Supporting Information:

A material flow analysis with multiple material characteristics to assess the potential for flat steel prompt scrap prevention and diversion without remelting

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1 Literature Review

In our paper we claim that no MFA studies were found that either disaggregated flows of steel into more than a few categories nor fully represented the manufacturing sector in adequate detail. This section presents the findings from that literature review to show that a thorough investigation has been performed to support this claim, as well as to aid other researchers by giving a summary of the work performed in this field so far.

Three reviews of MFA with regards to steel have been performed in the past. Gordon et al.\(^{49}\) reviewed the methods employed to calculate stocks of metal, which to that point had been focused on geologically rare metals such as chromium, nickel and zinc. All three of these metals are used in alloys or coatings of steel and thus substance flow analysis of these elements is often done through MFA of steel. Gerst and Graedel\(^{50}\) revisited MFA for metals to review the determination of in-use stocks, estimating the global in-use stock of 32 metals. They observed that while iron, primarily as steel, is by far the most prevalent metal in terms of annual production, it is only fourth most studied, likely due to the abundance of iron in the lithosphere. Müller et al.\(^{51}\) reviewed the current practice of MFA used to determine stocks and flows of metals, however their scope included all metals and thus only 17 studies of steel were considered, while to date 40 studies have been identified that apply MFA to the steel industry.

Müller et al. differentiated MFA studies by three characteristics: Whether studies are static or dynamic, retrospective or prospective (or both), and top-down or bottom-up. Static studies consider flows of material for only a single time period, while dynamic studies rely on a timeseries of flow data. Dynamic studies are thus able to look retrospectively at historical data, or look prospectively at future trends based on extrapolation and assumptions about
Table S1: All steel MFA studies considered by this work with associated type, spatial scope, product disaggregation and ranking of certainty.

| Authors                     | Year | Study Type                  | Spatial Scope      | Product Categories | Ranking of Certainty |
|-----------------------------|------|-----------------------------|--------------------|--------------------|----------------------|
| Michaelis and Jackson       | 2000 | Top-down Historical         | UK                 | 10                 | 4                    |
| Michaelis and Jackson       | 2000 | Top-down Prospective        | UK                 | 10                 | 3                    |
| Andersen and Hyman          | 2001 | Top-down Static             | US                 | 1                  | 3                    |
| Dahlström et al.            | 2006 | Top-down Historical         | UK                 | 1                  | 3                    |
| Dahlström and Ekins         | 2006 | Top-down Static             | UK                 | 3                  | 1                    |
| Müller et al.               | 2006 | Top-down Historical         | Global             | 4                  | 4                    |
| Daigo et al.                | 2007 | Top-down Historical         | Japan              | 7                  | 4                    |
| Davis et al.                | 2007 | Top-down Historical         | UK                 | 7                  | 3                    |
| Drakonakis et al.           | 2007 | Bottom-up Inventory         | Municipal (New Haven) | 100                | 3                    |
| Eckelmann et al.            | 2007 | Bottom-up Inventory         | Provincial (CT, USA) | 100                | 3                    |
| Geyer et al.                | 2007 | Top-down Historical         | UK                 | 7                  | 3                    |
| Igarashi et al.             | 2007 | Top-down Prospective        | Japan              | 8                  | 2                    |
| Wang and Müller             | 2007 | Top-down Static             | Global             | 1                  | 3                    |
| Igarashi et al.             | 2008 | Top-down Prospective        | National           | 7                  | 3                    |
| Hirato et al.               | 2009 | Top-down Historical         | National           | 5                  | 4                    |
| Hirato et al.               | 2009 | Bottom-up Inventory         | National           | 5                  | 3                    |
| Rauch                       | 2009 | Bottom-up Proxy             | Municipal, USA     | 1                  | 1                    |
| Tanikawa and Hashimoto      | 2009 | Bottom-up Inventory         | Municipal          | 1                  | 3                    |
| Daigo et al.                | 2010 | Top-down Historical         | Japan              | 1                  | 3                    |
| Hatayama et al.             | 2010 | Top-down Prospective        | Global             | 3                  | 3                    |
| Hu et al.                   | 2010 | Bottom-up Inventory         | National           | 1                  | 3                    |
| Oda et al.                  | 2010 | Top-down Historical         | National           | 1                  | 3                    |
| Reck et al.                 | 2010 | Top-down Static             | National           | 1                  | 4                    |
| Yellishetty et al.          | 2010 | Top-down Prospective        | Global             | 1                  | 2                    |
| Müller et al.               | 2011 | Top-down Historical         | National           | 4                  | 4                    |
| Hsu et al.                  | 2011 | Bottom-up Proxy             | National           | 2                  | 2                    |
| Cullen et al.               | 2012 | Top-down Static             | Global             | 19                 | 5                    |
| Pauliuk et al.              | 2012 | Top-down Prospective        | China              | 5                  | 4                    |
| Han and Xiang               | 2013 | Bottom-up Inventory         | China, Regional    | 7                  | 2                    |
| Hattori et al.              | 2013 | Bottom-up Proxy             | National, Regional | 2                  | 3                    |
| Oda et al.                  | 2013 | Top-down Prospective        | Global             | 6                  | 2                    |
| Pauliuk et al.              | 2013 | Top-down Prospective        | Global             | 4                  | 3                    |
| Pauliuk et al.              | 2013 | Top-down Historical         | National, Global   | 4                  | 3                    |
| Fishman et al.              | 2014 | Top-down Prospective        | Japan, USA         | 1                  | 3                    |
| Hatayama and Tahara         | 2014 | Top-down Prospective        | China              | 1                  | 3                    |
| Liang et al.                | 2014 | Bottom-up Proxy             | Provincial, China  | 1                  | 3                    |
| Nakajima et al.             | 2014 | Top-down Static             | Japan, USA         | 8                  | 4                    |
| Nakamura et al.             | 2014 | Top-down Prospective        | Japan              | 5                  | 2                    |
| Olmo et al.                 | 2014 | Top-down Static             | Japan              | 4                  | 4                    |
| Pauliuk et al.              | 2014 | Bottom-up Inventory         | Municipal          | 1                  | 3                    |
| Mohr et al.                 | 2015 | Top-down Prospective        | National, Global   | 1                  | 2                    |
| Tanikawa et al.             | 2015 | Bottom-up Inventory         | Japan              | 1                  | 2                    |
| Wang et al.                 | 2015 | Bottom-up Inventory         | Provincial, China  | 5                  | 4                    |
| Wang et al.                 | 2015 | Top-down Static             | China              | 3                  | 4                    |
| Wang et al.                 | 2015 | Top-down Prospective        | China              | 3                  | 3                    |
| Wen et al.                  | 2015 | Top-down Prospective        | China              | 5                  | 2                    |
| Guo and Zhang               | 2016 | Top-down Historical         | China              | 10                 | 4                    |
| Serrenho and Allwood        | 2016 | Bottom-up Inventory         | UK                 | 1                  | 4                    |
| Stijandt et al.             | 2016 | Top-down Historical         | Bangladesh         | 6                  | 4                    |
| He et al.                   | 2017 | Top-down Historical         | China              | 1                  | 4                    |
future system behaviour. Critically, studies are differentiated by their data sources, classifying them as top-down or bottom-up. Five types of studies were identified as relevant for MFA of steel: top-down static, top-down historic, top-down prospective, bottom-up direct inventory and bottom-up proxy.

The 48 studies considered in the review are listed in table S1. Each study has been classified as one of the five study types as well as determining the minimum and maximum spatial scopes over which the study applies, the number of product or end use categories employed, and a ranking of ‘certainty’, a qualitative measure between 1 to 5 to assess how tight the uncertainty bounds are on a given study. Studies were ranked based on an estimate of the expected accuracy of their results can be expected to be, from over 25% error at rank one to less than 5% error in rank five. Any studies employing scenario or sensitivity analysis were given an increase in rank. While this method is ad hoc, it at least gives some sense of comparison of data reliability across studies where no common metrics are easily found.

The majority of studies employ top-down methods to populate the flow data in their studies, with static studies concerning only a single year. Andersen and Hyman\textsuperscript{S3} were the first to produce a static MFA of steel as a means of producing a mass balance for steel making in the UK in order to calculate energy use. Wang and Müller\textsuperscript{S13} built upon this method to produce the first characterization of the global steel cycle. They calculated the flow of steel between production, manufacturing, use and waste management elements for 68 countries, determining steel flows at the national, regional and global level. This system of four overall elements was employed by most following studies, with the manufacturing sector typically disaggregated into construction, transport, machinery and metal goods. Cullen et al.\textsuperscript{S26} extended the work of Wang and Müller by considering different categories of intermediate steel goods, visualizing their allocation to different manufacturing sectors in a Sankey diagram. Static studies typically show the highest level of product disaggregation at large spatial scales, though due to their lack of system history they can say nothing about the accumulation of stocks.
Dynamic studies are required for such calculations. The first dynamic MFA of steel found was produced by Michaelis and Jackson,\textsuperscript{S1} which considered historical data from 1954-1994 to characterise steel production and scrap arisings in the UK. Future studies by Müller et al.\textsuperscript{S6} and Daigo et al.\textsuperscript{S7} extended this work by employing product lifetimes, relating the exit of goods from the use phase based on estimated probability of exit of historic inputs in a given year. A key work by Müller et al.\textsuperscript{S24} used this product lifetime data to show a saturation trend between stocks of steel per capita and GDP per capita: As economies develop, they tend towards a maximum of 8 to 12 tonnes of steel stocks per capita. Pauliuk et al.\textsuperscript{S32} (2013) extended this work further to produce the most extensive top-down estimate of steel stocks to date for 197 countries covering the period 1700 to 2008.

Prospective studies use a defined system history and assumptions about future system behavior to extrapolate future trends in steel production, stock accumulation and scrap. Michaelis and Jackson\textsuperscript{S2} were again the first to explore this area, extrapolating their previous study to estimate energy consumption by the UK steel industry. Igarashi et al.\textsuperscript{S12,S14} employed methods built around eq. 3 to explore scenarios for tramp element accumulation in scrap steel with ‘constant’ and ‘regression’ models to demonstrate upper and lower bounds for expected system behavior. Yellishetty et al.\textsuperscript{S23} performed another prospective study, extrapolating exponential historical production trends into the future. This method ignores the saturation phenomenon demonstrated by Müller et al. and as such likely overestimates future primary production. Saturation assumptions were adopted by Hatayama et al.\textsuperscript{S19} and Pauliuk et al.\textsuperscript{S27,S31} to produce more credible scenarios for future steel production, stock accumulation and scrap arisings. By considering multiple development scenarios and saturation phenomena, Pauliuk et al. were able to make reasonable predictions about the requirement of future primary and secondary steelmaking capacity.

If flow data is not required, bottom-up methods can be employed to estimate stocks of materials at a spatial scale and level of product disaggregation that is not possible with top-down analysis. The first method involves the inventory of all steel containing goods
within a system boundary, an estimate of average product mass, and an estimate of steel content across a range of product categories. Drakonakis et al.\textsuperscript{89} were the first to perform such a study by assembling a detailed inventory of iron-containing items in New Haven, Connecticut, USA. This study determined that New Haven contained 9.2 tonnes of iron per capita, a figure significantly lower than the 12 tonnes per capita national average calculated by Müller et al. using the top-down method one year earlier. Eckelman et al.\textsuperscript{10} extended the spatial bounds of this study to include the entire state of Connecticut and found the per capita iron stocks of the state to be 9.3 tonnes. Tanikawa and Hashimoto\textsuperscript{17} developed a method to exploit the vast amount of information available in geographic information system (GIS) data sets, estimating materials stocks at a 1 km\(^2\) resolution for the whole of Japan.\textsuperscript{41}

Stocks of material may also be estimated by correlation with an exogenous measure. Rauch\textsuperscript{16} estimated stocks of iron and other metals via a correlation with GDP/capita at a 1 km\(^2\) resolution. While the author found a statistically significant correlation of copper with GDP/capita, this was not possible for iron with only seven top-down studies of iron stocks available. Another recent method by Hsu et al.\textsuperscript{25} involved the correlation of total observed night-time light with steel stocks, a method developed a year earlier by Takahashi et al.\textsuperscript{52} to determine stocks of copper in Japan. Hattori et al.\textsuperscript{29} and Liang et al.\textsuperscript{35} improved the methods used by the former study and extended the above analysis for Asia and the rest of the world achieving correlations with \(R^2 > 0.9\). Liang et al. observed that correlations change significantly over time such that steel stocks per measured nighttime light is increasing, suggesting that only recent night-time light data should be trusted.

Figure S1 shows... Figure S2. Finally, Figure S3 shows...

### 1.1 Conclusions

The studies presented in the previous sections show that current methodology is sufficient to assess stocks and flows of steel in aggregate at the national level. Prospective studies have proven their use, but only as a means of exploring potential policy scenarios and not
Figure S1: The number of product categories or end use sectors employed by each study plotted against the minimum and maximum spatial scale achieved.

Figure S2: The minimum spatial scale of each study plotted against certainty ranking.
Figure S3: The number product categories or end use sectors employed by each study plotted against certainty ranking accurately predicting the future. Direct inventory using GIS data and proxy methods using night-time light are very promising and, when combined with top-down studies, may prove very useful as means of monitoring stocks at the regional, national and municipal level.

Figures S2 shows the minimum spatial scale achieved by the five categories of studies plotted against a certainty rank. There is a clear trade-off between certainty and spatial resolution, showing a lack of studies that provide flow data that are both reliable with regards to the study objectives and spatially disaggregated. Furthermore, most studies disaggregated steel into a small set of product categories and only four industry categories. Most importantly, no studies were found that disaggregate steel by grade, coating or thickness, essential properties that characterise how steel is processed. Current methodology is therefore not sufficient to suitably model changes such as downstream integration and closing of scrap loops within the steel supply chain given the wide range of industries and types of steel in use.
2 EU Flat Steel Production

For confidentiality reasons as well as maximising the utility of our work to other researchers we have scaled up our original database to represent all flat steel produced in Europe for the year 2013. Table S6 (found at the end of this section) was presented in our paper to show the top-down mass values that were used to perform the correct scaling. This section explains how we arrived at the values in that table.

Eurofer provided the mass of each steel product category consumed by each manufacturing sector for the years 2010 and 2015. It was assumed that while production volumes may fluctuate between years, the percentages of each product category consumed by each industry sector should stay relatively stable and change smoothly, thus allowing for linear interpolation of these percentages. As such, the 2010 and 2015 mass values were divided through by the sum of their respective product category to produce tables S2 and S3. Linear interpolation of these two tables for the year 2013 produced a similar table for our target year.

Table S2: Percent of each steel product category consumed by each industry sector for the year 2010.

| Steel Product Category   | Construction | Mechanical Engineering | Automotive | Electrical | Other Transport | Tubes | Metal Goods | Other Sectors |
|--------------------------|--------------|------------------------|------------|------------|----------------|-------|-------------|---------------|
| Hot Rolled               | 20.9%        | 15.4%                  | 16.4%      | 2.2%       | 1.7%           | 28.2% | 12.5%       | 2.7%          |
| Plate                    | 31.7%        | 28.4%                  | 1.7%       | 0.4%       | 9.9%           | 16.8% | 8.7%        | 2.4%          |
| Cold Rolled              | 13.6%        | 12.4%                  | 24.5%      | 13.3%      | 1.9%           | 7.5%  | 24.2%       | 2.6%          |
| Hot Dipped Galvanised    | 26.2%        | 5.3%                   | 46.3%      | 3.6%       | 1.6%           | 4.3%  | 10.5%       | 2.1%          |
| Electro Coated           | 8.6%         | 2.8%                   | 62.9%      | 6.9%       | 5.2%           | 0.5%  | 11.0%       | 2.1%          |
| Organic Coated           | 70.8%        | 5.8%                   | 4.7%       | 8.7%       | 0.5%           | 0.0%  | 6.4%        | 3.1%          |
| Tin Plate                | 0.1%         | 0.5%                   | 0.3%       | 0.1%       | 0.0%           | 0.0%  | 98.5%       | 0.4%          |

Shipment volumes for each of the seven steel product categories were then needed for the year 2013. values for Hot Rolled, Plate and Cold Rolled material were determined from Eurofer’s annual reporting. Eurofer only directly reports the aggregate total output of coated material. The percentages of total coated products for hot dip galvanised, electro
Table S3: Percent of each steel product category consumed by each industry sector for the year 2015.

| Steel Product Category | Construction | Mechanical Engineering | Automotive | Electrical | Other Transport | Tubes | Metal Goods | Other Sectors |
|------------------------|--------------|-------------------------|------------|------------|----------------|-------|-------------|--------------|
| Hot Rolled              | 16.5%        | 12.5%                   | 12.9%      | 1.2%       | 1.1%           | 27.2% | 10.6%       | 1.7%         |
| Plate                   | 29.8%        | 28.1%                   | 2.0%       | 0.1%       | 11.3%          | 13.3% | 10.8%       | 1.7%         |
| Cold Rolled             | 14.7%        | 18.1%                   | 26.6%      | 12.0%      | 1.7%           | 6.2%  | 28.6%       | 2.5%         |
| Hot Dipped Galvanised   | 25.4%        | 6.6%                    | 51.6%      | 2.9%       | 0.7%           | 3.6%  | 10.1%       | 1.8%         |
| Electro Coated          | 9.6%         | 3.2%                    | 68.8%      | 5.1%       | 1.8%           | 0.5%  | 11.5%       | 2.4%         |
| Organic Coated          | 74.6%        | 4.4%                    | 6.2%       | 7.8%       | 0.7%           | 0.1%  | 5.7%        | 3.4%         |
| Tin Plate               | 0.0%         | 0.0%                    | 0.0%       | 0.0%       | 0.0%           | 0.0%  | 8.6%        | 0.0%         |

coated, organic coated and tin plate steel from the years 2010 and 2015 were interpolated for the year 2013, as shown in table S4. When these percentages are multiplied by the total of 29,500 kt of coated steel for 2013 we arrive at the values for each coating type shown in table S5. By multiplying each share with its corresponding product total in table S5 we arrive at the production figures for 2013 as shown in table S6.

Table S4: Percentage of each coating type constituting the total coated steel shipments for 2010 and 2015 and the interpolated percentages for 2013.

| Eurofer Data | Interpolation |
|--------------|---------------|
| Year         | 2010  | 2015  | 2013  |
| Hot Dip Galvanised | 63.4% | 66.0% | **64.9%** |
| Electro Coated         | 10.7% | 9.0%  | **9.7%**  |
| Organic Coated          | 14.2% | 13.2% | **13.6%** |
| Tin Plated             | 11.6% | 11.8% | **11.7%** |

Table S5: Shipment by steel product category for the EU for 2013. All numbers in kt.

| Hot Rolled Plate Cold Rolled Hot Dipped Coated Electro Coated Organic Coated Tin Plated |
|----------------------------------|---------------------------------|----------------|-------------|--------------|----------------|--------------|
| 34,200                           | 11,000                          | 13,700        | 19,100      | 2,900        | 4,000          | 3,500        |
Table S6: Shipments of intermediate flat steel products to different industry sectors in the year 2013. All numbers in kt.

| Steel Product Category | Construction | Mechanical Engineering | Automotive | Electrical | Other Transport | Tubes | Metal Goods | Other Sectors |
|------------------------|--------------|-------------------------|------------|------------|----------------|-------|-------------|---------------|
| Hot Rolled             | 6,240        | 4,680                   | 4,890      | 560        | 460            | 9,440 | 3,870       | 730           |
| Plate                  | 3,370        | 3,110                   | 210        | 20         | 1,180          | 1,620 | 1,100       | 220           |
| Cold Rolled            | 1,950        | 2,160                   | 3,520      | 1,710      | 240            | 920   | 3,620       | 350           |
| Hot Dip Galvanised     | 4,930        | 1,170                   | 9,480      | 610        | 210            | 740   | 1,970       | 370           |
| Electro Coated         | 260          | 90                      | 1,900      | 190        | 90             | 20    | 320         | 70            |
| Organic Coated         | 2,940        | 200                     | 230        | 330        | 30             | 0     | 240         | 130           |
| Tin Plate              | 0            | 10                      | 10         | 0          | 0              | 0     | 1,540       | 10            |

3 Modelling Steelmaking and Manufacturing Sectors

This section describes how we modelled the upstream flows for each order coming from the steelmaking sector, how we allocated flows in the distribution sector to an appropriate manufacturing sector, and how we modelled the 22 manufacturing sectors based on interviews and site visits. No sites will be acknowledged by name for confidentiality purposes, though we acknowledge the country they operate in. Please contact the authors if further description or data verification of any sector is desired.

3.1 Steelmaking

As this study considers only flat products, only the flat steelmaking steel supply chain was modelled. Llewellyn and Hudd\textsuperscript{54} consulted for production pathway, verified as still representative during a tour of a Belgian integrated steel mill while values for yield at each stage were taken from Cullen et al.\textsuperscript{55} and Milford et al.\textsuperscript{56} with some adjustments made based on interviews during and following our site tour. It was assumed that all flat steel was made by the integrated, i.e. Blast Furnace - Basic Oxygen Furnace route, which is widely the case in the EU though some Electric Arc furnace production for flat goods takes place.

Figure S4 shows the process map for each of the eight steel product categories which complements table 2 in the main paper. Each box represents a steelmaking, rolling or
finishing process with the output of each process listed as a percentage of what was input. By tracing backwards through this process map for each coil of steel we determine the flows that must have occurred, with more scrap clearly arising for higher valued products such as tinplate against lower value products like hot rolled coil which undergo fewer production steps.

![Process map for the eight intermediate steel products considered in this study.](image)

Figure S4: Process map for the eight intermediate steel products considered in this study.

### 3.2 Distribution

Just over a third of all orders by mass were destined for a distributor, rather than a direct order to manufacturers. Distributors exist to match up the steady output of steel mills with the fluctuating demands of manufacturers, as well as to outsource processes that prepare coils of steel for manufacturing, typically levelling, end cutting, edge trimming and slitting to create a regular steel strip.

Three site visits to steel service centres and two phone interviews were performed to assess (a) how much scrap is associated with coil processing and (b) which sectors. From data provided on one slitting line that includes the four processes mentioned we found a scrap rate between 0.4% and 4.4%, averaging 2.2% as shown in figure S5. Whether coils are delivered via a service centre or not, coil preparation always occurs, and thus we can allocate the scrap generated in coil processing to the manufacturing sector for all orders.
Figure S5: Material Utilisation for 292 coils of steel processed in June 2015 at a British steel service centre shown as a PDF with 25 bins and a gaussian curve fit. Clearly utilisation cannot exceed 100%, so a truncated gaussian or lognormal distribution would be appropriate if using this data to predict utilisation.

From the three site tours we learned that all end use sectors employ distribution services to some degree. Instead of labour-intensively tracing the history of each flow, A Naive Bayes classifier was constructed to determine which industry sector that flow is most likely to end up at based on its characteristics. The set of flows sent directly to a manufacturer were used as a training set to construct these probabilities accordingly:

\[
p(S_k | c_1, c_2, \ldots, c_i) = \frac{1}{Z} p(S_k) \prod_{i=1}^{n} p(x_i | S_k)
\]

(1)

where \( S \) indicates the allocated manufacturing sector of the order, \( c_i \) represents each material characteristic, and

\[
Z = \sum_k p(S_k) p(\mathbf{c} | S_k)
\]

(2)

which is identical for all \( k \) and each set of characteristics \( \mathbf{c} \) in equation 1 and thus \( Z \) can be ignored when considering the relative probabilities of each potential sector \( S_k \).
Three characteristics were used as classifiers: grade, coating, and thickness, with thickness divided into only ten bins to avoid over-fitting. Any characteristic combinations that resulted probability of occurrence in a single or no sector, grade and coating along were used again to avoid over-fitting the training dataset.

With the probabilities of sector allocation for all possible material characteristic combinations calculated, each order allocated to the distribution sector was then assigned to a manufacturing sector.

The following four sections explain how the process maps were made that detail how steel is processed to produce vehicles, construction materials, machinery and other various goods.

### 3.3 Transport

Sheet steel is widely used in the transportation sector for both structural capability to form the body of a vehicle its formability to produce body panels. The automotive sector makes up the majority of transport steel consumption, in particular light vehicles, classified as vehicles with a curb weight below 3.5 tonnes. Automobiles above this weight category, Heavy vehicles, make up the next biggest fraction along with the component manufactured for parts such as wheels, ventilation and other non-structural applications. Finally, train carriage construction and ships produced from plate steel make up a small part of transport steel. Air transport, being primarily served by lighter metals such as aluminium and titanium, is not included in this analysis. As such, the sheet steel used for small applications in that sector were of too small a mass to be accounted for in this study.

#### 3.3.1 Light Vehicles

Light vehicles is the largest and most valuable sector of flat steel manufacturing — most high strength and advanced high strength grades were designed to make lighter cars, and due to tight quality margins these are also the most expensive steels, some exceeding double the cost per tonne of conventional cold rolled mild steel.
Three site visits were performed to an automotive manufacturer in the UK for this study, one of which took place over the course of two days to review the metal planning documents for all sheet steel components used in the body of two of their compact models. All steel components follow the same basic production pathway of coil inspection and processing, leading to small losses of approximately 3%, followed by blanking to produce the approximate shape of the part and then a multi-stage stamping process to create the final geometry of the part. Each steel component is then welded into a sub-assembly before being painted and assembled into the final vehicle.

Blanking losses were observed to vary greatly from as low as 5% up to 25% or more for complex components. Stamping losses varied even more from less than 10% to over 50% for parts with an exceptionally deep draw or complex geometry that required a large amount of addendum material to prevent wrinkling or tearing during stamping. Overall, for both vehicle the blanking and stamping processes were determined to have a 45% scrap yield, high for the light vehicles sector which is on average between 30 and 45%. As such, an intermediate value of 12% and 32% scrap yield for blanking and stamping were chosen respectively, giving a combined scrap yield of 40% for the two processes. The third visit to the manufacturer confirmed that these are representative. The process map for the Light Vehicles sector is shown in figure S6.

Figure S6: Process map for a unit flow passing through the Light Vehicles sector
3.3.2 Heavy Vehicles

Heavy vehicles are commercial vehicles such as trucks and buses, typically classed as having a curb weight above 3.5 tonnes. An interview with a truck manufacturer in the UK confirmed that while they are manufactured in much the same way as light vehicles, parts are typically of simpler geometry and thus less material is lost during the stamping process. The same 12% loss has been assumed as for the light vehicles sector, but stamping losses have been set to 25% based on the estimate from our interview. The same losses due to coil processing and assembly as the light vehicles sector were assumed. Figure S7 shows the process map for this sector.

![Figure S7: Process map for a unit flow passing through the Heavy Vehicles sector](image)

3.3.3 Components

Components is a broad category that encompasses all sub-system, non-structural applications of flat steel used in automotive manufacturing. This includes wheels, seats, ventilation systems, and exhaust pipes among other applications. An interview with a former designer in a British light vehicles manufacturer revealed that the majority of ancillary components in a car made from sheet steel will be water jet or laser cut, leading to substantial losses at this phase depending on the part. This ranges from 5% for rectangular components up to over 50% for more complicated parts. 25% was chosen as an intermediate figure for the cutting losses followed by a 10% loss due to forming, either from stamping or roll forming, based on interview estimates. Additional losses occurring during coil pressing and quality control in assembly. Typically smaller coils are used, so edge trimming was assumed to account for 2%
loss, with a 1% loss due to quality control in assembly. The process map for the Components sector is shown in figure S8.

Figure S8: Process map for a unit flow passing through the Components sector

3.3.4 Rail

Sheet steel is used primarily to make body components for rail, while plate is used to create the carriage frame. An interview with a British rail car manufacturer was arranged, from which we learned that the majority of scrap arises from cutting sheets and plates to shape, with an estimated loss of 10 to 25%. We have deemed this process blanking, as it serves the same purpose, and agreed a representative 17% scrap yield with our interviewee. Following coil processing (2%) and blanking, sheet parts are roll-formed (plates are not) and welded to produce the carriage body, both processes producing scrap only when an error leads to quality control scrap arising, thus why we have chosen a 0.5% loss for each. The process map for the Rail sector is shown in figure S9.

Figure S9: Process map for a unit flow passing through the Rail sector
3.3.5 Shipbuilding

Plate steel is the material of choice for producing large freight vessels. An interview with a Dutch shipbuilding firm was arranged, who explained that in their yard plates are shaped with a plasma cutter before being rolled into shape. Plates are then welded together using a submerged arc, before structural beams are added and welded in place to complete the hull section. Hull sections are then arranged in a dry dock before being welded together to produce the final structure. Losses occur due to plasma cutting (16%) and for quality control (3%) when manufacturing errors occur, as well as plate processing either on site or at a distributor (5%). The process map for the plates only are shown in figure S10, representative of the Shipbuilding sector.

![Figure S10: Process map for a unit flow passing through the Shipbuilding sector](image)

3.4 Construction

When one thinks of steel in construction, sheet steel is not typically what comes to mind. Beams, reinforcing bars and wire rod are more important in construction as they make the structural backbone of most non-residential buildings. However, sheet steel is often used as a cost effective way to create building envelopes, as well as in various applications across municipalities primarily in road infrastructure. Steel is also used for myriad applications inside buildings from sanitary work surfaces to light switch panels. As such, we have divided the use of sheet steel in construction into three sectors: Civil Engineering, Exterior, and Interior.
3.4.1 Civil Engineering

Steel plays an important role in creating the infrastructure that supports life in towns and cities as well the transport links between them. Our data showed that a significant range of thicknesses were consumed in this sector, and based on the companies that these orders were shipped to we have assumed that orders below 3mm in thickness can be represented by the manufacture of safety barriers while orders of thicker steel are used to manufacture lighting poles to capture at least two end-use applications.

A phone interview with a director of a safety barrier manufacturing plant in Italy has provided the information for the process map shown in figure S11. As with profiles, after coil processing (2%) sheets are cut to length (3%) before being hole punched (4%) and roll formed, for which a 2% scrap yield due to quality control has been assumed.

Another phone interview with a manufacturer of street lamp poles in the UK has provided the details of processes and scrap yields for this product. Sheets are cut to length (3%) before being angle or three-roll formed (2%) into their octagonal or circular cross-section respectively. These poles are then seam welded to a base plate which is produced by laser cutting, incurring a 1% scrap yield mostly due to quality control. Our interviewee estimated a 30% loss from laser plasma cutting of base plates, and that they make up 10% of the mass of each pole.

Figure S11: Process map for a unit flow of less than 3mm thick steel passing through the Civil Engineering sector, used to produce safety barriers
3.4.2 Exterior

The main application of flat steel to construction is in building cladding, covering frames and structures in steel sheets and panels to provide enclosures and environmental protection. As such, most steel sold to this sector is coated in some manner, either in pure zinc for general applications or in a specialized alloy if the material is exposed to specific conditions such as high temperatures or a corrosive environment. One site visit and one phone interview were performed to understand this sector.

From the site visit, we determined that as with other sectors about 3% of the coil mass is lost in processing from end cutting and edge trimming. From there, small losses occur during blanking and roll forming (1.5%). The factory produced both rolled profile cladding and sandwich panels, which have extra steel cut off (4%) to allow for interlocking and foam insulation inserted adhesively between the two panels. From market data presented on the tour, 3/8 of the market is taken up by sandwich panels with the remainder accounted for by profiles. We have therefore divided the flows in our process map such that 37% of the steel leaving the blanking process goes down the sandwich panel manufacturing chain, while the remainder produce panels. Overall, including quality control losses at the end of production (0.5%) scrap losses in this sector amount to 5%. The process map for the Exterior sector is shown in figure S12.

![Figure S12: Process map for a unit flow passing through the Exterior sector](image-url)
3.4.3 Interior

Interior construction comprises all the goods created to serve non-structural purposes on the inside and walls of a building. This sector encompasses doors, window frames, lighting panels, cable trays, work surfaces, among many other applications. Two interviews were performed to understand two of these products, one with a German metal door manufacturer and the other with a British manufacturer of cable trays. Instead of trying to understand the process map for every product in this sector, we chose to represent it by an indicative product: the cable tray.

Cable trays are roll formed and hole punched sheets of steel used in most non-residential buildings to carry electrical cables and pipework. These trays are produced by cutting rectangular blanks from slit coils, punching holes and roll forming to achieve the correct profile. The majority of the scrap generated in this process comes from the hole punching stage (10%), though losses also occur in blanking (4%) and during coil processing (2.5%) and for quality control, which we have allocated as a 1% loss during roll forming. The process map for a cable tray is shown in figure S13.

![Process map for a unit flow passing through the Interior sector](image)

Figure S13: Process map for a unit flow passing through the Interior sector

3.5 Machinery

3.5.1 Agricultural

Agricultural machinery consists of vehicles that support the creation, maintenance and harvesting of farms or other agricultural operations. Most machines perform a specialized task
such as planting, irrigation or harvesting and are mounted on a tractor-type vehicle to allow
the machine to move around a field. As such, the machines consist of a vehicle construction
similar to the heavy vehicles sector along with the addition of load bearing laser-cut plate
components. One site visit was arranged to understand this sector. Unlike most site visits,
the industry partner willingly shared their total scrap figures for the site: 24% of the mass
of coils entering the site left as scrap in 2015.

Steel arrives on site primarily as coils or processed coils, with the expected losses (2%) due to coil processing. All parts were cut to shape using a laser cutting system, with losses of 20%. Following this cutting process came angle or roll forming for 95% of components (0.5%) or deep drawing for the rest (10%), followed again by welding, painting and assembly leading to combined 2% loss.

3.5.2 Domestic Appliances

Alternatively called 'White Goods', Domestic Appliances includes any . This ranges from
washing machines and refrigerators to toasters and hairdryers. Steel may be used for the
construction of the machinery itself, but the largest application is typically to create the
structure as well as the panels that make up the casing of the machine. We spoke with a
British steel service centre that supplier as well as toured a British domestic boiler manufac-
turer to understand this sector. Our model for this sector will be based, but our interviewees
confirmed that you would expect similar losses for manufacturers of other white goods as well.

Coils are processed (2.5%) and blanked (5%) off site to minimise stock at the site we
toured. After blanks arrive they are formed into shape, in this case using deep drawing.
Though the components we saw manufactured were rectangular, a substantial loss of 18%
was associated with the deep drawing process in order to create the desired curvature. This
surprised our tour guide, who made a later effort to confirm that indeed for the past three
months the scrap rate for the site as a whole was 20.0%, confirming the scrap rates we
estimated when painting (1.0%) and assembly (1.0%) defects are taken into account. To account for non-rectangular components, we have assumed the deep-drawing process has a slightly higher yield loss of 23% based on values seen in the automotive sector, giving this sector a total scrap loss of 27%. The process map for the Domestic Appliances sector is shown in figure S14.

Figure S14: Process map for a unit flow passing through the Domestic Appliances sector

3.5.3 Electrical

The electrical machinery sector consumes a special grade of steel made with 4% silicon to increase magnetic permeability and reduce hysteresis. To understand this sector two phone interviews were conducted, one with the head of electrical steel sales for a European steel-maker and the other with a manufacturing engineering at a British generator manufacturer. This sector comprises three main products: generators, motors and transformers, each requiring slightly different grades of steel within the electrical category. These machines are all made from laminated steel pieces between 1-2mm in thickness - laminated to reduce the resistive effects of eddy currents.

For all three types of machines scrap losses come primarily from the blanking of the laminations, resulting in anywhere from 20% to 50% scrap due to the gear-like shape of the laminations. On the recommendation of the manufacturing engineer we interviewed we have used a value of 35% for the blanking process, along with 2.5% for coil processing and 1% losses in assembly due to manufacturing errors. The process map for the Electrical sector is shown in figure S15.
3.5.4 Other Machinery

This sector comprises all other applications of sheet steel and plate used in the mechanical engineering sector. This often involves the construction of a small run of machines, sometimes just one, for a tailored application in the oil and gas, energy and manufacturing sectors among others. As this sector encompasses many applications, rather than interviewing a single manufacturer we reached out to a British steel service centre that supplies some of the firms listed in this sector in the commercial database. They confirmed that the majority of the scrap-generating processes done for their customers occur onsite at the service centre, with mostly forming, finishing and assembling work occurring at the manufacturer, and thus we arranged a tour.

Steel, primarily heavier gauge, arrives as coil or plates to the site. Coils are leveled and processed (2.5%) to produce a regular edge, while plates are shipped directly to cutting. As such, there two distinct production pathways, as shown in figure S16. After processing coils were sent to a laser blanker, which according to our tour guide has a typical scrap rate of 20-25%, primarily because non-optimal nesting of parts are chosen. 22% scrap yield was chosen as an intermediate value. Plates are cut using an oxy-fuel torch due to their higher thickness. Losses were much higher for plate (40%) due to substantial spacing between components, though also because of the greater cutting width of an oxy-fuel torch compared to lasers. The tour guide was unable to explain why parts are spaced so far apart. Cut parts are then shipped to customers, where forming (1%), assembly (0.5%) finishing (0.5%) processes take place, where the scrap values here are estimates we have made based on similar processes in
other Machinery sectors.

Figure S16: Process map for a unit flow passing through the Other Machinery sector

3.5.5 Yellow Goods

Yellow goods comprises the machinery used to move materials in the construction sector such as bulldozers, cranes, and backhoes, so named because of the common yellow paint scheme used by most manufacturers. This sector bears a lot of resemblance to the agricultural machinery sector, distinguished only by its use of heavier gauges of steel for load bearing applications. One site tour was arranged with a British manufacturer to understand this sector, which proved the similarities with agricultural machinery. As such their process maps are the same, with the exception that losses from blanking are higher due to the use of oxy-fuel cutting for thicker components, leading our site tour guide to report an average blanking loss of 25%. The process map for the Yellow Goods sector is shown in figure ??.

3.6 Goods

3.6.1 Packaging

The packaging sector is unique as it is nearly the sole consumer to tin-coated steel. For most steels corrosion protection is provided by zinc, which acts as a sacrificial anode to protect the steel underneath. However, this is unsuitable for food as zinc oxides flaking off into foods is poisonous. Instead, as tin is less reactive than iron it is used as cathodic protector so that it will not react with the potentially acidic content of the can.
Steel in the packaging sector is used primarily for the manufacturing of three-piece food and drink cans, though also for containers for paint and other filling material. As food cans have the majority of the market share, a 440ml steel food can was used as the prototype product for this industry. Three interviews and a site visit to a British can manufacturer were secured to understand this sector.

Our interviewees were able to share a detailed production pathway for steel cans with estimated losses. After coil processing (2%), 38% of the steel is used to produce tops and bottoms while the remaining 62% produces the body. Tops and bottoms are cut in a hexagonally packed nest, leading to a 17% blanking loss, while body components have very minimal losses of 0.5%. A series of lacquering and baking processes are then performed (0.4%) for the body before being roll-formed (0.2%), lacquered internally along with the tops (0.2%), seam-welded (0.3%), and finally assembled, with a 0.5% loss assumed for quality control purposes based on a 1 in 200 rejection rate reported during our site visit. All in all, only 6% of the steel sent to this sector is scrapped. The process map for the Packaging sector is shown in figure ??.

3.6.2 Profiles

Profiles are roll-formed sheets of steel used in various structural applications, so named because of their cross-section or ‘profile’ is typically constant across its length. This sector could arguably fit under construction, though because it is used also to create machinery and storage facilities we have considered it a good based on its ubiquitous applications. One phone interview with a sales manager at a British manufacturer of profiles was performed, which verified our findings in the related racking sector where profiles are also produced.

The process map for the Profiles sector is shown in figure S17. Coils of steel are first processed (2.0%) and slit to the correct width before being hole-punched (1.0%) and roll-formed (1.2%), with a loss occurring due to the cutting of profiles after forming and unexpected errors in manufacturing. Profiles may then be painted, though most are not as they are
made of galvanised steel and thus we have not included that process.

Figure S17: Process map for a unit flow passing through the Profiles sector

### 3.6.3 Containers

20 and 40 foot intermodal containers conforming to ISO standards make up over 80% of global shipping capacity according to the World Shipping Council, making this sector easy to characterise with a single representative product. An interview with a British container manufacturer helped produce the process map for the Containers sector shown in figure S18. Containers on their site were produced from slit coils of steel, for which we assume a 2% loss due to edge trimming and end cutting. Thin gauge steel is used to produce corrugated panels while thicker gauge steel forms the structural frame of the container. Both undergo roll forming processes, for which our interviewee reports an estimated 1 in 200 error rate (0.5%), mostly due to maintenance or discarded panels made from the heads and tails of coils. These panels and posts are then spot and seam welded together using electric arcs (0.5%) before being painted.

Figure S18: Process map for a unit flow passing through the Containers sector
3.6.4 Drums and Barrels

This sector covers the steel used to produce drum and barrel used to contain and transport liquids and certain hazardous or volatile solid materials. A site visit to a drum manufacturer in Belgium was arranged to characterise this sector.

Steel arrives in coils that must be leveled and trimmed (2%). 62% of the steel purchased is used to make drum body columns while the remainder is used to make heads. Coils for the body column are a standard 1800m wide to produce a standard 573mm diameter drum. These coils are then cut to size depending of the height of the barrel (0.1%) before being 3-roll formed and welded into a cylindrical shape (0.5%). The cylinders are then pressed to produce flanges at either end and bead rolled to provide structural integrity (0.1%). Simultaneously circles are blanked (20%) and shaped in a press to create tops and bottoms (0.5%). The drums are then assembled by roll forming material to create a tight seal before the drums are painted and baked (1.5%).

3.6.5 Racking

Large scale storage of goods requires a substantial structural infrastructure, and several firms exists in Europe specialised entirely in producing racking solutions. These structures consist of roll-formed box sections, bracing profiles and shelves that are designed for rapid assembly and interchangeability. A site visit to a Belgian racking manufacturer was arranged to understand this sector.

Coils arrived at the toured site unprocessed and thus a loss of 1.5% was observed for cutting 2m end lengths and 1.0% loss for edge trimming. Coils are then slit to length and welded to allow for continuous processing, leading to a 1.2% loss when coils are then eventually cut after rolling. Before roll forming the slit coils are perforated (0.8%) and then roll formed into shape (0.1%) which includes the losses that arise from welding sections together for continuous processing. Rolled sections and shelves are then electrostatically painted and baked (0.5%), before being stacked and palletized ready for delivery to a customer and assembly.
3.6.6 Tubes

Metal tubes produced from steel sheet are welded, rather than extruded seamless tubes which are classified as a long product and thus out of the scope of this study. These tubes are used for transporting fluids, from car exhaust pipes to oil and gas conduits, as well as in structural applications especially in maritime foundations. Coils may be either, though both have effectively the same production pathway. Two interviews were performed to understand this sector, first with a technical support as well as the head of tubular products for a European steel company.

Coils are processed like other sectors, with their estimate of 1% loss in edge trimming and 2% loss for end cutting due to the thick material employed. Sheets are then beveled to prepare the welding surface (0.5%) before being roll formed and seam welded (0.5%) and then plasma cut to separate tubes to the correct length (0.2%), around 10-20m for most applications. An additional 2% loss is assumed on the advice of our interviewees based on the losses at downstream manufacturers since tubes are usually an intermediate product, which we have labeled here as assembly. The process map for the Tubes sector is shown in figure S19.

![Figure S19: Process map for a unit flow passing through the Tubes sector](image)

3.6.7 Boilers

Boilers comprises any vessel used to heat liquids, usually water, to boiling temperature, from 9kW residential boilers up to boilers for steam turbines. In small boilers steel is used more to
produce body components rather than the boiler itself, whereas for large boilers steel plates make up the entire boiler. As such, one site visit was arranged to a British residential boiler manufacturer to determine how steel below 3mm in thickness is processed while a phone interview with a British industrial boiler helped characterise how thicker steel is processed in this sector.

### 3.6.8 Pressure Vessels

Pressure Vessels broadly includes any container designed to hold liquid or gas under pressure. Steel vessels are used extensively in the chemical sector, as well as for the transport and storage of fluids for many other industries. A phone interview with a sales manager and technician at a British manufacturer of pressure vessels was performed to understand the production process. The majority of vessels are constructed from a cylindrical body section with two domed or hemispherical ‘heads’ that are welded to create a continuous body. More complex designs exist, but are often constructed in a similar general design with assumed similar scrap losses.

As with other goods, the manufacturing begins with processing steel sheets or plates into a regular shape before cutting them to size (2.5%). Body columns have a further estimated 3% loss associated with hole boring and, while the heads have an associated 30% loss due to their circular shape. Based on our interviewee’s assumption that the body columns are three times as tall as the diameter of the heads and the heads as hemispheres, we get that the body columns make up 75% of the mass of the pressure vessel. Therefore, the ‘blanking’ stage will have a 10% loss associated with it. Cut components are then roll-formed into shape, though for specialised applications heads may be deep-drawn or formed using an incremental process called dishing. Scrap losses remain minimal regardless of the forming technique, so we assume all vessels are roll formed. Vessels are then welded (1%), typically using submerged arcs, before possibly being painted. The process map for a representative pressure vessel is shown in figure S20.
3.6.9 Radiators

Radiators are vessels containing a fluid hotter than the surrounding air used either to heat the air or cool the fluid. The former application is the most common, and based on a review of the largest manufacturers in this sector it can suitably be represented by a domestic panel radiator. One phone interview with a key technical support for the radiator sector from a steel company helped to understand this sector.

Coils of steel are processed, leading to a loss of 2%, followed by blanking and press forming to create the corrugated exterior panels while interior baffles are roll formed (4%). All parts are then welded together, with an estimated loss of 1.5%, higher than other sectors due to the testing that follows. Radiators are then painted and baked (0.5%). The process map for the Radiators sector is shown in figure S21.

4 Results

Table S7 shows the detailed breakdown of the results presented in figure 3 of the main article text, along with demand, scrap output and calculated scrap rate for flows with each material
Table S7: Sector group proportions for each material characteristic group and total demand and scrap generated for flows associated with each characteristic. Thicknesses are listed in three groupings for sheet (0 < h <= 3mm) and one group each for heavy gauge, plate, and heavy plate thicknesses. Grades and coatings are collected into families representing similar properties. Note that HSS and AHSS stand for high and advanced high strength steel respectively, hence their usage predominantly in the transport sector and thus their higher scrap rate as compared with other grade families.

| Thickness | Transport | Construction | Machinery | Goods | Demand [kt] | Scrap [kt] | Scrap Rate |
|-----------|-----------|--------------|-----------|-------|-------------|------------|------------|
| 0 < h <= 1 | 25% | 20% | 22% | 33% | 29,700 | 6,170 | 21% |
| 1 < h <= 2 | 39% | 21% | 16% | 24% | 22,000 | 5,170 | 24% |
| 2 < h <= 3 | 28% | 23% | 19% | 30% | 10,400 | 2,300 | 22% |
| 3 < h <= 6 | 26% | 18% | 27% | 29% | 8,870 | 1,930 | 23% |
| 6 < h <= 25 | 10% | 16% | 37% | 37% | 13,100 | 2,570 | 20% |
| h > 25 | 4% | 17% | 52% | 27% | 4,250 | 930 | 22% |

| Grade | Drawing | Structural | HSS | AHSS | Other Mild | Other | Coating | Uncoated | Zinc | Zinc Alloy | Aluminium |
|-------|---------|------------|-----|------|------------|-------|---------|----------|------|-----------|-----------|
|       | 32%     | 5%         | 65% | 95%  | 58%        | 4%    |         | 16%      | 42%  | 69%       | 48%       |
|       | 21%     | 26%        | 9%  | 1%   | 15%        | 20%   |         | 18%      | 27%  | 9%        | 26%       |
|       | 22%     | 36%        | 13% | 2%   | 20%        | 23%   |         | 28%      | 16%  | 14%       | 15%       |
|       | 25%     | 33%        | 13% | 2%   | 7%         | 53%   |         | 38%      | 15%  | 8%        | 11%       |
|       |         |            |     |      |            |       |         |          |      |           |           |

|                | Demand [kt] | Scrap [kt] | Scrap Rate |
|----------------|-------------|------------|------------|
| Transport      | 24,700      | 5,780      | 23%        |
| Construction   | 24,100      | 4,360      | 18%        |
| Machinery      | 12,500      | 3,760      | 30%        |
| Goods          | 2,410       | 880        | 37%        |
|                | 4,530       | 1,400      | 31%        |
|                | 20,100      | 2,870      | 14%        |
|                | 61,900      | 12,100     | 20%        |
|                | 18,900      | 4,620      | 24%        |
|                | 5,660       | 1,820      | 37%        |
|                | 1,850       | 470        | 25%        |

5 Visualisation

Sankey diagrams for this paper were produced using the sankeyview software developed by R.C. Lupton available at https://doi.org/10.5281/zenodo.1098904. Further detail on how these types of diagrams are created from the underlying data is available in the paper published by Lupton and Allwood.557
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