be reused for each product, the catalogue formed the basis of a set of semistructured interviews with industrial experts. The results suggest that approximately 30% of steel and aluminum used in current products could be reused. Barriers against reuse are examined, prompting recommendations for redesign that would facilitate future reuse.



### 1. INTRODUCTION

To stabilize world temperature, the Inter-Governmental Panel on Climate Change (IPCC) has recommended a minimum 50% cut in global emissions from 2000 levels by 2050. The steel and aluminum industries contribute much to global emissions, creating 10% of the world's anthropogenic carbon dioxide from energy and processes.<sup>1</sup> Analysis of potential efficiency savings by Allwood et al.<sup>2</sup> demonstrates that, because the key energy intensive processes are already so efficient in these sectors, increased production efficiencies and maximized recycling rates—taken at 90% for both metals from Ayres<sup>3</sup>—alone cannot achieve this 50% reduction. Allwood et al.<sup>4</sup> therefore review strategies for demand reduction through material efficiency (providing material services with less material production). Among these, nondestructive component reuse could be highly effective; it avoids the high energy costs of recycling through melting by preserving the microstructure and geometry of existing components. See Allwood et al.<sup>5</sup> for an assessment of the absolute emission savings.

Reuse has received little attention despite being one of the well-known “3Rs”—reduce, reuse and recycle—promoted by government organisations such as WRAP in the U.K. “Reduce” in this context may mean reduce yield loss in manufacture, reduce product mass, reduce replacement rates, and/or reduce overcapacity. “Re-use” implies a nondestructive process, utilizing end of product life components without melting them. “Recycle” denotes melting components so that the metal can be recast and shaped into new intermediate products. Allwood et al.<sup>2</sup> estimate current recycling rates at 65% for steel and 39% for aluminum. Addis’<sup>6</sup> design handbook on building with reclaimed components is a rare example of practical reuse in the literature, but does not quantify possible reuse levels.

Policy makers must know the possible scale of reuse across all products and understand the technical, system, and policy changes required to develop reuse at scale for reuse to contribute significantly to emissions abatement. This work aims to provide an estimate of the technical potential for reuse, recognizing that subsequent work is required to evaluate its economic and policy consequences. This work targets component reuse in which old products are disassembled and components reused in a new product, rather than product reuse that might occur, for example, through second-hand sales.

Component reuse occurs in many sectors, but only on a small scale. The only industry-wide example identified in the literature is of ship dismantling in Asia, where the majority of discarded ships are broken. Tilwankar et al.<sup>7</sup> find that up to 95% of the steel recovered from vessels in India is in the form of rerollable ferrous sheets. The steel is rerolled (without melting) into flattened plates, bars, and rods used in the construction sector. Elsewhere, in construction, Gorgolewski et al.<sup>8</sup> assess reuse of structural sections, finding that, despite having good mechanical properties, uncertainty about the steel's origin and a lack of available stock leads to relatively limited reuse, generally only for less demanding applications—such as shoring of construction works. Kay and Essex<sup>9</sup> report that 1.5% of end-of-life structural steel in the U.K. was deconstructed in 2007. The amount reused is not reported but will be only a fraction of this. In the transport sector, Dong<sup>10</sup> discusses car engine remanufacturing, and Ferrer<sup>11</sup> tire

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retreading. Tekkaya et al.<sup>12</sup> demonstrate reshaping sheet metal scrap by applying hydro-forming to flatten contoured sheet metal parts. Takano et al.<sup>13</sup> investigate similar ideas through incremental forming of nonuniform sheet panels. These technologies could potentially be used to transform car closures, such as bonnets and doors, and appliance panels into other useful shapes.

No analyses have been found on the global potential of reuse across all products. Sherwood et al.<sup>14</sup> analyze the waste streams of remanufacturing companies, reporting that most discarded parts are worn and unusable, suggesting that efficient reuse of components might be feasible. This analysis, however, focuses only on existing remanufacturers, ignoring, for example, metal reuse in buildings and infrastructure. Umeda et al.<sup>15</sup> investigate the balance of supply and demand for components to determine maximum possible reuse rates: for rapidly developing products without any component standardization, any reclaimed components at end-of-life are incompatible with new product design and cannot be easily reused. Reuse is therefore more likely for mature products or for where certain components can be standardized across product generations.

An analysis of metal intensive products is required to estimate whether component reuse can make a significant difference to global demand for liquid metal. Existing global analyses of metal end-use include the World Steel Association<sup>16</sup> and International Aluminum Institute<sup>17</sup> for steel and aluminum, respectively, but both present only the destinations of intermediate metal products at a sector level, such as “transport” and “construction”, rather than attributing demand to final products. Assessing the potential scale of reuse requires knowledge of the actual products and components. This work therefore addresses three questions:

- In which final products is steel and aluminum used?
- What are the key design requirements for the steel and aluminum components in these products?
- What fraction of the end-of-life components in these products could technically be reused and how, and what physically prevents reuse of the remaining components?

## 2. METHODOLOGY

A comprehensive search of the academic and company literature, combined with a set of structured interviews, are used to address these questions. A vast range of data sources is used, so the paper is accompanied by an extensive 168 page Supporting Information (SI) in which a catalogue of 23 product descriptions is presented, derived from 200 literature sources and informed by 17 interviews with industry experts.

**2.1. In Which Final Products Is Steel and Aluminum Used?** Component reuse becomes possible when products reach end-of-life, so future reuse patterns depend on replacing the stock of products already in service. However, because of the lack of historical records of past production, such stock estimates can at present be made only in aggregated form. Instead, this section focuses on the final products made with current steel and aluminum production. This data is also not collected in any uniform manner, so must be inferred from other sources. Three methods could achieve this: using input–output economic data, scaling national or local studies to global level, and combining top-down and bottom-up studies on end-use.

Input–output analysis could be used to predict current applications of steel and aluminum if metal tonnages were

assigned to money flows that could be traced from production to end-use. However, metal tonnages do not necessarily relate directly to money flows; double counting due to trade when considering multiple regions is likely; data is sparse; the relevant data tables provide only end-use data at the sector level, so further analysis would be required in order to resolve metal use to specific products.

Various academic studies and large company reports provide data on local metal use in regions and states, which could be scaled to a world level. For example, refs 18 and 19 present detailed aluminum stock data for China and Connecticut respectively, and ref 20 provides scrap stream data for 9 different U.K. product categories. However, most of these studies target either stock or scrap flows, so production data must be inferred from estimates of product life distributions. Furthermore, regional differences inhibit scaling. For instance, there are more steel framed buildings in the U.K., Japan, and the U.S. than elsewhere. This method cannot therefore be used in isolation, but can help to estimate demand for specific products when cross-validated with global studies on aggregated end-use.

Integrated top-down and bottom-up analysis is therefore used to determine the current end-use destinations of steel and aluminum. Top-down data, recording the production of intermediate goods, are collected by large metal producers and collated by global and regional trade organisations (refs 16, 21, 22, and 23 for steel, and 17 and 24 for aluminum). This has a low resolution, for example reporting tonnages for “transport” and “packaging” rather than products such as “cars”, “ships”, “drink cans”, “packaging foil”, and so forth. As these top-down sources do not typically report fabrication yield losses that occur when manufacturing finished products from intermediate goods, yield data from Hatayama et al.<sup>25</sup> for steel and IAI<sup>17</sup> for aluminum are used to create top-down estimates of end-use requirements in major sectors.

Bottom-up data for particular products can be derived from sales figures for particular product types multiplied by academic or commercial data on product composition, in the form of “bills of materials”. For example, ref 26 presents global car sales, and ref 27 reports the average aluminum content in cars. Such bottom-up studies give more detailed resolution for specific products, but only for some products in some regions. Therefore, bottom-up data must be reconciled with top-down figures by scaling bottom-up figures from regions to global coverage, applying yield ratios between intermediate products and final goods, and organizing the mix of products into the sectors used in top-down analyses. Such reconciliation is intensive so is reported in detail in section 1 of the SI. The SI also shows estimates of the results’ likely reliability. The analysis is based on a 2008 production mix, the most recent year for which sufficiently detailed data is available.

Wherever possible, 2008 production data is used; when this is not feasible, figures from surrounding years are used and interpolated where possible. As metal use can vary drastically with recessions and government spending, this introduces some uncertainty into the results.

For some products only regional data on composition is found. Care is taken to avoid scaling local distortions in relative metal use to a world level. For example, the relative use of aluminum in transport in China is much lower than the worldwide average. Typically, the largest aluminum components in a passenger car are the cast engine and, in a few cases, the body structure. The high cost of aluminum may reduce its

prevalence in developing markets such as China, where a cast iron engine block and steel sheet body structure are more common, accounting for the reduced relative use. In this work, the “typical” car material composition is an average from North American, European, and Japanese manufacturers,<sup>27</sup> representing over 65% of the market.

**2.2. Design Requirements for Major Components in the Main Steel and Aluminum Using Products.** For each product accounting for at least 1% of end-use, a product design description has been created and is presented in the SI section 2. The descriptions were informed by an extensive product specific literature review, for which the main references are listed in the SI. Each description defines the major steel and aluminum components in the product, including design constraints, materials (alloy and coating), construction process, life expectancy, reasons for failure, historic, and predicted future trends, and identifies current examples of reuse. The descriptions were validated by interviews with industry experts familiar with the product, who were also asked to comment on the opportunities and barriers for reusing key components.

**2.3. Determining the Fraction of Components That Can Be Reused, And the Barriers to Reusing the Remainder.** The product catalogue created by the methodology of section 2.2 was used to seed a series of interviews with relevant industrial experts. For each of the 23 products in the catalogue, appropriate individuals were selected based on their familiarity with the product in use, ensuring practical knowledge of both design requirements and end-of-life condition. Table 1 presents the product descriptions and lists the corresponding interviewees.

For each interview, the experts received in advance the catalogue product description to facilitate discussion of the key design features that enable or inhibit component reuse. Each interview lasted for at least thirty minutes and, following four trial interviews, a set of standard questions was used to direct the discussion:

- What is the average lifetime/design life of the main components?
- What is the prominent cause of failure of each of the main components?
- How does the performance of an equivalent new component compare?
- Can the components be retrieved from the product without destruction?
- Can any degraded components be restored?
- Can the components be standardized across brands and products?
- Does any reuse currently take place and what is the potential from any of these known reuse activities?

Detailed notes for each interview were recorded and analyzed to identify common strategies and barriers.

The potential fraction of metal components that could be reused in each product was then estimated. All existing component reuse activities and constraints were examined and four common strategies emerged: relocation, remanufacture, reshaping, or cascading to an alternative use (see Section 4.1 for definitions and discussion of these terms). The potential for reuse of each component by employing these strategies was then examined. Where possible the estimates are based on explicit information from the interviews or literature. For example, ref 5 states that over the life-span of a ship approximately 10% of the steel is lost by corrosion and that

**Table 1. Product Descriptions and Interviews Conducted for Metal Intensive End-Use Products**

product description	fraction of end-use		interviewee
	steel (%)	aluminum (%)	
cars 2 descriptions	7	20	Jaguar Land Rover
trucks	1	4	Isuzu Truck Ltd. & Professor in heavy vehicle design
ships	3	4	Professor specializing in Indian ship breaking
aeroplanes	negligible	negligible	Boeing
structural sections	9		Tata Steel Europe, Portal Power and a leading demolition contractor
concrete reinforcement	22		Celsa Steel U.K., Arup and a leading demolition contractor
steel sheet in construction	16		Portal Power
window frames		8	Innoval Technology
curtain walls		5	Innoval Technology
roofing and cladding		5	Innoval Technology & Portal Power
line pipe	2		Siemens VAI
rail track	1		Network Rail
mechanical machinery	13	7	Siemens VAI
electrical cables		9	National Grid U.K.
other electrical equipment 2 descriptions	3	5	National Grid U.K.
drink cans		7	Crown Cork and Seal
steel packaging	3		Crown Cork and Seal
aluminum foil packaging		6	Novelis
consumer durables (domestic appliances)	3	7	ISE Appliances
lithographic plate		1	Alcoa
deox of steel		3	Tata Steel Europe, Celsa Steel U.K.

95% of the steel at end-of-life is in the form of rerollable sheet, suggesting that approximately 85% by mass of the ship’s original steel could be reused.

Reforming sheet metal components requires flattening, cutting and bending into new shapes. Estimates of reuse potential must include predictions of the material loss in these processes, which was set at 50%—the worst yield ratio for stamping automotive parts. Life expectancies are used to estimate the potential reuse fraction of other components; for example, buildings typically last approximately ten years longer than the first set of aluminum window frames, allowing only the second set to be reused—approximately 50% of all window frames. When there is a limited but clear opportunity to reuse components, a conservative potential of 10% is assumed; for instance, some aluminum heat exchangers in cars could be reused, but designs vary according to brand and they are also subject to corrosion and damage from front-end vehicle collisions.

It is impossible to anticipate future technology and motivations accurately. However, the aim in deriving these percentages is to provide logical estimates based on sensible technical limitations. They account for both the fraction of products eligible for component reuse and the mass breakdown of reusable components within the steel or aluminum product.

3. RESULTS

In 2008, 1025 Mte of steel and 45 Mte of aluminum end-use products were made globally. Liquid metal production in the same year was 1330 Mte of steel<sup>21</sup> and 73 Mte of aluminum,<sup>17</sup> implying an average yield from liquid to final product of 77% and 62%, respectively.

A detailed breakdown of steel and aluminum end-use products is shown in the SI, leading to the estimates in Tables S23 and S24.

Figures 1 and 2 show the end-use breakdown, the potential reuse of components and reuse strategy, and the barriers

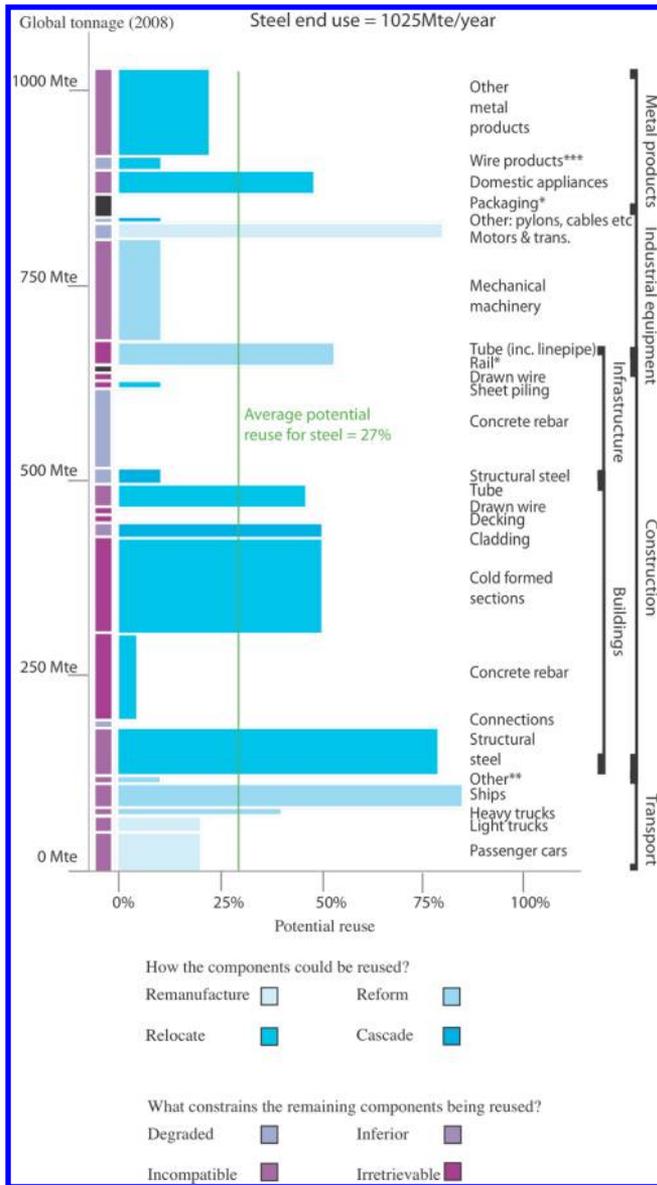


Figure 1. Potential reuse of steel components in metal intensive products.

constraining reuse of the remaining components. These reuse strategies and constraints are defined and discussed in sections 4.1 and 4.2. The y-axis sum to the global consumption in 2008.

Aggregating across end-use, the two figures show that the global technical potential for component reuse is 27% for steel and 33% for aluminum. Little reuse of both metals occurs at

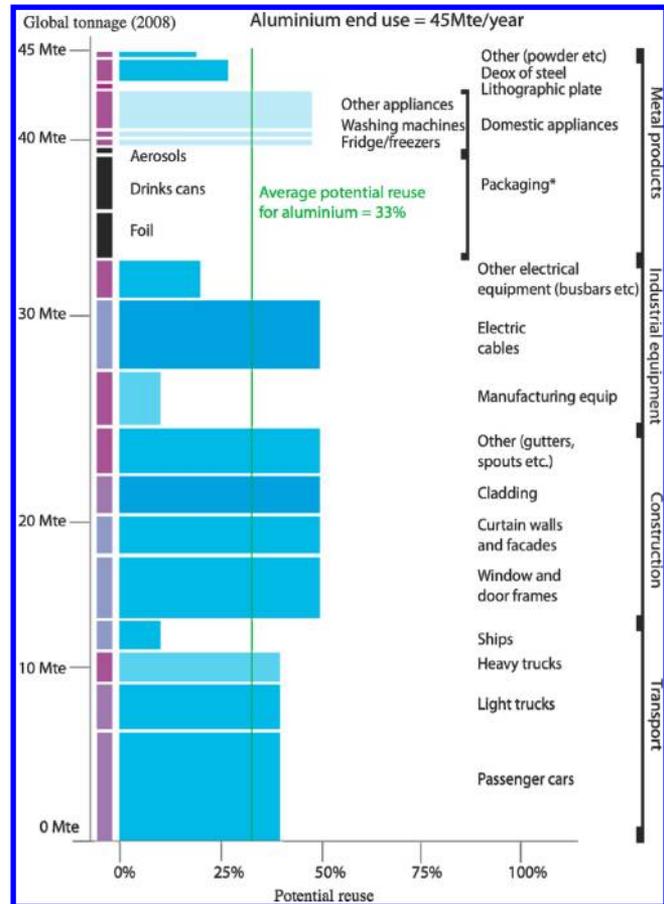


Figure 2. Potential reuse of aluminum components in metal intensive products. \*As reuse is component based, returnable packaging/continued use of rail track is instead classed as life extension and has not been included in this analysis. \*\*Military, rolling stock, aerospace, etc. \*\*\*Barbed wire in agriculture, wire ropes in the mining sector, wire springs, etc.

present, excepting reforming of steel ship plate, which accounts for less than a tenth of the potential reuse of steel.

4. DISCUSSION

The potential reuse of components in metal intensive products is derived using the product descriptions and interviews with industry experts. The descriptions were informed by an extensive product specific review of academic and company literature and up to three interviews were conducted for each product, ensuring that the majority of reuse opportunities are considered.

**4.1. Physical Strategies for Component Reuse.** From the interviews, two key factors appear to determine the type of component reuse that can occur: the performance of the component and the demand for the service it provides. The service is the function of the component, whereas the performance is the success or efficiency with which the component completes this function. For example, a worn engine block has low performance despite the demand for the service (automotive power) remaining high.

When demand for the service provided is high and the component is in a good condition, it may simply be **relocated** (typically a large single component) into another product with little refurbishment, such as cleaning and simple repairs/adjustments. When both demand is low and the condition poor

**Table 2. Re-Use Strategies and Potential Application on 2008 End-Use Production**

	...and are used in the same type of product	...and are used in a different type of product
The component(s) undergo extensive reconditioning...	<b>Remanufacture</b> 25 Mte steel; 2 Mte aluminium e.g., Remanufactured engines and electrical transformers	<b>Reform</b> 60 Mte steel; 1 Mte aluminium e.g., Ship plate and line pipe to reinforcing bar
The component(s) undergo superficial reconditioning...	<b>Relocate</b> 170 Mte steel; 9 Mte aluminium e.g., Recovered aluminium alloy wheels and transmission casings put on another car	<b>Cascade</b> 15 Mte steel; 3 Mte aluminium e.g., Reclaimed structural steel used as shoring; building cladding used on agricultural sheds

or unknown, the component may be **cascaded** to a less demanding use, or **reformed** (reshaped) to form a new, more useful, geometry. If demand exists but the component has suffered significant degradation, or an upgrade is needed, then the component/subassembly may need to be **remanufactured**. Remanufacture typically entails further disassembly (of a subassembly), redrilling, and metallic spraying/thermal techniques to recover worn and fatigued surfaces. Relocation and remanufacture are the most effective strategies; they maintain the value of the component in its second use. Reforming and cascading, however, typically apply when a downgrading of required properties is acceptable. Greater cascading reuse opportunities are possible with stronger alloys. For example, 7xxx series aerospace aluminum alloys could be reused in automotive applications.

These reuse opportunities, with examples, are structured in Table 2. The potential application of each strategy on 2008 end-use production, summed from Figures 1 and 2, is also shown. The remaining metal must be recycled. However, application of “reduce” strategies—discussed in the Introduction and explored in Allwood et al.—will help lower the absolute metal mass for recycling.

Reuse is often used synonymously with remanufacture, whereas Table 2 shows that remanufacture offers relatively little potential for reuse. The greatest potential reuse strategy is relocation. For steel, this is dominated by the potential to relocate hot rolled structural steel. For aluminum, potential relocation of aluminum extrusions used in buildings (curtain walls and window frames) and car wheels are dominant. These items are all large single components (as opposed to more complex subassemblies) and therefore do not have moving parts. This generally limits degradation by wear and fatigue, and remanufacture is not required. For steel, the other significant reuse strategy is reforming of the metal. An existing example is the rerolling of discarded ship plate into construction products in India. There is also potential to reroll retrieved line pipe into construction products. Such “rerolling” opportunities account for 40 Mte of steel, two-thirds of the reforming potential. With a global demand for reinforcement steel of 210 Mte, this reformed steel would not saturate the market. In addition to rerolling of plate, it is assumed some reshaping of steel sheet from cars, trucks, and domestic appliances could happen in the future. Such reforming of small sheet metal has already been demonstrated by Tekkaya et al.<sup>9</sup> and was discussed in section 1.

For any businesses or for policy makers wishing to maximize reuse activities, they should therefore first examine the opportunity to relocate metal. Associated technology development may include automated disassembly and machines or processes to validate properties. For example, coupon tests can determine the mechanical properties of reclaimed structural steel; however, at present these tests are typically expensive so

properties are currently identified through the use of a historic sections book and the lowest grade is assumed. If an accurate and affordable testing method (perhaps based on a portable Vickers hardness test) could be devised, then it would maximize the value of the steel and the carbon savings associated with reuse.

**4.2. Constraints to Reusing Metal.** Barriers to reuse were also considered in the interviews. The performance of the component is again important and, in addition, the value of the component to the designer may have decreased. Component reuse requires that the component or subassembly is **retrievable** from the rest of the product at end-of-life. Even for components that can easily be recovered and are neither damaged nor obsolete, they may be **incompatible** with new products as the component design is not standardized, or because the component is of unknown specification. Both of these constraints reduce the value of the old component to the designer.

The performance of the retrieved component can prevent reuse if its condition is **degraded** beyond repair or remanufacture. Products with a high rate of technological evolution may be difficult to reuse due to falling demand for older products, and their components' performance can be classed as **inferior**. These constraints, with examples, have been organized in Table 3. The prevalence of each barrier against the potential reuse of 2008 end-use production, summed from Figures 1 and 2, is also shown.

**Table 3. Re-Use Constraints and Prevalence of These Barriers against Re-Use of 2008 Consumption**

	...relative to before product fabrication	...relative to new components
The components performance has declined...	<b>Degraded</b> 170 Mte steel; 6.5 Mte al e.g., Offshore corroded steel; structural steel in bridges	<b>Inferior</b> 10 Mte steel; 6.5 Mte al e.g., Building cladding and car engines
The components value has declined...	<b>Irretrievable</b> 200 Mte steel; 0.5 Mte al e.g., Rebar in foundations; purlins from industrial sheds (without damage)	<b>Incompatible</b> 335 Mte steel; 10.5 Mte al e.g., Bespoke fabricated structural sections; building gutters and spouts

Note that the sum of all steel or aluminum in Tables 2 and 3 equals the total sum of end-use products minus the metal associated with packaging and rail track (as single component-products they are deemed to be applicable for life extension).

The greatest constraint on the reuse of components is incompatibility. For example, bespoke or irregular lengths and depths of hot rolled and fabricated structural steel limit reuse in new designs. Also, relocation of steel and aluminum paneling in domestic appliances is limited, as the profiled paneling and connections to the interior components are brand and product generation specific. Car closures and body panels are also

incompatible with new car designs. Therefore, the upper technical limit on reuse is limited predominantly by the degree of standardization possible across business, products and time. The other major constraint to reuse is degradation of components. For example, steel in infrastructure, such as in bridges and offshore structures, is subject to severe corrosion and fatigue loadings; for aluminum building components, corrosion is not a problem, but the appearance of anodized or painted frames may degrade (for example due to water staining), impeding reuse; cast aluminum engine blocks wear; and aluminum and steel electric cables corrode and may anneal in service. Most products can be dismantled and the components retrieved, so with some anticipation of future design requirements, many components could be standardized across both brands and products. The only significant components limited by the “inferior” constraint are aluminum drive-trains and metal cladding on buildings. Aluminum drive-trains are becoming smaller with widespread implementation of hybrid and turbocharger technology, and changing gearbox design also drives obsolescence of aluminum transmission housings. Cladding is subject to improving thermal rating regulations, preventing reuse in commercial buildings. Reuse of cladding is therefore currently mainly limited to agricultural sheds.

This work focuses on the technical potential of reuse. However, significant economic and behavioral barriers also limit uptake. These include concerns over increased labor costs and time in deconstruction, logistical challenges of returning and sorting components, the lack of an established supply chain, and consumer trends and habits. Prior to implementation, the technical assessment of potential reuse presented in this work must be evaluated against such socio-economic considerations, but without the technical analysis in this work, it would not be possible to evaluate the scope of potential change.

**4.3. Can Component Reuse Be Greatly Expanded to Reduce Demand for New Metal?** Only a small fraction of metal components is currently reused. To move close to the potential reuse figures discussed in this work will require aggressive pursuit of the strategies outlined in section 4.1.

There are immediate and significant areas of opportunity in the relocation of steel building components and through reforming ship plate and line pipe. Ship plate and line pipe are both corroded at end-of-life, but as demonstrated by Tilwankar et al.,<sup>5</sup> this does not inhibit reforming such products into construction products. Extracting line pipe can be difficult if it is underground or offshore, but is technically feasible in many cases. Aluminum building components may also be reused in the future: window frame and curtain wall extrusions could be more standardized and be installed with a connection that would allow deconstruction without compromising future seal quality. Realization of the above opportunities alone, to the intensity depicted in Figures 1 and 2, would allow reuse of 180Mte of steel (18%) and 5.5Mte of aluminum (12%).

Design for future reuse must consider the barriers presented in Table 3. For example, components that would otherwise fail due to wear could be designed to be more **durable** to prevent excessive degradation, and **standardized** across brands and time to allow compatibility. It must be possible to **disassemble** products and to acquire **knowledge** of the original component specification through either product marking at the time of fabrication (many steel mills already stamp sections to enable tracking in-house), or post-disassembly testing.

The durable properties of the alloy (corrosion, fatigue, and wear resistance) should be considered when future reuse is currently constrained by degradation. For example, there is a case for using stainless steel in select locations in infrastructure. For components susceptible to wear, each application must be considered on a case-by-case basis to determine the trade-off between selection of a harder alloy and recovery/replacement of the worn surface.

Standardized and durable components may limit bespoke optimization and require more material. If use-phase emissions are dominant and largely dependent on mass—such as in transport applications—then optimization may be preferable. However, for the majority of products, the steel content determines embodied carbon only, and the large carbon savings associated with reuse can allow for modest increases in component mass.

The largest single end-use of steel is as reinforcement in concrete, using 210 Mte in 2008 (approximately one-fifth of all steel). A top priority for increasing the potential reuse fraction of metal is to investigate whether this reinforcement steel could in future be reused. Currently, reinforced concrete must be crushed to allow recovery of steel bars for recycling, while subsurface reinforcement in foundations is left in the ground at end-of-life and cannot be recycled. Developing reusable foundations for multiple building types and loadings could potentially lead to effective reuse of this steel. For above-surface concrete, Wace et al.<sup>28</sup> investigate the potential for cracking concrete and recovering the rebar using microwaves; however, creating sufficient penetration is problematic, and this technology is in its infancy. At present, it is difficult to recover steel bars undamaged from concrete, but by developing modular precast designs that are easier to disassemble and reuse, greater reuse may occur in future. Research on dry connections to enable disassembly of precast concrete could help maximize reuse of this, the largest single end-use of steel.

## ■ ASSOCIATED CONTENT

### 📄 Supporting Information

The derivation of the end-use metal product breakdown, the product catalogue, and detailed evaluation of the potential for reusing metal components. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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### Notes

The authors declare no competing financial interest.

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