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

Iain P. Flint, André Cabrera Serrenho, Richard C. Lupton, and Julian M. Allwood*

Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom

E-mail: jma42@cam.ac.uk

Phone: +44 1223 748 271

Abstract

32% of the liquid metal used to make flat steel products in Europe does not end up in a final product. 60% of this material is instead scrapped during manufacturing and the remainder during fabrication of finished steel products. Although this scrap is collected and recycled, remelting this scrap requires approximately 2 MWh/t, but some of this material could instead be diverted for use in other applications without remelting. However, this diversion depends not just on the mass of the scrapped steel, but also on its material characteristics. To enhance our understanding of the potential for such scrap diversion, this paper presents a novel material flow analysis of flat steel produced in Europe in 2013. This analysis considers the flows of steel characterized not only by mass but, for the first time, also by grade, thickness and coating. The results show that thin gauge galvanized drawing steel is the most commonly demanded steel grade across the industry and most scrap of this grade is generated by the automotive industry. There are thus potential opportunities for preventing and diverting scrap of this grade. We discuss the role of geometric compatibility of parts and propose tessellating blanks for various car manufacturers in the same coil of steel to increase utilisation rates of steel.

Introduction

With wide ranges of available strength, formability, weldability, toughness and hardness, there is a grade of steel suitable for most engineering applications. Combining this variety with abundant ores and a relatively cheap cost of production, steel has become ubiquitous across the globe. 1.63 billion tonnes of steel were produced in 2016,[1] more than any other material apart from cement.[2] This ubiquity has its price: According to Allwood et al.[3] steel accounts for 6% of global CO_2 emissions, giving it the largest footprint of any material in use today. With the combined pressures of emission targets, overcapacity of blast furnaces and cheaper production in developing economies, it is pertinent to ask: is this a good time to change the way we use steel?

Improvements in energy efficiency over the last 50 years have already substantially decreased CO_2 emissions from the steel industry to half of what they were per tonne in the 1960s.[4] However, over that same period demand for steel has quadrupled, leading to a net doubling in emissions, a trend that is likely to continue as global economies develop. As an alternative, Allwood et al.,[5] Milford et al.,[6] and Pauliuk and Müller[7] among others have shown that pursuing material efficiency strategies can substantially reduce the carbon footprint of the steel industry. However, not all steel is created equal. The World Steel Association estimates that there are approximately 3,500 grades in use today, each tailored for particular applications. Evaluation of material efficiency strategies such as process scrap diversion across different manufacturing sectors require an understanding of the physical dimensions, mechanical properties and corrosion protection required by each sector. For this reason, more than just measuring mass flows of steel for each application, additional resolution on the grade, thickness and coating of steel uses would provide new insights on the most efficient uses of all steel products.

Material Flow Analysis (MFA) applies conservation of mass within a well-defined system boundary to determine the flow of material between elements of that system.[8] Over the past two decades MFA has been used to calculate trade flows of materials between nations,[9] estimate material stocks,[10] and project trends of steel scrap supply.[11] MFA studies can be classified as *top-down* if they rely upon nationally-collected statistics to form their dataset, or *bottom-up* if the data is gathered by inventory of the stocks within a system.

Top-down studies determine the flows in each time interval, from which stocks can be deduced. Previous top-down studies have calculated flows of energy required during steelmaking,[12] mapped global production and consumption of steel,[13] and estimated future demand for steel and the availability of scrap. These studies have been applied to inform decisions including the requirement for new blast furnace or electric arc furnace capacity.[7,11,14,15]

Conversely, bottom-up studies involve the determination of stocks within a system boundary, from which flows could in theory be determined. This would require knowledge of stock levels over consecutive time intervals, but in practice this has not yet been attempted. Bottom-up studies have calculated stocks of iron at the municipal,[16] state[17] and national[18] levels through direct inventory of iron containing goods, as well as at state and national levels using correlations with proxy measures such as night-time light intensity[19–21] and GDP/capita.[22]

A review of 50 MFA studies calculating stocks and flows of steel in the supporting information reveals that methods to date provide compelling insights on both the aggregate flows of steel at the global and national scale as well as determinations of steel stocks at a remarkably fine level of spatial resolution. However, two major gaps were identified in this literature: steel flows have only been disaggregated into few types of steel, and where this detail is provided, higher-resolution steel flows have been assessed into a small set of manufacturing industries.

In most assessments, steel is treated as a single material type, where, because of the range of available grades, coatings and thicknesses, it is in reality a class of many different material types. A few studies have considered various steel grades. For example, Nakajima et al.[23] used input-output methods to assess the flows of three alloying elements of steel in Japan. More recently, Ohno et al.[24] have assessed the flows of steel in vehicles with detail on the alloying elements present in steel to minimise their losses in steel recycling. However, for all previous studies, manufacturing with steel has been disaggregated into a small set of industry sectors, most of them only for the automotive industry. But yield losses vary considerably across manufacturing processes and grades of steel, and therefore the availability of prompt scrap varies substantially for different grades of steel. Lack of detail on the quantities of prompt scrap by grade have been preventing the identification of opportunities for scrap diversion as feedstock across different industries, and further opportunities for reducing the generation of prompt scrap. However, a higher resolution MFA, capable of tracking flows of steel by grade, but also other material characteristics, such as thickness and coating, in addition to mass, coupled with a detailed assessment of manufacturing processes across industries could enable the identification of novel opportunities to reduce steel production and to prevent unnecessary recycling, and consequent energy uses and emissions.

In this paper, for the first time, an MFA is constructed from commercial, statistical and interview data, disaggregated by both material characteristics and manufacturing process for Europe. This assessment enables the identification of potential opportunities for scrap diversion of flat steel across European industries, and it provides new insights on novel opportunities to combine similar grades of steel in the same coils by tessellation across products.

Methods

The following sections outline how adapting conventional MFA to allow for material characteristics can open the path to assessing the real potential for scrap diversion across manufacturing sectors. Then the creation of a dataset detailed around material characteristics and production stages in both steelmaking and manufacturing is described, created from three main data sources.

Allowing for Material Characteristics

Conventional MFA considers flows described by four dimensions:

1. Source: Where the flow originates,
2. Target: Where the flow is sent,
3. Time: When the flow occurred, and
4. Measure: The quantity and units of the flow.

However, a fifth dimension can be introduced to differentiate between multiple material types in the same study:

5. Material: The composition of the flow.

The material dimension could simply differentiate between a few different metals, or be as complex as tracking the elemental composition, microstructure and geometry of flows of steel moving through a system. In the framework devised by Lupton and Allwood[25], the material dimension for each flow, along with the source, target and time dimensions, can be assigned an ID that describes the characteristics of that material within a 'Dimension Table'. These four IDs when paired with a measure then form a flow within the 'Fact Table', with all the tables together constituting the MFA database.

For conservation of mass across all materials, MFA require the satisfaction of two equalities, which can therefore be adapted to include material characteristics as:

$$\sum_i [f_{i,p,m,t} - f_{p,i,m,t}] + c_{p,m,t} - d_{p,m,t} + \Delta S_{p,m,t} = 0 \quad for\ all\ p, m, t \tag{1}$$

$$S_{p,m,t+1} = S_{p,m,t} + \Delta S_{p,m,t} \quad for\ all\ p, m, t \tag{2}$$

where $f_{i,p,m,t}$ and $f_{p,i,m,t}$ are the quantities of material characteristic m, flowing to and from process p from and to process i,respectively during time t, $c_{p,m,t}$ and $d_{p,m,t}$ are the quantity of material created and destroyed respectively in p during t, and $S_{p,m,t}$ is the total stock in p at time t.

Data required for a disaggregated steel MFA

To produce an MFA with dissagregation in material and manufacturing processes, three types of data were required. Firstly, a large European steelmaker provided shipment data for 2013 that describes the physical dimensions, mechanical properties and surface quality of each order sold along with its mass. Secondly, top-down data from Eurofer, the European Steel Trade Association, describing the flows of each product category of steel into each industry sector was used to scale the commercial data to represent all European flat steel. Thirdly, models for the production of each type of intermediate steel product and each manufacturing sector were developed based on data gathered in industry interviews and site visits. These models, which we will call *process maps*, determine the sequence of processes required to produce each coil of steel and to convert each coil into final goods or scrap. Figure 1 shows examples of these process maps for (a) the production of a unit of galvanised steel and (b) the conversion of a unit of steel by the light vehicles sector.

The following sections provide an overview of how the data was gathered and processed to produce the dataset and associated analyses in the results section. Full details of how this

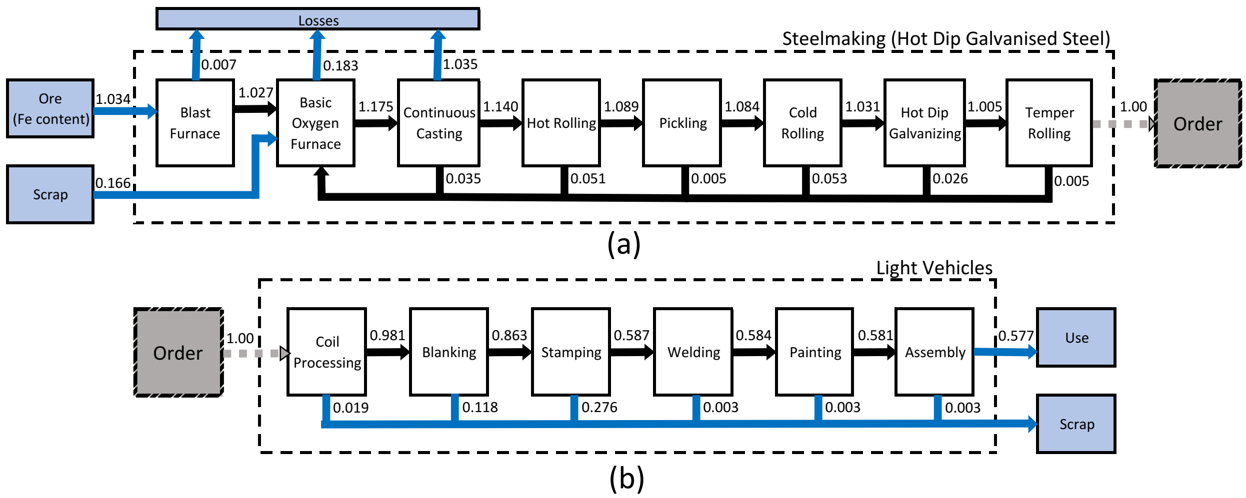


Figure 1: Example process maps for (a) a backward-allocated order of hot dip galvanised steel and (b) a forward-allocated order to the light vehicles sector.

MFA was constructed and supplementary information associated with each of the following sections are available in the supporting information.

Shipment Data

The shipment database acquired for this study comprises all orders of flat steel delivered by one European steelmaking company for the year 2013. Each order is associated with many pieces of information including the physical characteristics of the steel sold, such as its grade and thickness, as well as the mill of origin, the end user, and other commercially relevant data. To describe each order as a flow in equations 3 and 4, five classes of information were extracted from the database:

- Source: Where the flow originates, determined by the product category of each order, one of seven types of intermediate steel products (see table 2) since this allows estimation of what steelmaking processes must have occurred to produce this order.
- Target: The destinations of steel orders from the commercial data set were consolidated into 22 industry sectors within the broad classifications of Transport, Construction, Machinery and Goods. Some flows were shipped via distributors, providing stock

holding and coil processing services. Two interviews and three site visits to steel stockists and service centres were conducted to estimate the proportion of each sector served by distributors. It was assumed that orders sent directly to an end user and those sent via distribution would lead to the same levels of scrap.

- Material: The physical dimensions of width and thickness, the grade and grade family of the steel and the types and thicknesses of metallic or organic coatings were used to classify the material.

- Time: This study used data from 2013 only.

- Measure: The mass of each order in tonnes was used as the measure of flow, written as $f_{i,j,m,t}$ where i, j, m, and t represent the source, target, material and timeframe of the flow respectively.

Table 1: Estimates of shipments of flat steel products to different industry sectors in Europe in 2013. All numbers in kt.

Steel Product Category	Construction	Mechanical Engineering	Automotive	Electrical	Other Transport	Tubes	Metal Goods	Other Sectors
Hot Rolled	6,550	4,910	5,130	580	480	9,900	4,060	760
Plate	3,530	3,260	220	20	1,240	1,700	1,150	230
Cold Rolled	2,050	2,270	3,690	1,790	250	970	3,800	360
Hot Dip Galvanized	5,170	1,230	9,950	640	220	780	2,060	390
Electro Coated	280	90	1,990	170	90	20	340	70
Organic Coated	3,080	210	240	340	30	0	250	140
Tin Plate	0	10	10	0	0	0	1,610	10

EU Flat Steel Production

The shipment database describes the flat steel produced in Europe in 2013 by one European steelmaking company. Although data for only one company was used, their production volumes and the market share of this company is sought to provide insights about all European flat steel flows. Therefore, this data was scaled up to European levels using specific ratios of the steel company's output to that of the EU, for each end user and product category.

Table 1 shows the mass of EU-produced steel for each of seven product categories consumed by each of eight manufacturing sectors. This table was produced by combining a linear interpolation of similar tables for 2010 and 2015 from Eurofer with other publicly reported data.[26] The flows extracted from the commercial database were categorized into one of these 56 product-sector pairs to allow scaling, with the total mass summing correctly to 88.4 Mt, the total output of the European flat steel industry in 2013.

Modelling Steelmaking and Manufacturing Sectors

The flows upstream and downstream of each order of steel were determined by process maps. Each flow in the scaled database was assigned an upstream process map based on its product category and a downstream process map based on its target location and material composition. The upstream maps describe the series of steelmaking processes from creating liquid metal through to rolling and coating. The downstream maps describe the series of manufacturing processes from blanking and stamping through to final assembly required to produce final goods. The upstream and downstream maps together tell the full production history of that order from iron ore and scrap inputs to the output of goods and new process scrap, allowing calculations of material efficiency at the process level and up to the whole system level.

The steel industry process maps were developed from those of Llewellyn and Hudd[27]. Each process leads to yield losses (scrap) which was determined from values in the literature[13,28] and consultation with technicians during visits to an integrated steelmill in Belgium. The production outputs and associated losses for each process map are displayed in table 2.

34 interviews, 12 of which included site visits, were conducted to develop the downstream manufacturing process maps. For some sectors, distinct production pathways were identified for material of different thicknesses, and thus some sectors are represented by multiple process maps. Table 3 summarises this research and lists the demand, output and scrap rate of each sector. The full details of these are provided in the supporting information.

Table 2: Production output and steel-making losses associated with each flat steel product in Europe in 2013. All values in Mt.

	Output	
Product Category	Losses	Coils Out
Hot Rolled Non-Picked	1.0	7.0
Hot Rolled Pickled	3.9	26.6
Cold Rolled	2.1	13.5
Hot Dip Galvanised	3.0	18.8
Electro-Galvanised	0.5	2.9
Organic Coated	0.6	3.9
Tin Coated	0.5	3.4
Plate	1.5	10.8
Total	13.0	87.0

Results

The procedure described in the previous section was followed to produce an MFA dataset of flat steel production and manufacturing in the EU for the year 2013. This dataset has been visualised as a Sankey diagram in figure 2 with no differentiation of steel characteristics and with all steelmaking processes shown in detail while manufacturing processes are aggregated at the sector level. Figure 2 demonstrates that the method employed in this study achieved the same level of detail as previous top-down studies for a single year like the one produced by Cullen et al.,[13] albeit at European rather than global scale.

Figure 2 shows that in 2013 a total input of 116.6 Mt of iron contained in ore, process scrap and home scrap was converted into 67.9 Mt of final products, an overall material efficiency of 58.3%. 19.1 Mt of process scrap was produced in manufacturing. Production of light vehicles created the most losses, with a yield of only 57%. Out of a total material demand of 16.5 Mt, 7.1 Mt of scrap was produced in this sector, most of which is galvanised and of relatively high value compared with other flat steel.

Figure 3 shows alternate views of the dataset with flows separated into bundles defined

Table 3: The 22 manufacturing sectors considered in this study with the number of interviews and site visits used to determine the process map for each sector. The calculated demand for steel in each sector as well as the output of final goods and scrap are listed in thousands of tonnes [kt] as well as the scrap rate for each sector.

Sector	Subsector	Interviews and Site Visits	Demand [kt]	Output [kt]	Scrap [kt]	Scrap Rate
Transport	Components	1	2,630	1,680	950	36%
	Heavy Vehicles	1	1,190	760	430	36%
	Light Vehicles	3	16,500	9,400	7,100	43%
	Rail	1	250	200	50	20 %
	Shipbuilding	1	730	560	170	23%
Construction	Civil Engineering	3	2,120	1,890	230	11%
	Exterior	2	10,200	9,690	490	5%
	Interior	2	5,600	4,650	950	17%
Machinery	Agricultural	1	4,990	3,790	1,190	24%
	Domestic Appliances	1	3,930	2,870	1,060	27%
	Electrical	2	6,640	4,190	2,460	37%
	Other Machinery	1	4,020	2,810	1,210	30%
	Yellow Goods	1	2,170	1,540	530	29%
Goods	Packaging	3	5,570	4,990	580	10%
	Profiles	1	1,540	1,450	90	6%
	Containers	1	2,210	2,120	90	4%
	Drums and Barrels	1	4,070	3,580	490	12%
	Racking	2	3,130	2,970	160	5%
	Tubes	2	8,980	8,620	360	4%
	Boilers	2	720	630	90	13%
	Pressure Vessels	1	640	560	80	13%
	Radiators	1	590	560	30	4%

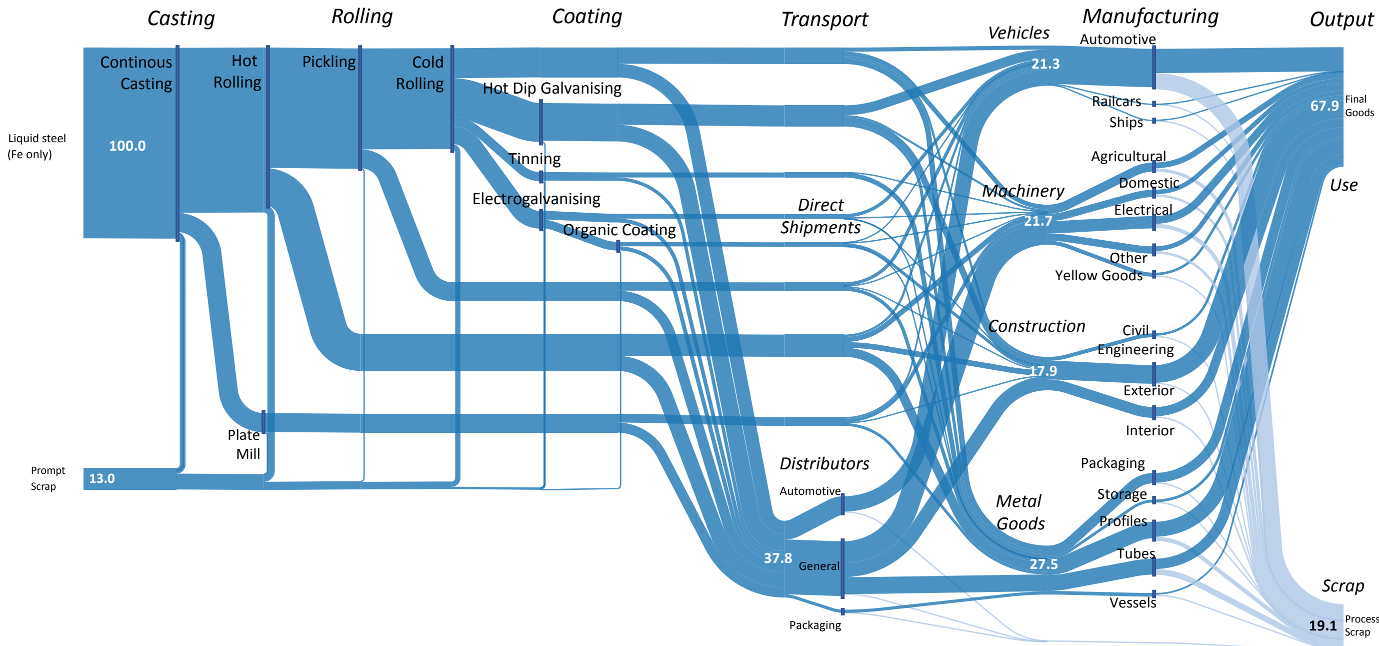


Figure 2: Sankey diagram visualisation of the European steel flows for 2013. All values are in million tonnes of iron.

by one material category. The left side of each diagram shows inputs of steel to each manufacturing sector group, while the right side shows the products of each manufacturing sector and the scrap generated in processing. Figures 3a-d show flows divided by intermediate steel product category, thickness, grade family and coating respectively, while fig. 3e and 3f show the dataset with uncoated flows filtered out coloured by material and manufacturing sector respectively. From figs. 3b and 3c it is clear that steel with a thickness below 2mm or made of a drawing grade is required by all four manufacturing sectors, suggesting that there may be potential for substituting materials across different industries. Further details are provided in section 4 of the supplementary information file.

Figure 4a is in the same format as figure 3 filtered for drawing-grade, thin-gauge galvanized steel, characteristics shown in figures 3b-f to be demanded across multiple sectors. Figure 4b shows the demand for this material in each manufacturing sector as well as the scrap produced. The highest demand and greatest scrap output of any sector for this material type is in the Light Vehicles sector, which creates more scrap than the total demand of most other sectors.

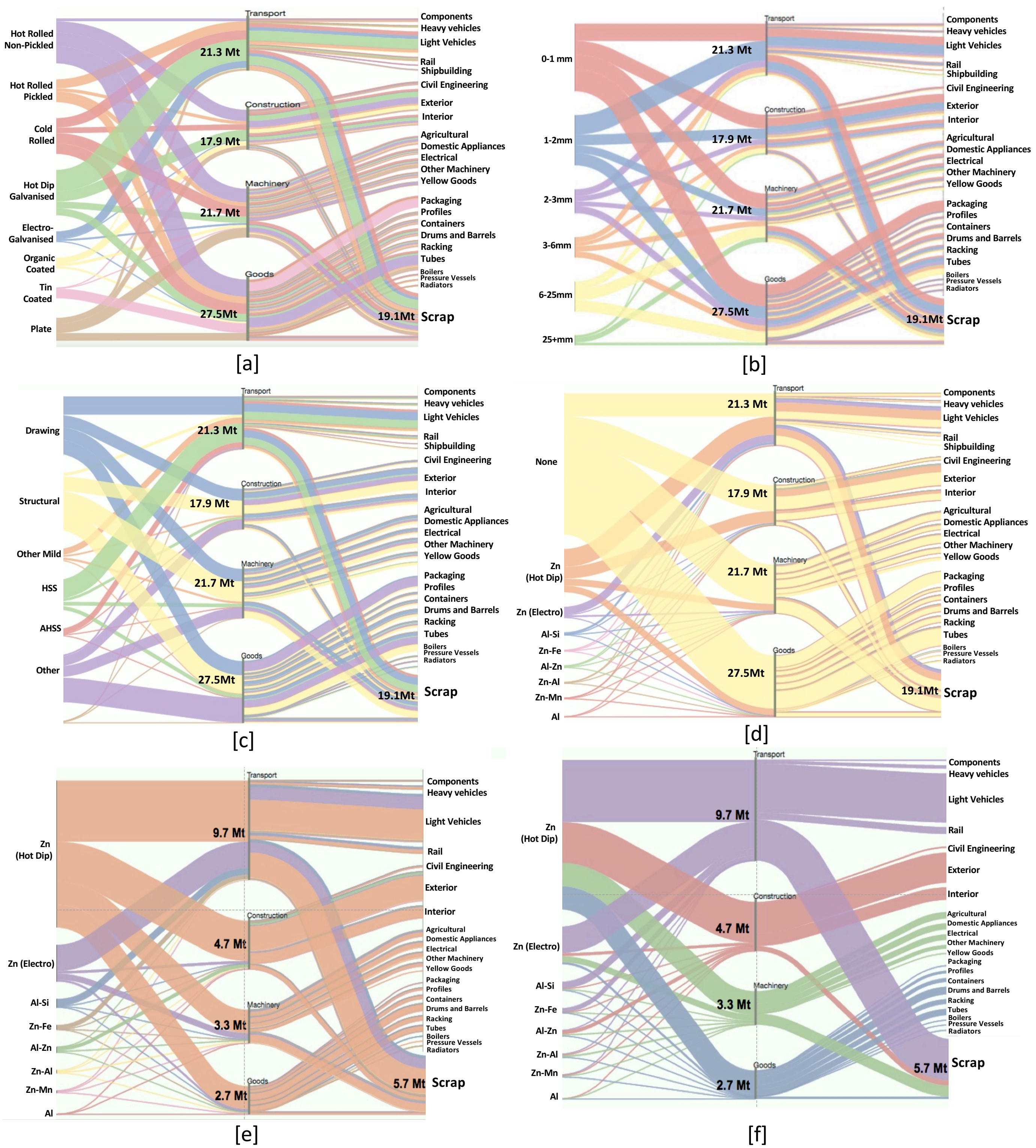
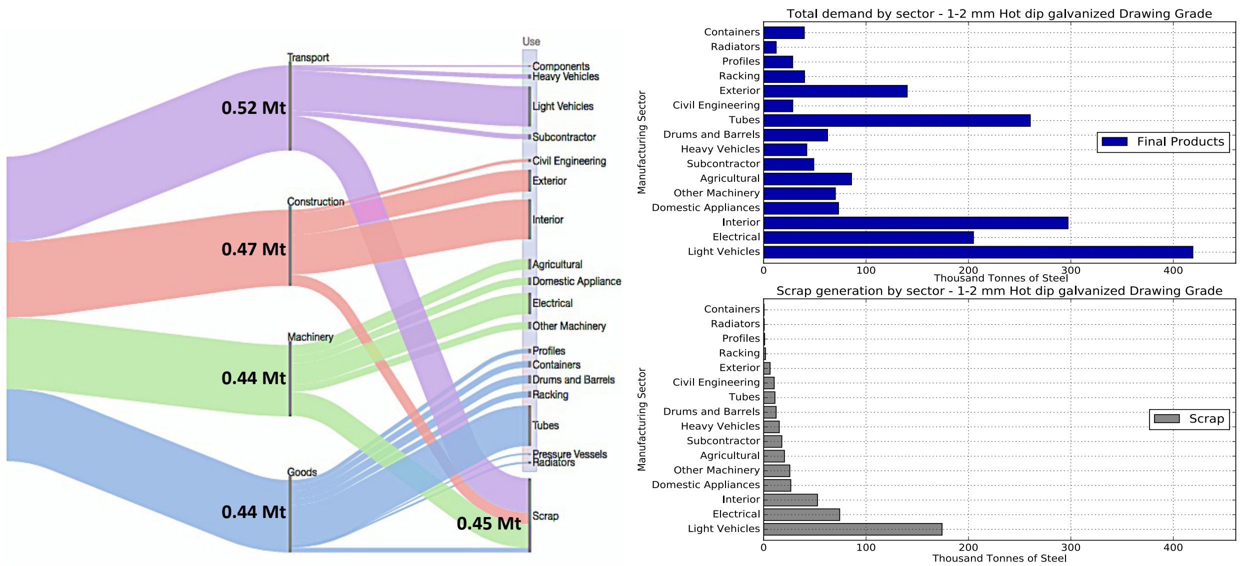


Figure 3: EU steel flows for 2013, divided by material characteristics. Each view shows inputs of steel to manufacturing from steelmaking and outputs of end-use goods as well as scrap from each of the four main manufacturing sectors: Transport, Construction, Machinery and Goods. The views are differentiated by [a] product category, [b] thickness, [c] grade, and [d] coating. Diagrams [e] and [f] show steel flows, excluding all uncoated material, coloured by coatings [e] or by manufacturing sector [f].



[a] [b]

Figure 4: [a] European flows of galvanised drawing steel with a thickness of 1-2mm. [b] Demand for galvanised drawing steel with a thickness of 1-2mm and scrap generated by industry sector.

Discussion

The results show that thin gauge galvanised drawing steel is the most common steel grade demanded across the European manufacturing sectors, and is thus the easiest grade of flat steel scrap that could be prevented or diverted as feedstock to other manufacturing industries. The European automotive industry produces 190 kt of this grade per year (Figure 4), as a result of 43% yield losses in their manufacturing processes. Various interventions can improve material utilisation rates in this sector, but even if only current best practices were implemented by all manufacturers,[29] this would create savings of 32–42 M€ and 125–171 kt CO_2 in the EU every year, at €570–730[30] and 2.2–3.0 t CO_2 per tonne of flat steel.[1]

The results show that 37% of manufacturing scrap is generated by light vehicle manufacturers, even though this sector accounts for just 19% of demand. Approximately 30% of this scrap comes from blanking, where both the scrap and parts leaving the blanking dies remain flat, and thus with higher chances of having geometries compatible with other uses. Although there are opportunities for improving material utilisation in the automotive industry,[29] part of its high yield losses arises from the production of each component from a different coil of steel. Since automotive manufacturers are simultaneously the greatest producers and users of 1–2 mm hot dip galvanised drawing grade, there may be opportunities to reuse this scrap within this sector. However this is unlikely to take place, unless the steel industry tessellates blanks for various automotive manufacturers from the same coil.

The potential improvements of tessellating components could be enhanced by relaxing specifications for steel grade for individual components across industry, which would allow for more components to be obtained from the same coil, and by matching component geometries.[31] Further opportunities may exist across industries, if other sectors using identical materials were able to communicate their part geometry to the steelmaker alongside the requirements of the vehicle manufacturer. Steelmakers could thus provide blanks rather than coils of steel, avoiding fabrication scrap downstream of the supply chain. In doing so, the same service to consumers could be provided with less metal production. This would reduce supply-side costs without reducing demand-side value, saving both emissions and resources in the process.

The results shown in the previous section reveal a potential opportunity for diversion of thin gauge galvanised drawing steel, by assessing the compatibility of mass and material grade across the EU flat steel supply chain. The opportunities for scrap reuse depend on grade compatibility, but also on geometry and size. An assessment on automotive sheet metal components by Horton et al.[32] shows that the excess material from blanking in the automotive industry does not result in small fragments. Since this is one of the most abundant sources of flat steel scrap, blanking scrap can thus be used in other applications. However, real opportunities for scrap diversion would also require detailed information on the geometry of scrap parts produced. Although this information is not currently available, the methodology demonstrated in this analysis could be used to estimate this opportunity by adding eventual data on geometry as a material dimension in the model described in equations 1 and 2.

Steel scrap generated by all manufacturers is collected by scrap merchants and sold for remelting and recycling. Although steel recycling produces up to three times less emissions than primary steel production, this is still a very energy intensive process, requiring an average of 2 MWh/t of recycled steel.[33] However, the method demonstrated in this article enables the identification of opportunities to divert fabrication scrap to be used as feedstock by other manufacturers, potentially avoiding unnecessary recycling. This is possible by the identification of the material grades with highest potential for scrap diversion, because they are widely used across various industries. Moreover, this identification provides important insights into material grade choice, since relaxing grade tolerances across many applications could increase uses of the most common grades and thus enhancing the opportunities for scrap diversion. For example, as shown in figure 4, galvanised drawing steel with a thickness of 1–2 mm is the most common grade of steel across most European manufacturing sectors, and therefore relaxing the thickness tolerances within this grade would create potential diversion opportunities.

Manufacturing practices evolve as a result of changes in demand and progress in engineering and manufacturing technology. Consequently, the demand for material grades in each sector is equally likely to evolve, and thus the opportunities for scrap diversion depend on the dynamic of demand for different grades and quantities to steel products over time. The method described in this paper could be applied to update potential opportunities according to the dynamics of steel demand at each time. This method could also be applied to other material industries where significant differences in material characteristics could be exploited and large companies in possession of reliable commercial data could provide a similar starting database to the one used in this study. This might be of particular interest to aluminium suppliers.

Rigorous data on national flows of steel, scraps arisings, and on the allocation of grades of steel to manufacturers is difficult to obtain, since there are no official statistics reporting them, and there is a lack of national studies quantifying these flows. The analysis presented here is thus subject to uncertainty. A shipment database of a big European steelmaking company was used to represent European flows and the material flow analysis required several assumptions described in detail in the Supplementary Information file. Despite these limitations, the data used in this paper is the best available data for the entire European flows of flat steel and it is sufficient to determine the scale of flows, since the market share of the company considered for this assessment is big enough to be representative of the European market, and the assumptions used here resulted from several interviews conducted across various European countries.

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Supporting Information Available

Supporting information is available comprising the full literature review, extended discussion of the methodology employed in this study, and further detail on the data gathered and generated to create the MFA flow dataset.

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Graphical TOC Entry