SI Mapping the global flow of steel: from steelmaking to end-use goods

Jonathan M. Cullen,[a]* Julian M. Allwood,[a] Margarita D. Bambach[b]

[a] Department of Engineering
University of Cambridge
Trumpington Street
Cambridge, CB21PZ
United Kingdom
Tel: +44 1223 760360
Fax: +44 1223 332 643
Email: jmc99@cam.ac.uk

[b] Institute of Ferrous Metallurgy, RWTH Aachen University

* corresponding author

Number of pages: 25
Number of figures: 3
Number of tables: 4

1. Data sources for steel statistics

The World Steel Association (worldsteel) publishes the most comprehensive view of global steel production. This is complemented by national statistics offices, regional associations, trade organisations, research institutes, and private media groups, who collect steel data across regional, country, and company levels, and publish in annual reports, magazines and online statistics. Examples of important data sources are presented, Table S1.

Organisation	Scope	Representation and data	Publications
World Steel Association (worldsteel)	Global	Represents the global steel industry (170 steel producers, representing 85% of global production) and collates data from member companies, national statistics offices, regional associations and research institutes.	*Steel statistical yearbook 2009* (worldsteel, 2010a) *World steel in figures* (worldsteel, 2010b)
International Iron Metallics Association (IIMA)	Global	Represents the global iron metallic industry and collects statisitics on the production of pig iron, hot briquetted iron (HBI), directly reduced iron (DRI) and iron nuggets.	(IIMA, nd)
U.S. Geological Survey (USGS)	Global (with US focus)	Tracks global iron ore extraction and stocks, and pig iron, steel and scrap resources for the US industry.	(USGS, nd)
European Confederation of Iron and steel Industries (EUROFER)	Europe	Represents the European steel industry (100% of production), and publishes data from steel companies and national steel federations, including Switzerland and Turkey (non-EU).	*European steel in figures* (EUROFER, 2010)
American Iron and Steel Institute (AISI)	North America	Represents the North American steel industry (80% of US and North American capacity) and collects data from 26 steelmaking companies and 130 associate/affiliate members	*Profile of the American Iron and Steel Institute* (AISI, 2011)
UK Steel (EEF)	United Kingdom	The trade association for the UK steel industry (a division of EFF, the manufacturers' organisation) that reports data from steel producing and processing companies in the UK.	*UK Steel key statistics* (UK Steel, 2010)
Japan Iron and Steel Federation (JISF)	Japan	Represents the Japanese steel industry and collates data from iron and steel producers and distributing processors in Japan.	*Annual statistics* (JISF, 2010)
ArcelorMittal	Global (producer)	The world's largest steel company (100Mt of crude steel production across 60 countries) publishes data relating to the company's steel and iron activities.	*Fact Book* (ArcelorMittal, 2009)
Tata Steel	Global (producer)	A global steel producer and vertically integrated supplier of steel products.	*Annual Report* (Tata Steel, 2010)
Steel Business Briefing (SBB)	Global (media)	Writes independent global steel news and tracks steel prices.	(SBB, nd)
World Steel Dynamics (WSD)	Global (media)	Collects global steel production and financial data.	(WSD, nd)
CRU	Global (media)	Provides business intelligence for global metal production, mining and other industrial sectors.	(CRU, nd)
Modern Casting	Global (media)	Publishes a monthly magazine for foundries and diecasters, and an annual census of world casting production.	*Census of World Casting Production* (Modern Casting, 2008)

Table S1—Steel data is collected by numerous organisations covering various aspects of the steel industry.

2. Using Sankey diagrams to visualise steel flows

The beauty of Sankey diagrams is that resource flows are represented by arrows or lines, where the thickness of each line is proportional to the amount of flow. They are an improvement over a simple flowchart, as the viewer can instantly compare the scale of resource flows, see the interconnectedness of flows, and visualise the conservation of mass and energy. Schmidt (2008a, 2008b) provides an excellent overview of the history and methodology for using Sankey diagrams to visualise energy and material resources flows, and comments quite rightly that Sankey diagrams, “with their intuitive readability and transparency, … are ideal for interpreting complicated sets of resource flows.” These maps are particularly useful under conditions of resource constraint, where efficient use of energy or materials becomes paramount. Yet, surprisingly, Sankey diagrams have rarely been used to visualise the flow of steel.

Sankey diagrams were first used by the Irish engineer Riall Sankey in 1898 to study the thermal efficiency of steam engines, by comparing an actual steam plant from the Louisville Leavitt pumping engine with an idealised steam plant based on the Rankine cycle (Sankey, 1898). Schmitz (2008a) notes that only a decade later, a series of ‘heat balances’ for blast furnaces and coke ovens used in steel production, appeared *the Journal of the Association of German Engineers*. In post-First World War Germany, under the economic constraints of reparation payments, Sankey diagrams were used to improve the yield of energy-intensive cement, glass and steel production, with detailed plant analyses were carried out to manage both heat and raw material demands, for example diagram of German iron flows in Figure S1.

Despite the utility of Sankey diagrams in driving efficient use of resources, post-war prosperity and expansion led to an age of cheap energy and materials, thus removing the resource constraints and the need for modelling resource flows with Sankey diagrams. It is only in recent years, amidst growing concerns about climate change and resource limitations, that the Sankey diagram is once again being used as a tool to drive efficiency—for example the global energy maps of Cullen and Allwood (2010a, 2010b).

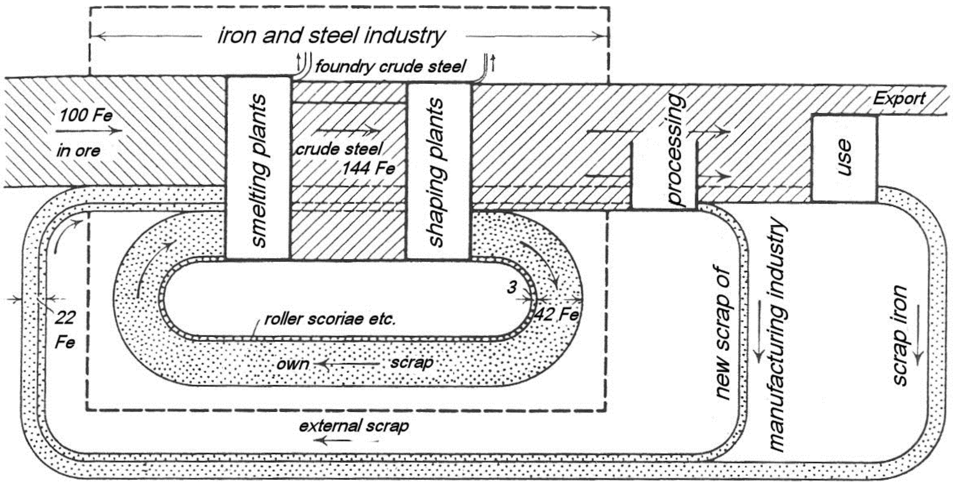


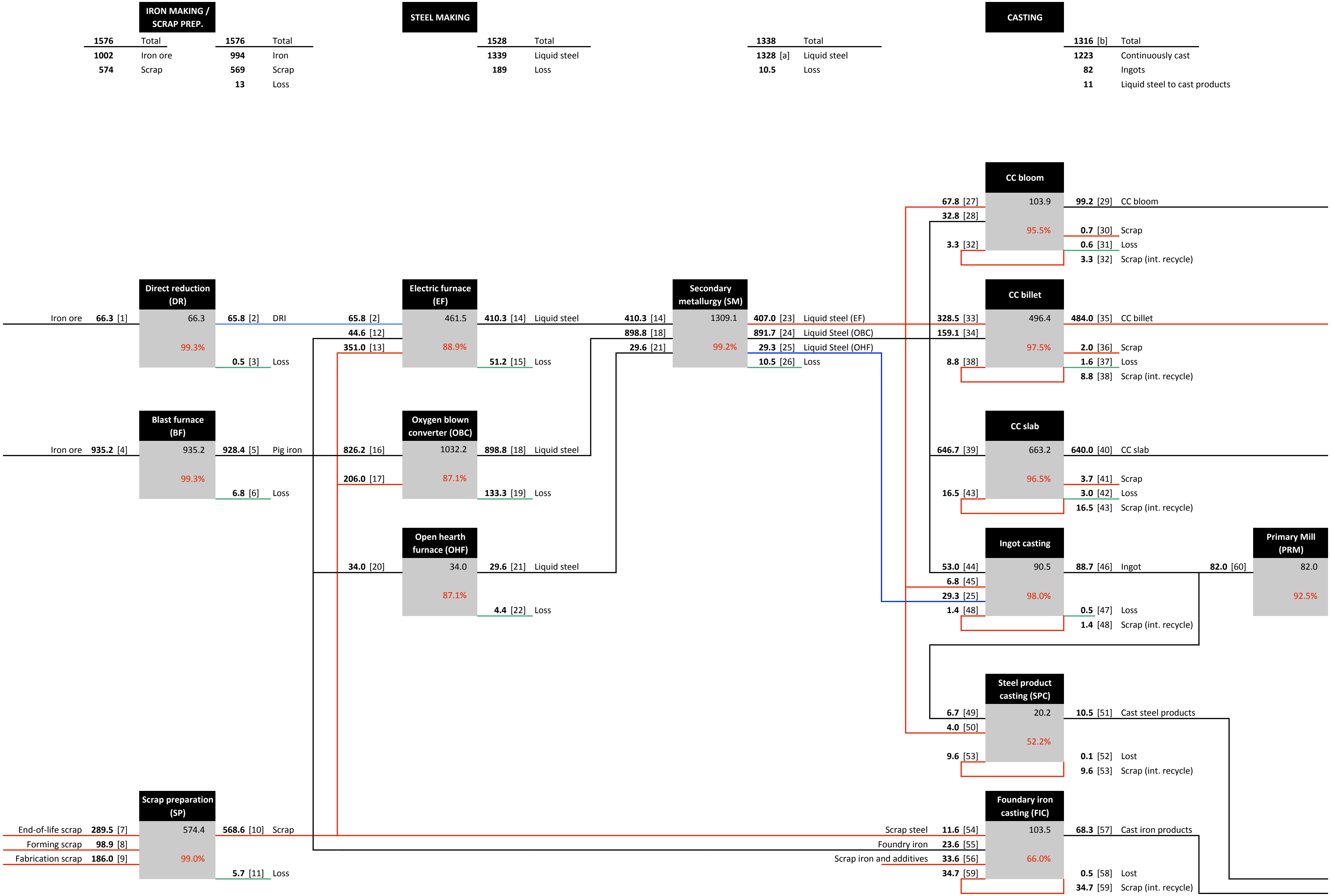
Figure S1—Example of post-First World War Sankey diagram, showing the German iron industry (Reichardt 1937, fig.2, in Schmitz 2008a, fig.4).

3. From steelmaking to intermediate products

The flow of steel, from iron ore and scrap to final products, is measured in millions of tonnes of steel, or mega-tonnes (Mt), per year. As steel moves through the various production and manufacturing pathways, its mass cannot be lost, and the inputs to each process must balance the outputs. However, each manufacturing process divides the steel material into valuable products (coloured lines), less valuable scrap steel (grey lines), and a small amount of unrecoverable oxides (black lines).

In Figure S2 we show the flows of steel from steelmaking processes (basic oxygen and electric) through to intermediate products. Table S2 gives the data sources and detailed calculations used to determine each flow. The label 'intermediate product' refers to the 'bulk' or 'stock' outputs from the steel industry—beams, rod and bars, sheet and tubes. The steel industry calls these 'finished products', or sometimes 'semi-finished products', even though they require further fabrication to convert them to consumer ready products. We adopt the label 'intermediate products' to avoid confusion.

Figure S2 (following two pages)—Global steel flows. Each flow is given in millions of tonnes (Mt, bold) and labelled using square brackets, which link to Table S2. Material yields percentages are given for each process (red). Flows continue across both pages.


IRON MAKING / SCRAP PREP.
1576 Total
1002 Iron ore
574 Scrap
1576 Total
994 Iron
569 Scrap
13 Loss
STEEL MAKING
1528 Total
1339 Liquid steel
189 Loss
1338 Total
1328 [a] Liquid steel
10.5 Loss
CASTING
1316 [b] Total
1223 Continuously cast
82 Ingots
11 Liquid steel to cast products
Direct reduction (DR)
Iron ore 66.3 [1]
66.3
99.3%
65.8 [2] DRI
0.5 [3] Loss
Blast furnace (BF)
Iron ore 935.2 [4]
935.2
99.3%
928.4 [5] Pig iron
6.8 [6] Loss
Scrap preparation (SP)
End-of-life scrap 289.5 [7]
Forming scrap 98.9 [8]
Fabrication scrap 186.0 [9]
574.4
99.0%
568.6 [10] Scrap
5.7 [11] Loss
Electric furnace (EF)
65.8 [2]
44.6 [12]
351.0 [13]
461.5
88.9%
410.3 [14] Liquid steel
51.2 [15] Loss
Oxygen blown converter (OBC)
826.2 [16]
206.0 [17]
1032.2
87.1%
898.8 [18] Liquid steel
133.3 [19] Loss
Open hearth furnace (OHF)
34.0 [20]
34.0
87.1%
29.6 [21] Liquid steel
4.4 [22] Loss
Secondary metallurgy (SM)
410.3 [14]
898.8 [18]
29.6 [21]
1309.1
99.2%
407.0 [23] Liquid steel (EF)
891.7 [24] Liquid Steel (OBC)
29.3 [25] Liquid Steel (OHF)
10.5 [26] Loss
CC bloom
67.8 [27]
32.8 [28]
3.3 [32]
103.9
95.5%
99.2 [29] CC bloom
0.7 [30] Scrap
0.6 [31] Loss
3.3 [32] Scrap (int. recycle)
CC billet
328.5 [33]
159.1 [34]
8.8 [38]
496.4
97.5%
484.0 [35] CC billet
2.0 [36] Scrap
1.6 [37] Loss
8.8 [38] Scrap (int. recycle)
CC slab
646.7 [39]
16.5 [43]
663.2
96.5%
640.0 [40] CC slab
3.7 [41] Scrap
3.0 [42] Loss
16.5 [43] Scrap (int. recycle)
Ingot casting
53.0 [44]
6.8 [45]
29.3 [25]
1.4 [48]
90.5
98.0%
88.7 [46] Ingot
0.5 [47] Loss
1.4 [48] Scrap (int. recycle)
Primary Mill (PRM)
82.0 [60]
82.0
92.5%
Steel product casting (SPC)
6.7 [49]
4.0 [50]
9.6 [53]
20.2
52.2%
10.5 [51] Cast steel products
0.1 [52] Lost
9.6 [53] Scrap (int. recycle)
Foundary iron casting (FIC)
Scrap steel 11.6 [54]
Foundry iron 23.6 [55]
Scrap iron and additives 33.6 [56]
34.7 [59]
103.5
66.0%
68.3 [57] Cast iron products
0.5 [58] Lost
34.7 [59] Scrap (int. recycle)

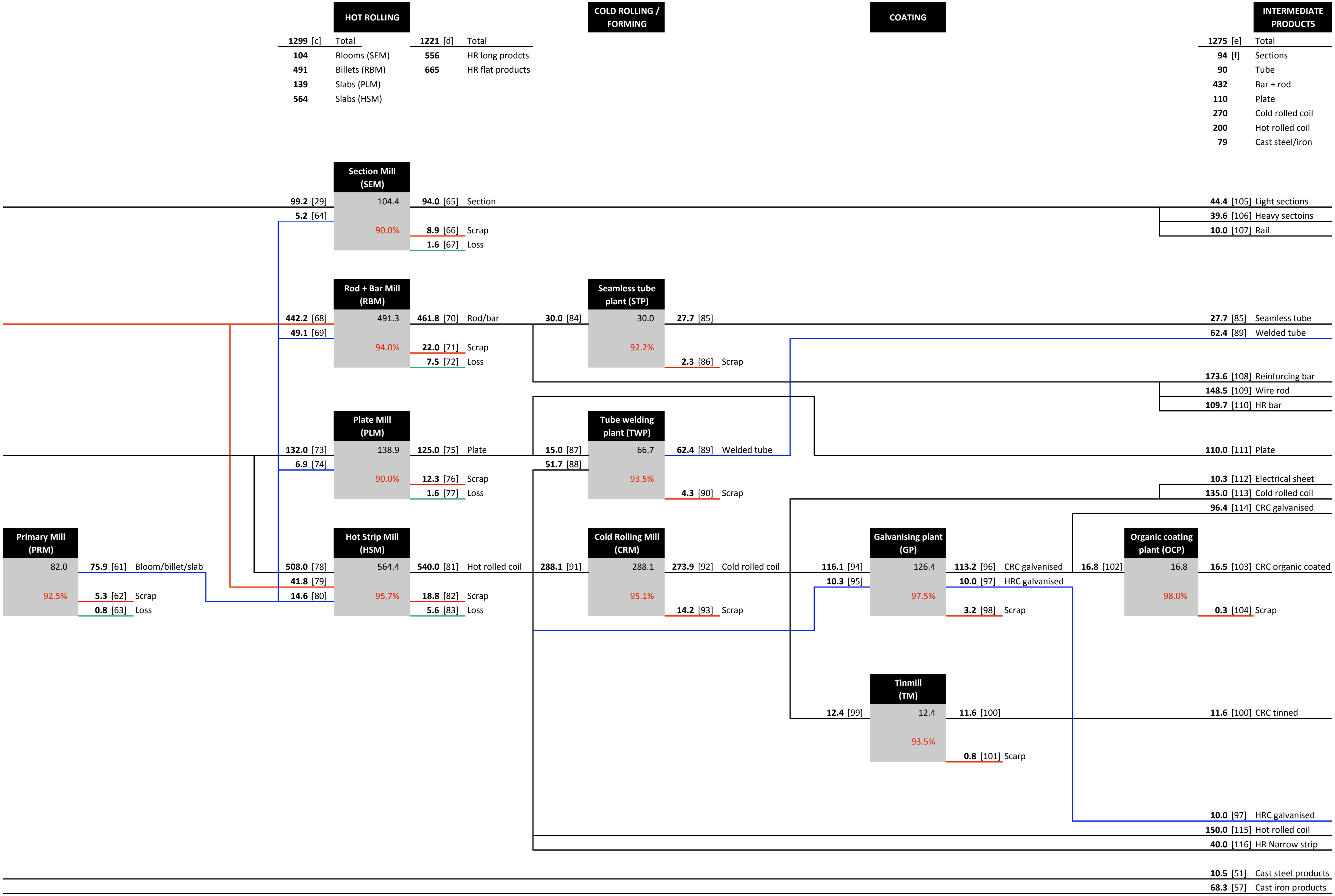

HOT ROLLING
1299 [c] Total
104 Blooms (SEM)
491 Billets (RBM)
139 Slabs (PLM)
564 Slabs (HSM)
1221 [d] Total
556 HR long prodcts
665 HR flat products
COLD ROLLING / FORMING
COATING
INTERMEDIATE PRODUCTS
1275 [e] Total
94 [f] Sections
90 Tube
432 Bar + rod
110 Plate
270 Cold rolled coil
200 Hot rolled coil
79 Cast steel/iron
Section Mill (SEM)
99.2 [29]
5.2 [64]
104.4
90.0%
94.0 [65] Section
8.9 [66] Scrap
1.6 [67] Loss
44.4 [105] Light sections
39.6 [106] Heavy sectoins
10.0 [107] Rail
Rod + Bar Mill (RBM)
442.2 [68]
49.1 [69]
491.3
94.0%
461.8 [70] Rod/bar
22.0 [71] Scrap
7.5 [72] Loss
Seamless tube plant (STP)
30.0 [84]
30.0
92.2%
27.7 [85]
2.3 [86] Scrap
27.7 [85] Seamless tube
62.4 [89] Welded tube
173.6 [108] Reinforcing bar
148.5 [109] Wire rod
109.7 [110] HR bar
Plate Mill (PLM)
132.0 [73]
6.9 [74]
138.9
90.0%
125.0 [75] Plate
12.3 [76] Scrap
1.6 [77] Loss
Tube welding plant (TWP)
15.0 [87]
51.7 [88]
66.7
93.5%
62.4 [89] Welded tube
4.3 [90] Scrap
110.0 [111] Plate
10.3 [112] Electrical sheet
135.0 [113] Cold rolled coil
96.4 [114] CRC galvanised
Primary Mill (PRM)
82.0
92.5%
75.9 [61] Bloom/billet/slab
5.3 [62] Scrap
0.8 [63] Loss
Hot Strip Mill (HSM)
508.0 [78]
41.8 [79]
14.6 [80]
564.4
95.7%
540.0 [81] Hot rolled coil
18.8 [82] Scrap
5.6 [83] Loss
Cold Rolling Mill (CRM)
288.1 [91]
288.1
95.1%
273.9 [92] Cold rolled coil
14.2 [93] Scrap
Galvanising plant (GP)
116.1 [94]
10.3 [95]
126.4
97.5%
113.2 [96] CRC galvanised
10.0 [97] HRC galvanised
3.2 [98] Scrap
Organic coating plant (OCP)
16.8 [102]
16.8
98.0%
16.5 [103] CRC organic coated
0.3 [104] Scrap
Tinmill (TM)
12.4 [99]
12.4
93.5%
11.6 [100]
0.8 [101] Scarp
11.6 [100] CRC tinned
10.0 [97] HRC galvanised
150.0 [115] Hot rolled coil
40.0 [116] HR Narrow strip
10.5 [51] Cast steel products
68.3 [57] Cast iron products

Table S2—Data sources and calculations used to map the flows of steel from steelmaking to intermediate products. Each flow is given in millions of tonnes (Mt) and labelled using square brackets, e.g. [15] which link to Figure S2. Citations are shown in curved brackets, e.g. (1, p,21, tab.3), with full references provided at the end of the table, and abbreviations at the end of the document.

Flow	Mt	Description	Reference / Calculation	Notes
[1]	66.3	Iron ore	=[2]/0.99	DR yield =99.3%, assumed to be equal to the BF yield, see note for [4]. Fe content only.
[2]	65.8	DRI	(1, p.102)	Compare with 65.2 Mt (2, p.34). It is assumed that all DRI is fed to the EF.
[3]	0.5	Loss	=[1]-[2]	Fe losses only.
[4]	935.2	Iron ore	=[5]/0.99	BF yield = 99.3%, the product of the sinter plant yield 99.84% (3, p.32) and the BF yield 99.43% (3, p.33). Represents the small amount of Fe that is lost to landfill and the atmosphere. The total includes on average 7.2% Fe recycled mill scale/dust (3, p.34) as an input to the sinter plant.
[5]	928.4	Pig iron	(1, p.101)	The BF total includes 1.4Mt of pig iron from smelt reduction process: Corex 0.6Mt and Hsmelt 0.8Mt. Pig iron includes pig iron for steelmaking and foundry iron used in casting. The iron content of the pig iron is approximately 94% Fe
[6]	6.8	Loss	=[4]-[5]	Fe losses only.
[7]	289.5	Scrap (end-of-life)	=[10]+[11]-[8]-[9]	End-of-life scrap, also known as post-consumer scrap. Calculated as the balance of scrap. Compare with the extrapolated value of 370Mt of discards for 2008 in Hatayama et al. (4, fig.2) multiplied by the worldsteel recovery rate for end-of-life scrap of 80% (5, p.2), equals 296Mt.
[8]	98.9	Scrap (forming)	=[30]+[36]+[41]+[62] +[66]+[71]+[76]+[82] +[86]+[90]+[93]+[98] +[101]+[104]	Equals the sum of all scrap from rolling and forming processes. An additional 39Mt is recycled internally in steel casting (continuous, ingot and product) and 35Mt in iron foundry casting, but is not included in this total.
[9]	186.0	Scrap (fabrication)		World Steel Dyamics estimate that globally 'new steel scrap' (from fabrication processes) equals 14% of apparent steel consumption (6, p.19). Using a crude steel figure of 1,328Mt gives 186Mt for fabrication scrap.
[10]	570.2	Scrap	=(475.5+[8])*0.99	Reported scrap consumption is 475.5Mt (7, p.26) but is assumed to exclude forming scrap [8], which is internally recycled and typically not included in recycling statistics. SP yield =99.3%, assumed to be equal to the BF yield. Fe content only and excludes recycling collection inefficiencies.
[11]	4.2	Loss	=[7]+[8]+[9]-[10]	Fe losses only.
[12]	44.6	Pig iron	=(36.2+9.3)*0.98	Based on reported global pig iron inputs to EAF steel making in 2008 (2, p.34), which includes: 36.2Mt pig iron and 9.3Mt hot metal (liquid pig iron). Scaled using the ratio of EAF production totals from the two sources: 407.0Mt (1, p.25) divided by 414.9Mt (2, p.34) = 0.98.
[13]	351.0	Scrap	=[14]/0.889-[2]-[12]	EF yield =88.9%, from the gross metallic yield =1000/1125 (3, p.67, fig.63), which is within the range for overall yield 86.1%-95.7%. Note the Fe yield, which excludes non-iron materials, is much higher 92.8%-98.6%. The EF scrap input is comparable to 345.8Mt (2, p.34).
[14]	410.3	Liquid steel	=[23]/0.992	SM yield = 99.2% (3, p.70), which is the average of the overall yield range 98.3-100%. (Note the Fe yield is 99.4%-100%.) The mass of alloying elements is ignored.
[15]	51.2	Loss	=[2]+[12]+[13]-[14]	Slag losses are sent for reprocessing and the resulting FeO is sintered and fed to the BF.
[16]	824.6	Pig iron	=[18]/0.871-[17]	OBC yield =87.1%, calculated as the product of: the pretreatment yield = 98.4%, calculated as 1000/1015 (3, p.52, fig.38) with a range of 94.5%-100%; and the BOF yield =85.5%, calculated as 1000/1130 (3, p.59, fig.49) with a range of 81%-100%. (Note the Fe yield for the BOF is 90-100%.)

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Flow	Mt	Description	Reference / Calculation	Notes
[17]	207.5	Scrap	=[10]-[13]-[54]	Assumes no scrap is used in OHF. This equals 20% of the charge to OBC, but includes forming scrap from the rolling mills (internal run-around scrap). This value is above the 10% scrap charge assumed by Worrell et al. (8, p.6) and the value of 13.8% used by Tata Steel for their carbon footprint calculation (9), however these values may not include forming scrap. The maximum thermodynamic limit for scrap charge is 25-30% without the addition of extra fuel (10, p.181).
[18]	898.8	Liquid steel	=[24]/0.992	SM yield =99.2%, see note for [14].
[19]	133.3	Loss	=[18]*(1/0.871-1)	OBC yield =87.1%, see note for [16]. Slag losses are sent for reprocessing and the resulting FeO is sintered and fed to the BF.
[20]	34.0	Pig iron	=[21]/0.871	OHF yield =87.1%, assumed to be equal to the OBC yield. It is assumed that only pig iron (no scrap) is fed to the OHF.
[21]	29.6	Liquid steel	=[25]/0.992	SM yield =99.2%, see note for [14].
[22]	4.4	Loss	=[21]*(1/0.871-1)	OHF yield =87.1%, see note for [20]. Slag losses are sent for reprocessing and the resulting FeO is sintered and fed to the BF.
[23]	407.0	Liquid steel (EF)	(1, p.25)	Crude steel production from EF. Assumed to be post SM value. Compare with 414.9Mt (2, p.34).
[24]	891.7	Liquid steel (OBC)	(1, p.25)	Crude steel production from OBC. Assumed to be post SM value.
[25]	29.3	Liquid steel (OHF)	(1, p.25)	Crude steel production from OHF. Assumed to be post SM value. Assumed to all be cast as ingots.
[26]	10.5	Loss	=([23]+[24]+[25]) *(1/0.992-1)	SM yield =99.2%, see note for [14]. Slag losses are sent for reprocessing and the resulting FeO is sintered and fed to the BF. The mass of alloying elements is ignored.
[27]	67.8	Liquid steel (EF)	=([23]-[45]-[50]) *([29]+[30]+[31]) / ([29]+[30]+[31] +[35]+[36]+[37])	The EF liquid steel (less a small fraction to ingots and products) is assumed to be divided between blooms and billets on a pro-rata basis, using the throughput of each process (less any internal recycle).
[28]	32.8	Liquid steel (OBC)	=[29]/0.955-[27]-[32]	CC billet yield =95.5%, taken as the median prime yield for blooms (conditioned blooms over the liquid steel fed to the caster) (3, p.81, fig. 87).
[29]	99.2	CC bloom	=([105]+[106]+[107]) / 0.90 *0.95	SEM yield =90%, taken as the average prime yield (output of acceptable rolled product over material input) of heavy sections, medium sections, angles and rails (3, p.170, fig.21). The breakdown of input material to the rolling mills, ingot versus CC, is taken from the worldsteel chart (3, p.139, fig.172). It shows 95% of the input to SEM is CC bloom, and 5% is ingot rolled to bloom in the PRM.
[30]	0.7	Scrap	=[29]*(1/0.955-1)*0.16	CC bloom yield =95.5%, see note for [28]. 16% of the scrap/lost material from CC is scrap that is returned as forming scrap to the EF or OBC for steelmaking (3, p.83, fig.90).
[31]	0.6	Loss	=[29]*(1/0.955-1)*0.13	CC bloom yield =95.5%, see note for [28]. 13% of the scrap/lost material from CC is lost as scale (mainly FeO) that is reprocessed and sintered before being returned to the BF (3, p.83, fig.90).
[32]	3.3	Scrap (int. recycle)	=[29]*(1/0.955-1)*0.71	CC bloom yield =95.5%, see note for [28]. The remaining 71% of scrap/lost material from CC is recycled internally in the casting facility (3, p.83, fig.90).

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Flow	Mt	Description	Reference / Calculation	Notes
[33]	328.5	Liquid steel (EF)	=([23]-[45]-[50]) *([35]+[36]+[37]) / ([29]+[30]+[31] +[35]+[36]+[37])	The EF liquid steel (less a small fraction to ingots and products) is assumed to be divided between blooms and billets on a pro-rata basis, using the throughput of each process (less any internal recycle).
[34]	159.1	Liquid steel (OBC)	=[35]/0.975-[33]-[38]	CC billet yield =97.5%, taken as the median prime yield for billets (conditioned billets over the liquid steel fed to the caster) (3, p.81, fig. 87).
[35]	484.0	CC billet	=[68]+[79]	
[36]	2.0	Scrap	=[35]*(1/0.975-1)*0.16	CC bloom yield =97.5%, see note for [34]. 16% is forming scrap, see note for [30].
[37]	1.6	Loss	=[35]*(1/0.975-1)*0.13	CC bloom yield =97.5%, see note for [34]. 13% is lost, see note for [31].
[38]	8.8	Scrap (int. recycle)	=[35]*(1/0.975-1)*0.71	CC bloom yield =97.5%, see note for [34]. 71% is recycled internally, see note for [32].
[39]	646.7	Liquid steel (OBC)	=[40]/0.965 –[43]	CC slab yield =96.5%, taken as the median prime yield for slab (conditioned slab over the liquid steel fed to the caster) (3, p.81, fig.87). It is assumed that only OBC liquid steel is used for CC for slab, as a higher purity of steel is demanded for slab and the strip mills.
[40]	640.0	CC slab	(11, p.4)	Global estimate of 640Mt cast as slab in 2008.
[41]	3.7	Scrap	=[40]*(1/0.965-1)*0.16	CC bloom yield =96.5%, see note for [39]. 16% is forming scrap, see note for [30].
[42]	3.0	Loss	=[40]*(1/0.965-1)*0.13	CC bloom yield =96.5%, see note for [39]. 13% is lost, see note for [31].
[43]	16.5	Scrap (int. recycle)	=[40]*(1/0.965-1)*0.71	CC bloom yield =96.5%, see note for [39]. 71% is recycled internally, see note for [32].
[44]	53.0	Liquid steel (OBC)	=[46]/0.98 –[25]-[45] -[48]	Ingot casting yield =98.0%, taken as the average of 97% and 98.9% for the reference plant yield (12, p.2). In most cases CC has replaced the IC/PM route.
[45]	6.8	Liquid steel (EF)	=[49]/0.98	Ingot casting yield =98%, see note for [44]. It is assumed that product casting uses only EF liquid steel and EF ingots, see note for [51].
[46]	88.7	Ingot	(1, p.9)	Crude steel production, cast as ingots.
[47]	0.5	Loss	=[46]*(1/0.98-1)*0.25	Ingot casting yield =98%, see note for [44]. 25% of the scrap/lost material is assumed to be lost as scale (mainly FeO) that is reprocessed and sintered before being returned to the BF.
[48]	1.4	Scrap (int. recycle)	=[46]*(1/0.98-1)*0.75	Ingot casting yield =98%, see note for [44]. 75% of the scrap/lost material is assumed to be recycled internally in the casting facility.
[49]	6.7	Ingot	=[51]/0.522 -[50]-[53]	Ingots used in product casting must be remelted (a second time) using additional energy. It is assumed that product casting uses only EF liquid steel and EF ingots, see note for [51].
[50]	4.0	Liquid steel (EF)	(1, p.9)	Liquid steel for castings is assumed to come from EF liquid steel, see note for [51].
[51]	10.5	Cast steel product	(11, p.19)	The value of 10.5Mt is the global 2008 total for steel casting (11, p.19). It is assumed that only EF based steel and internal recycled scrap is used in product casting, giving a recycled content of 88%. Shifo and Radia comment that over 90% of raw materials melted for ferrous casting are from recycled sources (13, p.9).
[52]	0.1	Loss	=[51]*(1/0.522-1) *[47]/([47]+[48])	SPC yield =52.2%, calculated as the weighted average of US 2003 data for steel castings (13, p.52, tab.30). The lost fraction for SPC is assumed to be the same as for ingot casting.

Table S2—Data sources and calculations used to map the flows of steel from steelmaking to intermediate products. Each flow is given in millions of tonnes (Mt) and labelled using square brackets, e.g. [15] which link to Figure S2. Citations are shown in curved brackets, e.g. (1, p,21, tab.3), with full references provided at the end of the table, and abbreviations at the end of the document.

Flow	Mt	Description	Reference / Calculation	Notes
[53]	9.6	Scrap (int. recycle)	=[51]*(1/0.522-1)-[52]	SPC yield =52.2%, see note for [52].
[54]	11.6	Scrap (steel)	=[57]*0.17	The fraction of scrap steel include in the cast iron product output can be calculated by considering the dilution of carbon from pig iron (4%C) to cast iron (3.4% gray iron and ductile iron, 2.5% malleable iron), giving approximately 17% of scrap steel.
[55]	25.2	Foundry iron	=[5]-[12]-[16]-[20]	Calculated as the balance of pig iron not used in steelmaking. Note that the value for foundry iron input to FIC (25.2Mt) is comparatively much smaller than the total for pig iron used in steelmaking (total ~900Mt). Small % fluctuations or errors in steelmaking pig iron will have a large effect on the calculated value for FIC pig iron.
[56]	32.0	Scrap iron	=[57]/0.66 -[54]-[55]-[59]	FIC yield =66.0%, calculated as the weighted average of US 2003 data for gray and ductile iron castings (13, p.52, tab.30).
[57]	68.3	Cast iron product	(11, p.19)	The value of 68.3Mt cast iron products is the sum of 42.9Mt of gray iron, 23.8Mt of ductile iron and 1.5Mt of malleable iron (11, p.19). The recycled content, calculated as 76% is below the value of 90% suggested by Shifo and Radia (13, p.9). Possible causes are the uncertainty in the foundry iron and scrap iron inputs, see note for [55].
[58]	0.5	Loss	=[57]/0.522 *[47]/([47]+[48])	FIC yield =66.0%, see note for [56]. The lost fraction for SPC is assumed to be the same as for ingot casting.
[59]	34.7	Scrap (int. recycle)	=[57]*(1/0.66-1)-[58]	FIC yield =66.0%, see note for [56]. No yield value is given for the lost metal in the casting process, so all scrap is assumed to be recycled.
[60]	82.0	Ingot	=[46]-[49]	The remaining ingots (less SPC) are assumed to be made from OBC liquid steel, in older integrated plants (pre-CC) with PRM for processing ingots into blooms, billets and slab.
[61]	75.9	Bloom/billet /slab	=[60]*0.925	PRM yield =92.5%, calculated as the average from the range 91.5% and 93.5% (3, p.142).
[62]	5.3	Scrap	=[61]*(1/0.925-1)-[63]	Scrap steel is returned as forming scrap to the EF or OBC for steelmaking.
[63]	0.8	Loss	=[61]/0.925*0.01	PRM yield =92.5%, see note for [61]. Scale loss (mainly FeO) equals 1% of PRM throughput (3, p.143, tab.27) and is reprocessed and sintered before being returned to the BF.
[64]	5.2	Bloom (ingot)	=[65]/0.900 *0.05	SEM yield =90%, is calculated as the weighted average of heavy sections, medium sections (assumed to be same as light sections) and rail. Median values for each are estimated from the graph (3, p.170, fig.201). 5% of the input to SEM is ingot rolled to bloom in the PRM, see note for [29].
[65]	94.0	Section	=[105]+[106]+[107]	Equals the sum of heavy sections, light sections and rail.
[66]	8.9	Scrap	=[64]*(1/0.900-1)-[67]	SEM yield =90%, see note for [64].
[67]	1.6	Loss	=[64]/0.900*0.015	SEM yield =90%, see note for [64]. Scale loss (mainly FeO) equals approximately 1.5% of SEM throughput (3, p.165, fig.197) and is reprocessed and sintered before being returned to the BF.

Table S2—Data sources and calculations used to map the flows of steel from steelmaking to intermediate products. Each flow is given in millions of tonnes (Mt) and labelled using square brackets, e.g. [15] which link to Figure S2. Citations are shown in curved brackets, e.g. (1, p,21, tab.3), with full references provided at the end of the table, and abbreviations at the end of the document.

Flow	Mt	Description	Reference / Calculation	Notes
[68]	442.2	CC billet	=[70]/0.940 *0.90	RBM yield =94.0%, which is solved so that the sum of the liquid steel (OBC) to casting (=[28]+[34]+[39]+[44]) is equal to the worldsteel value of 892Mt [24]. Compare with the worldsteel yield report which does not give an overall yield for RBM due to incomplete data, but describes the average losses from: scale =0.81% (3, p.174, fig.203); cobbles =0.30% (3, p.177, fig.207); cropping =0.83% (3, p.179, fig.210); subdivision/cutting (average) =1.24% (3, p.180, 212). Adding these up gives an overall yield of approximately 96.8% which is higher than the solved value used in our model, however it is difficult in practice to see how the RBM yield could be 7% higher than the SEM yield of 90%. The breakdown of input material to the rolling mills, ingot versus CC, is taken from the worldsteel chart (3, p.139, fig.172). It shows 90% of the input to RBM is CC bloom, and 10% is ingot rolled to billet in the PRM.
[69]	49.1	Billet (ingot)	=[70]/0.940 *0.10	RBM yield =94.0%, and 10% of the input to RBM is ingot rolled to billet in the PRM, see note for [68].
[70]	461.8	Rod/bar	=[84]+[108] +[109]+[110]	Equals the sum of reinforcing bar, wire rod, hot rolled bar, and seamless tube (extruded from rod and bar). Note, the general term 'rod and bar' is assumed to include all types of wire, rod and bar (3, p.172, tab.43).
[71]	22.0	Scrap	=[70]*(1/0.940-1)-[72]	RBM yield =94%, see note for [68].
[72]	7.5	Loss	=[70]/0.940*0.015	RBM yield =94%, see note for [68]. Scale loss (mainly FeO) is assumed to equal the SEM value of 1.5% of throughput, and is reprocessed and sintered before being returned to the BF.
[73]	132.0	CC slab	=[75]/0.900 *0.95	PLM yield =90%, is the final prime yield for plate (3, p.159, tab.37). The breakdown of input material to the rolling mills, ingot versus CC, is taken from the worldsteel chart (3, p.139, fig.172). It shows 95% of the input to PLM is CC bloom, and 5% is ingot rolled to slab in the PRM.
[74]	6.9	Slab (ingot)	=[75]/0.900 *0.05	PLM yield =90%, and 5% of the input to PLM is ingot rolled to slab in the PRM, see note for [73].
[75]	125	Plate	=[87]+[111]	Equals the sum of plate (sold as intermediate product) and plate rolled into welded tubes. Compare with 120Mt (14, p.3).
[76]	12.3	Scrap	=[75]*(1/0.900-1)-[77]	PLM yield =90%, see note for [73].
[77]	1.6	Loss	=[70]/0.900*0.0115	PLM yield =90%, see note for [73]. Scale loss (mainly FeO) equals approximately 1.15% of PLM throughput (3, p.159, tab.37) and is reprocessed and sintered before being returned to the BF.
[78]	508.0	CC slab	=[81]/0.957-[79]-[80]	HSM yield =95.7%, which is solved so that the sum of CC slab to the PLM and HSM (=73]+[78]) is equal to the Steel Business Briefing value of 640Mt [40]. Compare with the worldsteel yield report which gives a prime yield for HSM of approximately 96% (3, p.126, fig.159).
[79]	41.8	CC billet	=[116]/0.957	HSM yield =95.7%, see note for [78]. It is assumed that HR narrow strip is all made from CC billet (rather than CC slab which is used for other HSM products).
[80]	14.6	Slab (ingot)	=[61]-[64]-[69]-[74]	Calculated as the balance of ingot rolled in the PRM. The affects the breakdown of ingot versus CC slab for the HSM, with 2.5% of the input to HSM being ingot rolled to slab in the PRM. This is half of the approximate value from worldsteel of 5% (3, p.139, fig.172), which would give a higher value of 29Mt for the slab (ingot) input to HSM. However, SBB estimate a lower value of 10Mt for HR flats from ingots.
[81]	540.0	HRC	(14, p.3)	Steel Business Briefing estimate the total HRC as 500Mt in 2008 with an addition 40Mt of HR narrow strip.
[82]	18.8	Scrap	=[81]*(1/0.957-1)-[83]	HSM yield =95.7%, see note for [78].
[83]	5.6	Loss	=[81]/0.957*0.01	HSM yield =95.7%, see note for [78]. Scale loss (mainly FeO) equals approximately 1% of HSM throughput (3, p.97, fig.105) and is reprocessed and sintered before being returned to the BF.

Table S2—Data sources and calculations used to map the flows of steel from steelmaking to intermediate products. Each flow is given in millions of tonnes (Mt) and labelled using square brackets, e.g. [15] which link to Figure S2. Citations are shown in curved brackets, e.g. (1, p,21, tab.3), with full references provided at the end of the table, and abbreviations at the end of the document.

Flow	Mt	Description	Reference / Calculation	Notes
[84]	30.0	Rod/bar	(14, p.1)	Based on the estimated value from Steel Business Briefing for intermediate products. Gives a STP yield =92.2%, which seems reasonable.
[85]	27.7	Seamless tube	(1, p.60, tab.25)	Global total for seamless tube in 2008.
[86]	2.3	Scrap	=[84]-[85]	
[87]	15.0	Plate	=[89]/0.935-[88]	TWP yield =93.5%, which is solved so that the sum of all HR flat product =[75]+[81], is equal to the worldsteel value of 665Mt (1, p.43, tab.13), which seems a reasonable yield for the welded tube process. The extra 15Mt of HR plate, over and above the worldsteel value of 110Mt [111], is assumed to be hidden in the statistics for welded tube. This equates to 12% of all plate being diverted to welded tube fabrication. For comparison, EUROFER calculates that about 25% of all quarto plates, produced in Europe, are fabricated into welded tube (15, p.8). The EUROFER value excludes plate delivered to merchants and stockists, and it is possible that some additional intermediate plate is converted to welded tube, but is not counted in the statistics.
[88]	51.7	HRC	=[81]-[91]-[95] -[115]-[116]	Calculated as the balance of hot rolled coil from the HSM, less: HRC and HR narrow strip (sold as products) and HRC diverted to the CRM and GP. This equates to 10% of all HRC being diverted to welded tube fabrication. For comparison, EUROFER calculates that about 17% of all strip mill products, produced in Europe, are fabricated into welded tube (15, p.8). The EUROFER value excludes strip delivered to merchants and stockists, and it is possible that some additional intermediate HRC is converted to welded tube, but is not counted in the statistics.
[89]	62.4	Welded tube		Solved so that the total of all intermediate products (excluding cast iron product) matches the worldsteel apparent consumption figure of 1207Mt. The comparable worldsteel value for welded tube is 44.5Mt (1, p.62, tab.26). The difference cannot be accounted for.
[90]	4.3	Scrap	=[89]*(1/0.935-1)	TWP yield =93.5%, see note for [87].
[91]	288.1	HRC	=[92]/0.951	CRM yield =95.1%, calculated as the product of the average throughput yield for pickling =97%, cold rolling =99% and batch annealing =99% (3, p.126, fig.159). Compare with the SBB value of 280Mt (14, p.4).
[92]	273.9	CRC	=[94]+[99]+[112]+[113]	Sum of the cold rolled coil products.
[93]	14.2	Scrap	=[92]*(1/0.951-1)	CRM yield =95.1%, see note for [91].
[94]	116.1	CRC	=[96]/0.975	GP yield =97.5%, equal to the average throughput yield for both hot dip galvanising and electrolytic galvanising (3, p.126, fig.159). Note the weight of zinc is ignored.
[95]	10.3	HRC	=[97]/0.975	GP yield =97.5%, see note for [94].
[96]	113.2	CRC galv.	=[102]+[114]	Sum of the galvanised CRC products.
[97]	10.0	HRC galv.	(14, p.4)	Global total for galvanised hot rolled coil in 2008, from SBB.
[98]	3.2	Scrap	=([96]+[97]) *(1/0.975-1)	GP yield =97.5%, see note for [94].
[99]	12.4	CRC	=[100]/0.935	TM yield =93.5%, equal to the average throughput yield for tinning lines (3, p.126, fig.159). Note the weight of tin is ignored.
[100]	11.6	CRC tinned	(1, p.54, tab.21)	Global total for tinmill products in 2008. Compare with the SBB value of 15Mt for tinplate products (14, p.4)
[101]	0.8	Scrap	=[100]*(1/0.935-1)	TM yield =93.5%, see note for [99].

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Flow	Mt	Description	Reference / Calculation	Notes
[102]	16.8	CRC galv.	=[103]/0.98	OCP yield =98%, equal to the average throughput yield for organic coating lines (3, p.126, fig.159). Note the weight of the organic coating is ignored.
[103]	16.5	CRC org.	(1, p.57, tab.23)	Global total for non-metallic coated sheet and strip in 2008, from worldsteel, assumed to be the same as organic based coatings (i.e. paint). Organic coating is assumed to be applied only to galvanised CRC.
[104]	0.3	Scrap	=[103]*(1/0.98-1)	OCP yield =98%, see note for [102].
[105]	44.4	Light sections	(1, p.46, tab.16)	Global total for light sections (<80mm) in 2008, from worldsteel.
[106]	39.6	Heavy sections	(1, p.45, tab.15)	Global total for heavy sections (≥80mm) in 2008, from worldsteel.
[107]	10.0	Rail	(1, p.44, tab.14)	Global total for railway track material in 2008, from worldsteel.
[108]	173.6	Reinforcing bar	=147.0+26.6	Global total for concrete reinforcing bar in 2008=147Mt (1, p.48, tab.17), from worldsteel. An additional 26.6Mt is added to the reinforcing bar total, so that the sum of all HR long products [65]+[70], equals the sum of the worldsteel values for: HR long products 525Mt (1, p.41, tab.12), seamless tubes 28Mt (1, p.60, tab.25) and the yield loss from STP 2.3Mt [86]. Compare with the SBB value for rebar of 210Mt (14, p.3) which is much higher than both the worldsteel and our model value. See also note for [f].
[109]	148.5	Wire rod	(1, p.52, tab.19)	Global total for wire rod in 2008, from worldsteel.
[110]	109.7	HR bar	(1, p.50, tab.18)	Global total for hot rolled bars (other than concrete reinforcing bars) in 2008, from worldsteel.
[111]	110.0	Plate	(14, p.4)	Global total for plate in 2008, from SBB.
[112]	10.3	Electrical sheet	(1, p.53, tab.20)	Global total for electrical sheet and strip in 2008, from worldsteel.
[113]	135.0	CRC	(14, p.4)	Global total for cold rolled coil (sold as a intermediate product) in 2008, from SBB.
[114]	96.4	CRC galv.	(1, p.56, tab.22)	Global total for other metallic coated sheet and strip, from worldsteel, assumed to be primarily galvanised cold rolled coil.
[115]	150.0	HRC	(14, p.4)	Global total for hot rolled coil (sold as a intermediate product) in 2008, from SBB.
[116]	40.0	HR narrow strip	(14, p.4)	Global total for hot rolled narrow strip in 2008, from SBB.

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Additional notes	
[a]	The model has been balanced so that the liquid steel total (post SM and excluding FIC products) equals the reported worldsteel value for crude steel production by process of 1328Mt in 2008 (1, p.25, tab.6). The breakdown of liquid steel by process (EF, OBC and OHF) is also balanced to equal the crude steel production by process values reported in the worldsteel table. Note for the Sankey diagram the SM process and yield losses are incorporated in the steelmaking processes (EF, OBC, OHF).
[b]	The total cast steel (excluding FIC products) is calculated as 1316Mt, which is 8Mt less than the worldsteel value for crude steel production by product of 1324Mt in 2008 (1, p.9, tab.2). It is noted in the worldsteel table that “totals may differ”, but more concerning is the table appears to combines output values from continuous casting and ingots, with input values for steel products, leading to errors. The main discrepancy lies in the sub-total for continuously cast steel: 1223Mt in this model compared to 1231Mt in the worldsteel data. The model could not be balanced further without affecting the agreement for [a]. The difference is small (around 0.5%) and probably derives from simple adding up errors when collecting data from surveys. The sub-totals for ingots (82Mt) and cast steel products (11Mt) agree with the worldsteel data, if the diversion of 6.7Mt of ingots to cast steel products is accounted for.
[c]	The worldsteel does not publish production values for blooms, billets and slabs. The model shows these intermediate products total 1299Mt, including the output from PM which pre-roll ingots ready for the subsequent hot rolling. However, worldsteel does give a value for hot rolled steel equal to 1315Mt in 2008 (1, p.39, tab.11). It is difficult to see how this could be the output of the hot rolling processes (SEM, RBM, PLM and HSM) given that 1315Mt is only 13Mt less than their crude steel production total of 1328Mt (see note [a]), giving an impossibly high combined yield of 99% for the continuous casting and hot rolling processes. It is more likely, and thus presumed, that the reported tonnage of 1315Mt is an input value to the hot rolling mills, 16Mt above our calculated value of 1299Mt. The source of this difference is unknown, but is small (~1%) especially in comparison to the apparent labelling error in the worldsteel data.
[d]	Our calculated total for hot rolled products is 1221Mt, which is 94Mt less than the reported 1315Mt by worldsteel (see note [c]). The sub-total for long products is 556Mt, balanced to equal worldsteel’s reported sum of hot rolled long products, 526Mt (1, p.41, tab.12) and seamless tubes, 27.7Mt (1, p.60, tab.25) with a small correction of 2.3Mt for the seamless tube forming yield. The sub-total for HR flat product is 665Mt and is balanced to equal the worldsteel value of 665Mt (1, p.43, tab.13).
[e]	The steel and iron industry produces 1275Mt of intermediate products (note the industry labels these as finished products, despite requiring further fabrication to be transformed to end-use goods). Cast iron products contribute only 68Mt of this total. The remaining 1207Mt of intermediate steel products has been balanced to agree with the World Steel Association’s published value for apparent consumption of intermediate steel products of 1207Mt in 2008 (1, p.96, tab.39), by adjusting the intermediate product total for welded tube from 44.5Mt (1, p.62, tab.26) up to 62.4Mt, see note for [89].
[f]	Steel Business Briefing gives a value of 60Mt for structurals/rail/piling (14, p.4), some 34Mt less than the total value for all sections from worldsteel (1, p.45–46). It is likely that SBB has included less light sections in their total (10Mt instead of 44Mt), preferring to group the light sections made from rod and bar under reinforcing bar. This may explain some of the reason why the SBB value for reinforcing steel (210Mt) is 63Mt greater than the world steel value (147Mt) and 36Mt greater than the solved value (174Mt) used in this model. See note for [108] and also [e].

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4. From intermediate products to end-use goods

To map intermediate products to end-use goods we create two matrices: an *allocation matrix* **A** and a *fabrication yield matrix* **Y**. In the *allocation matrix*, the flow of each intermediate product (m rows) is allocated by fractions to each end-use product (n columns). The *fabrication yield matrix* accounts for the steel lost in manufacturing each end-use product from an intermediate product. The matrix is equal in size to the *allocation matrix* permitting different yields to be assigned to different end-use goods. Multiplying the corresponding cells in each matrix (element-wise) allows us to link the output of end-use goods to the input of intermediate products.

Written formally:

$$\mathbf{y} = (\mathbf{A} \circ \mathbf{Y})\mathbf{x}$$

where **y** is a vector of end-use goods, **x** is a vector of intermediate products, and the ∘ symbol indicates the Hadamard product (element-wise) of the two matrices. An equivalent loss vector $\mathbf{y}_L$ can be defined as:

$$\mathbf{y}_L = \big(\mathbf{A} \circ (\mathbf{J} - \mathbf{Y})\big)\mathbf{x}$$

where **J** is a matrix of ones, of the equal size to **Y** and **A.**

Figure S3 shows this mapping of intermediate products to end-use goods in actual steel flows in millions of tonnes (Mt), with the columns labelled A to O and the rows 1 to 25. Intermediate product flows (vecto*r* **x**) are given in column [A], with [A2–A20] the specific products, [A21-A25] the category subtotals, and [A1] the overall total. End-use goods (vector **y**) are given in row [1], with [B2–K2] the specific goods, [L2–O2] the category subtotals, and [A1] the overall total, once again.

Each cell represents a fabrication process and shows three key numbers: the input of intermediate products (top-right in each cell, in Mt); the output of end-use goods (bottom-right, in Mt); the fabrication yield (bottom-left, blue, as fraction). The fabrication yield is the ratio of end-use goods to intermediate products. Blank cells indicate that steel is not fabricated using that particular combination of intermediate product and end-use good (or that the steel flow is below the threshold of 1Mt). For example, we can read from the Figure that 174Mt [A5] of *reinforcing bar*, is allocated to *buildings* 92Mt [B5] and *infrastructure* 82Mt [C5]. The yields in both fabrication processes are 95%, giving end-use goods (i.e. reinforcing bar in concrete) of 87Mt for *buildings* and 77Mt for *infrastructure.*

Figure S3 (following page)—Mapping intermediate products on to end-use goods. Each cell of the matrix shows the intermediate product input flow (top) and the end-use goods output flow (bottom), with flows in millions of tonnes (Mt), and the fabrication yield as a fraction (left, blue).

	A	**TOTAL**	B	Buildings	C	Infrastructure	D	Cars	E	Trucks	F	Ships + other	G	Mechanical equipment	H	Electrical equipment	I	Metal goods	J	Domestic appliances	K	Food packaging	L	**Construction**	M	**Vehcles**	N	**Industrial equipment**	O	**Metal goods**
INTERMEDIATE PRODUCTS		1275		385		252		127		25		38		178		38		180		38		12		637		191		217		229
END-USE GOODS 1	0.85	1088	0.93	358	0.95	238	0.69	88	0.80	21	0.81	31	0.80	143	0.87	33	0.77	138	0.80	31	0.70	8	0.94	596	0.73	139	0.81	176	0.77	177
Light sections		44		34		11																		44						
2	0.95	42	0.95	32	0.95	10																	0.95	42						
Heavy sections		40		30		9																		40						
3	0.95	38	0.95	29	0.95	9																	0.95	38						
Rail		10				9								1										9				1		
4	0.95	9			0.95	9							0.95	1									0.95	9			0.95	1		
Reinforcing bar		174		92		82																		174						
5	0.95	165	0.95	87	0.95	77																	0.95	165						
Wire rod		149		43		38		5		5	0.03	1		1	0.05	8		47						81		11		9		47
6	0.90	133	0.95	41	0.95	36	0.90	4	0.90	4	0.90	1	0.90	1	0.90	7	0.80	38					0.95	77	0.90	10	0.90	8	0.80	38
Hot rolled bar		110		3		1		14	0.13	3		1		41		4		42						4		19		45		42
7	0.77	84	0.90	3	0.90	1	0.80	11	0.80	3	0.80	1	0.80	33	0.80	3	0.70	29					0.90	4	0.80	15	0.80	36	0.70	29
Plate		110		5		1					0.86	33		33		4		33						6		33		37		33
8	0.79	87	0.90	4	0.90	1					0.80	27	0.80	27	0.80	3	0.75	25					0.90	6	0.80	27	0.80	30	0.75	25
Hot rolled coil (HRC)		150		75		24			0.29	7				35		2		7						98		7		37		7
9	0.86	129	0.90	67	0.90	21			0.80	6			0.80	28	0.80	2	0.75	6					0.90	88	0.80	6	0.80	30	0.75	6
HRC galvanised		10		8		2																		10						
10	0.90	9	0.90	7	0.90	2																	0.90	9						
HR narrow strip		40		15		5											0.50	20						20						20
11	0.83	33	0.90	14	0.90	4											0.75	15					0.90	18					0.75	15
Cold rolled coil (CRC)		135		51		16								32				7		30				67				32		37
12	0.80	108	0.90	46	0.90	14							0.60	19			0.70	5	0.80	24			0.90	60			0.60	19	0.78	29
CRC galvanised		96						91	0.17	6																96				
13	0.60	58					0.60	54	0.60	3															0.60	58				
CRC organic coated		17																8		8										17
14	0.75	12															0.70	6	0.80	7									0.75	12
CRC tinned		12																				12								12
15	0.70	8																			0.70	8							0.70	8
Electrical sheet		10													1.00	10												10		
16	0.80	8													0.80	8											0.80	8		
Welded tube		62		14	0.41	25			0.03	1		1	0.28	17		4	0.01	1						39		1		21		1
17	0.95	59	0.95	13	0.95	24			0.95	1	0.95	1	0.95	17	0.95	4	0.95	1					0.95	37	0.95	1	0.95	20	0.95	1
Seamless tube		28	0.48	13		4	0.05	5		1	0.03	1		3	0.03	1		0						17		6		4		0
18	0.95	26	0.95	13	0.95	4	0.95	4	0.95	1	0.95	1	0.95	3	0.95	1	0.95	0					0.95	16	0.95	6	0.95	4	0.95	0
Cast iron products		68		3	0.36	25		13	0.15	3		1		9		6		9						27		17		15		9
19	1.00	68	1.00	3	1.00	25	1.00	13	1.00	3	1.00	1	1.00	9	1.00	6	1.00	9					1.00	27	1.00	17	1.00	15	1.00	9
Cast steel products		11												5				5										5		5
20	1.00	11											1.00	5		0	1.00	5									1.00	5	1.00	5
Shapes		94		64		29								1										93				1		
21	0.95	89	0.95	61	0.95	28							0.95	1									0.95	88			0.95	1		
Bars		432		138		121		19		8		2		43		12		89						259		30		54		89
22	0.88	382	0.95	131	0.95	115	0.83	16	0.86	7	0.85	2	0.80	34	0.87	10	0.75	67					0.95	246	0.84	25	0.82	44	0.75	67
Flat / plates		580		153		48		91		13		33		100		16		76		38		12		201		137		116		126
23	0.78	453	0.90	138	0.90	43	0.60	54	0.71	9	0.80	27	0.74	73	0.80	13	0.74	56	0.80	31	0.70	8	0.90	181	0.66	90	0.75	86	0.75	95
Tubes		90		27		29		5		1		2		21		4		1						56		7		25		1
24	0.95	86	0.95	26	0.95	28	0.95	4	0.95	1	0.95	2	0.95	20	0.95	4	0.95	1					0.95	54	0.95	7	0.95	24	0.95	1
Casting		79		3		25		13		3		1		14		6		14						27		17		20		14
25	1.00	79	1.00	3	1.00	25	1.00	13	1.00	3	1.00	1	1.00	14	1.00	6	1.00	14					1.00	27	1.00	17	1.00	20	1.00	14

4.1 Steel flow allocation

In Table S3 we explain the rational for allocating the steel flows (matrix **A**), with each cell calculation described sequentially.

Table S3—Data sources and calculations used to map the flows of intermediate steel products to end-use goods. Cells refer to columns and rows of Figure S3 and are labelled in square brackets, e.g. [A15] is column A and row 15. Citations are shown in curved brackets, e.g. (1, p,21, tab.3), with full references provided at the end of the table.

Cells	Notes
[A1]	Total flow of all intermediate products, including cast steel and iron products, is 1,275Mt (as calculated in §3). Fabrication processes create 186Mt of scrap steel (see Table S2, flow [9]) leaving 1,088Mt in end-use goods. The overall fabrication yield = 1,088Mt/1,275Mt = 85%. The individual fabrication yields in the matrix are firstly estimated from literature, then adjusted so the total scrap generation equals 186Mt.
[A2–A20]	Intermediate product flows (top-right) are taken directly from the results calculated in §3 (equivalent to vector **x**). (The end-use good flows (bottom-right) and fabrication yields (left) are back-calculated from the matrix data for information only.)
[A21–A25]	Intermediate products are grouped into 5 categories: flows: shapes [A2–A4], bars [A5–A7], flats/plates [A8–A16], tubes [A17–A18], and castings [A19–A20].
[B1–K1]	The total flow for intermediate products [A1] is allocated directly to end-use goods (top-right, without fabrication yields) using the worldsteel breakdown (16, p.7 and personal communication): construction 50%; mechanical machinery 14%; metal products 14%; automotive 12%; electrical equipment 3%; other transport 3%; domestic appliances 3%. Based on this data we create a slightly different breakdown of end-use goods. *Automotive 12%* is divided into cars 10% and trucks 2% based on OICA's global 2008 production statistics for vehicles (17), multiplied by the average mass of steel and iron in each vehicle type. For passenger cars MCI calculate the mass of steel and iron to be 960kg per car (18), which equals 96% of the total unladen mass. Using this same percentage, multiplied by the average unladen mass for other vehicles from TRL (19) we find steel masses for other vehicles: light commercial 1,400kg (SUVs, utilities, small vans); heavy trucks 3,700kg; buses/coaches 2,700kg. Adding these up we find that 82% of steel flow to automobiles is in cars (passenger cars and light commercial vehicles) and 18% in trucks (heavy trucks and buses/coaches). *Other transport 3%* is assumed to be mainly ships, but also includes a small amount of rail transport. The split of *construction 50%* into buildings and infrastructure is left open, to be calculated once the spilt for specific intermediate products in known. The worldsteel breakdown adds up to 99% so an additional 1% is added to metal products, and then separated out as a new intermediate product category of *food packaging,* assuming all tin-plated cold rolled coil 12Mt is allocated here. The data behind the worldsteel breakdown is not available, so cannot be confirmed, but shows good agreement with European data (15, p.8) despite some difference in category definitions: construction 27%, tubes 12%, structural steelwork 12% (which total 51% for our construction category); automotive 16%; shipyards 1%; mechanical engineering 14%; domestic appliances 4%; metal ware 12%, miscellaneous 2% (which total 14% for our metal products category). It is noted that more steel is used in automotive transport 16% (cf. 12% globally) and less in shipbuilding 1% (cf. 3% globally), which fits our understanding of the distributions of these industries internationally. However the worldsteel data shows less agreement with the 2000 multiregional analysis by Wang et al. (20, fig.5) which shows: construction 45% (cf. 50%); transport equipment 24% (cf 15%); industrial machinery 20% (cf. 17%); consumer durables 7% and other 4% (cf. 18%). It is noted that between 2000 and 2008 the production of crude steel increased from 848Mt to 1,315Mt, perhaps explaining the difference.
[D2–20]	*Cars* includes both passenger vehicles (excluding buses) and light commercial vehicles. Bull et al. in a report for the Aluminum Association provide an end-use breakdown of steel and aluminium in the components of a typical car (21, tab.5). This is combined with an example breakdown for a typical car by materials, in a life-cycle report prepared for WorldAutoSteel (22, tab.1). From these two studies, and accounting the steel in replacement tyres, we calculate: sheet metal 62% (assumed to be *CRC galvanised*); castings 15% (assumed to be *cast iron*); *hot rolled bar* 13%*; wire rod* 5% (mainly in tyres); *seamless tube* 5%. This breakdown describes the steel and cast iron in a typical car—the end-use good—so these steel flows must be divided by the fabrication yields to estimate the amounts of steel as intermediate products entering the global car industry.

Table S3—Data sources and calculations used to map the flows of intermediate steel products to end-use goods. Cells refer to columns and rows of Figure S3 and are labelled in square brackets, e.g. [A15] is column A and row 15. Citations are shown in curved brackets, e.g. (1, p,21, tab.3), with full references provided at the end of the table.

Cells	Notes
[E2–20]	*Trucks* includes heavy trucks and buses/coaches. The allocation of intermediate products to trucks starts with the allocation cars [D2–20], but with the following differences. The 5% figure for *seamless tube* in cars, is split equally into *welded tube* and *seamless tube* in trucks, to account for the larger diameter tubes commonly used in trucks. The *wire rod* used in truck tyres is increased to equal the same mass as for cars (4Mt), which equates to 21% of the steel in trucks (cf. 5% for cars). This is based on the RMA analysis of the US scrap tyre market (23, tab.1), which gives the number of tyres and approximate tyre weight for different vehicle classes. Annually in the US, 260 million tyres are used for cars and 45 millions tyres for trucks, giving a ratio of 5.7:1. However, an average car tyre weighs 11kg and an average truck tyre 57kg, giving a ratio of 1:5.3kg. These ratios roughly cancel out, noting that both tyre types contain about 15% steel by mass. The increase in *wire rod* is balanced by a decrease in sheet metal in trucks to 44% (cf. 62% in cars). There is insufficient *CRC galvanised* to satisfy demand in both cars and trucks, so the balance for trucks (29%) is found from *hot rolled coil (HRC)*, reflecting the use of heavier grade sheet metal particularly in truck trailer construction. (*Hot rolled bar* 13% and *cast iron products* 15% remain the same.)
[F2-20]	*Ships + others:* we calculate that about 30Mt of intermediate steel products (out of 38Mt) is used in the shipping industry, noting that Europe builds 6% of the world's ships (24) using 1% (or 2Mt) of Europe's steel (15, p.8), and scaling this up to global shipbuilding production. Tilwankar et al. give ship breaking statistics from India with percentage breakdowns by material for general cargo, bulk carriers and oil tankers (25, tab.2). Taking averages and removing all non-ferrous materials gives: re-rollable steel sheets 86% (allocated to *plate*); meltable steel scrap 10% (allocated evenly to *wire rod, hot rolled bar, seamless tube* and *welded tube*); cast iron scrap 3%.
[H2-20]	*Electrical equipment:* Mueller and Besant provide a streamlined life cycle analysis for an electric motor with the following material breakdown: copper 8%; grey cast iron 30%; dynamo sheet iron 40% (electrical steel); steel 10%; other 12% (26, tab.1). Steel and cast iron make up 80% of the motor mass. Electrical steel 10Mt [A16] is only used in electric motors with a fabrication yield of 80%, accounting for 8Mt of electrical steel in motors. Electrical steel is half (40% / 80%) of the iron and steel in a motor, so the total mass of steel in electric motors equals 16Mt (cf. 33Mt for all electrical equipment). Using the same logic, 6Mt of *cast iron*, 1Mt of *hot rolled bar* and 1Mt of *plate* are also assigned to electric motors. The remaining *electrical equipment* is allocated to: *wire rod* (see note for [B6–16]); *welded tube* [B17–I17]; *seamless tube* [B18–I18]; with the balance of 6Mt divided evenly between *hot rolled bar*, *plate* and *hot rolled coil (HRC).*
[B2–C2]	*Light sections* is allocated to buildings 76% and infrastructure 24% based on European statistical bulletin for constructional steelwork, produced by the ECCS (European Convention for Constructional Steelwork) (27). ECCS provide a breakdown between buildings and infrastructure for the 17 ECCS member countries from Europe. The 76:24 ratio comes from averaging data over 3 years (2008–2010), after correcting for when a country supplied no data for a category.
[B3–C3]	*Heavy sections* is allocated to buildings 76% and infrastructure 24%, see note for [B2–C2].
[B4–C4]	*Rail* is allocated to infrastructure 90% and mechanical equipment 10% (in industrial plants), based on the product-to-uses matrix (PTUM) by Wang et al. (20, Table S-4, supporting information).
[B5–C5]	*Reinforcing bar* is allocated to buildings 53% and infrastructure 47%. No global data could be found which divides reinforcing bar by application, however data is available for concrete use (usually in the form of cement production data), by application, which can be used as a proxy for reinforcing bar. To understand how much reinforcing bar is used in concrete we compared estimates for UK reinforcing bar data provided by from Celsa (28) with UK cement data from the British Cement Association (BCA) (29). This implied that reinforcing bar was used proportionately to cement in commercial buildings and infrastructure projects, but not for residential buildings where much less reinforcement is required. The BCA confirmed that about half of the cement used in residential buildings was in unreinforced concrete blocks, which when accounted for brought the reinforcing bar to cement ratio back in line with the other applications. This logic was applied to trade association data for cement from the BCA for the UK (29), the Portland Cement Association (PCA) for the US (30), and the Turkish Cement Manufacturers' Association (TCMA) for Turkey (31), and a weighted average taken to find the global ratio of 53:47 for reinforcing bar in buildings versus infrastructure.

Table S3—Data sources and calculations used to map the flows of intermediate steel products to end-use goods. Cells refer to columns and rows of Figure S3 and are labelled in square brackets, e.g. [A15] is column A and row 15. Citations are shown in curved brackets, e.g. (1, p,21, tab.3), with full references provided at the end of the table.

Cells	Notes
[B6–I6]	*Wire rod:* 50% of wire rod is used as wire mesh in concrete construction, based on the UK market where the estimated wire mesh production is 0.17Mt (28) compared to wire rod production of 0.35Mt in 2009 (32, p.12). The 50% for construction is divided between buildings and infrastructure using the 53:47 ratio for reinforcing bar [B5-C5]. A quarter of wire rod is assumed to be drawn wire (28). The wire manufacture Bekaert (33) gives an approximate breakdown: automotive 36%; energy 21%; construction 19% (i.e. steel fibre in concrete, steel cable, steel cages, fencing wire); agriculture 8%; consumption 8%; basic materials 4%; equipment 4%. The automotive fraction 36% is ignored, as we already assigned wire rod to cars [D6], trucks [E6] and ships [F6], which together equal to 29% of drawn wire (cf. 36%). Construction 19% is allocated to buildings and infrastructure using the 53:47 ratio for reinforcing bar [B5-C5]. Energy 21% is allocated to *electrical equipment,* and equipment 4% to *mechanical equipment.* Agriculture 8%, consumption 8% and basic materials 4% are allocated to *metal goods,* along with the balance of all other wire rod (including the remaining quarter).
[B7–I7]	*Hot rolled bar* is allocated previously to cars [D7], trucks [E7], ships [F7] and electric equipment [H7]. We estimate that construction steelwork connections make up 10% of the combined mass of light and heavy sections, for both buildings and infrastructure, half of which is allocated to *hot rolled bar* to make bolts. The remaining bar is distributed between *mechanical equipment* and *metal goods*, weighted according to their respective totals [G1] and [I1].
[B8–I8]	*Plate* is allocated previously to *ships+other* [F8] and *electrical equipment* [H8]. 5% of the combined mass of light and heavy sections is used for steelwork connections in both buildings and infrastructure. An additional 5% of *heavy sections* is used for plate girder beams in buildings and infrastructure (34). The remaining plate is distributed between *mechanical equipment* and *metal goods*, weighted according to their respective totals [G1] and [I1].
[B10–C10]	*HRC galvanised* is allocated to buildings 76% and infrastructure 24%, see note for [B2–C2].
[B11–I11]	*HR narrow strip* is divided equally between *metal goods* and construction (with buildings 76% and infrastructure 24%, see note for [B2–C2]).
[I13–J13]	*CRC organic coated* is cold rolled coil, which is galvanised and then coated with an organic paint. It is used mainly in folded products (cars are painted after forming to avoid problems with the stamping process). We allocate this sheet product equally to *metal goods* and *domestic appliances* (mainly white-goods, e.g. refrigerators).
[K15]	*CRC tinned* is tinplated cold rolled sheet, used almost exclusively in food packaging, e.g. steel cans and tins.
[B17–I17]	*Welded tube* is allocated previously to *trucks* and *ships+other* [E17–F17] (but not cars). Wang et al. provide a breakdown for tube in their product-to-use matrix (PTUM): construction 62.7%; consumer durables 1.1%; industrial machinery 29.3%; transport equipment 7% (20, Table S-4, supporting information). This breakdown is used for both welded and seamless tubes. For our allocation of *welded tube*: construction is further divided into *buildings* and *infrastructure*, using the estimate of 25Mt for linepipe in infrastructure (35); consumer durables is allocated to *metal goods*; transport equipment is ignored (cf. 4% for welded and seamless tube in vehicles); the balance is distributed to *mechanical equipment* 28% and *electrical equipment* 6%, weighted according to their respective totals [G1] and [H1].
[B18–I18]	*Seamless tube* is allocated previously to *cars, trucks* and *ships+other* [D18–F18]. The remaining material is allocated as per *welded tube* [B17–I17].
[B19–I19]	*Cast iron products* is allocated previously to *cars, trucks, ships+other* [D19–F19] and *electrical equipment* [H8]. Wang et al. provide a breakdown for castings in their product-to-use matrix (PTUM): construction 40%; consumer durables 10%; industrial machinery 15%; transport equipment 35% (20, Table S-4, supporting information). For our allocation of *cast iron products*: construction is further divided into *buildings* 10% and *infrastructure* 90% (given most cast iron products in construction are used in infrastructure, e.g. storm-water grates and service-hole covers); consumer durables is omitted; transport equipment is ignored (cf. 9% for castings in vehicles); the balance is distributed to *mechanical equipment* 13% and *metal goods* 13%, weighted according to their respective totals [G1] and [I1].
[G20–I20]	*Cast steel products* is divided evenly between *mechanical equipment* and *metal goods*.
[G9] [G12]	*Mechanical equipment* is balanced using *hot rolled coil (HRC)* 35Mt and *cold rolled coil (CRC)* 31Mt, weighted according to their respective totals [A9] and [A12].
[I9] [I12]	*Metal goods* is balanced using *hot rolled coil (HRC)* 7Mt and *cold rolled coil (CRC)* 7Mt, weighted according to their respective totals [A9] and [A12].
[J12]	*Domestic appliances* is balanced using *cold rolled coil (CRC)* 30Mt.
[B9-C9]	*Hot rolled coil (HRC)* is balanced by allocating the remaining steel to buildings 76% and infrastructure 24%, see note for [B2–C2].
[B12–C12]	*Cold rolled coil (CRC)* is balanced by allocating the remaining steel to buildings 76% and infrastructure 24%, see note for [B2–C2].

Table S3—Data sources and calculations used to map the flows of intermediate steel products to end-use goods. Cells refer to columns and rows of Figure S3 and are labelled in square brackets, e.g. [A15] is column A and row 15. References are shown in curved brackets, e.g. (1, p,21, tab.3).

References for Table S3

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4.2 Fabrication yields

Fabrication yields are rarely listed in literature at the detailed level that we require for this study. A few studies give fabrication yields (or 'prompt scrap rates') for end-use sectors. Two examples are shown in Table S4, and compared to the average end-sector yields from this study. The Hatayama et al. (2010) yield values are estimated from a Japanese study. There is good agreement with the values for this study, particularly for construction (building and civil engineering) and vehicles. The Dahlström et al. (2004) yield values are less convincing, as all values are set to 90% except for construction and cans/metal boxes. It is unlikely that the overall yield for vehicles is as high as 90%; steel parts for cars can have fabrication yields as low as 60% (Milford et al., 2011).

This study		**Hatayama et al. (2010)**[a]		**Dahlström et al. (2004)**[b]	
Global estimate		Global estimate		UK estimate	
Category	Yield	Category	Yield	Category	Yield
Buildings	93%	Building	94%	Structural steelwork/ building/ civil engineering	95%
Infrastructure	95%	Civil engineering	94%		
Cars	69%	Vehicles	81%	Vehicles	90%
Trucks	80%				
Ships/other	81%	Shipbuilding	93%	Shipbuilding	90%
Mechanical equipment	80%	Machinery	86%	Mechanical engineering	90%
Electrical equipment	87%			Electrical engineering	90%
Metal goods	77%			Metal goods	90%
Domestic appliances	80%	Electrical appliances	81%		
Food packaging	70%	Containers/Packaging	92%	Cans / metal boxes	83%
		Other	95%	Others	90%
Overall	**85%**	**Overall**	**90%**[c]	**Overall**	**90%**

[a] Fabrication and manufacturing yields from Hatayama et al. (2010, tab.S3, supporting information)

[b] Prompt scrap rates (100% – yield) for the manufacturing sector from Dahlström et al. (2004, tab.3.2)

[c] Estimated using the global steel flows for each sector, from this study

Table S4—Comparison of fabrication yields for end-use categories. The categories have been aligned, as best as possible, to allow comparison between sectors.

The overall yield for both studies from literature is calculated as 90%. Other studies also provide an overall yield for fabrication. For example, Müller et al. calculate that the 'yield of iron in manufacturing' has increased from 80% to 88% from 1965 to 2005 (2011, tab.S2 SI). Whereas Moll et al. calculate that for the EU 135Mt of 'finished products' are manufactured from 147Mt of semi-finished steel, giving an overall yield of 92% (2005, p.3), however it is noted that their calculation is based on yield values taken from Dahlström et al. (2004) with the problems mentioned above. For this study the overall yield is calculated to be 85% based on the fabrication scrap value of 186Mt (see table S2, flow [9]).

The approach taken for calculating fabrication yields in this study differs from those found in literature. For this study a fabrication yield is estimated for each intersection of an intermediate product with an end-use good. This offers a vast improvement over estimating an average yields either only end-use categories, or only intermediate products, as we can differentiate the yields for separate components of each end-use good and make use single data points from case studies. For example, the cold rolled galvanised sheet used in car bodies has a low fabrication yield of 60% whereas the steel wire used in the car tyres is much higher at 90%.

The selected yield values for each fabrication process are shown at the bottom-left of each cell in Figure S3 (these fabrication yields makes up the **Y** matrix). The yield values range from 100% to 60% and are organised into 5% intervals. The highest yield value is for cast steel and iron products (100%) as we assume that most post-casting machining happens near the foundry, and therefore is included in the forming yield for casting. The next highest yield value of 95% is based on evidence from a large UK structural steel contractor, who calculate a 95% yield at their fabrication plant (Severfield-Rowen, 2010, site visit), and agrees well with the construction yields reported in Table S4. This value is used for all fabrication processes where a simple cut is made in one-dimension (all sections, all tube and some rod/bar). Where two simple cuts are made the yield is decreased to 90%, for example sheet products in construction where most sheet sections are rectangular. Simple cuts of one or two dimensions are assumed for all construction processes.

Fabrication processes for vehicles and industrial equipment will typically produced more complex geometries and thus more scrap, for example, hot rolled bar is firstly turned in two dimensions and then cut to length in the third, and given a lower average yield of 80%. Where steel sheet is cut into circular profiles (for tin cans and electrical steel in motors) lower yields are also used (70–80%) because circular shapes do not tessellate leaving ‘skeletons’ behind after cutting. The average yield for metal goods (77%) is lower than construction (94%) and industrial equipment (81%) because the products are typically smaller, complex and more varied. The body-in-white for cars is made from cold rolled galvanised sheet, which is ‘stamped’ (a profile cut in two-dimensions which rarely tessellates well) and then deep-drawn to give shape (requiring excess sheet around the stamped profile for gripping). A yield value of 60% is selected based on a case study of a steel car door by Milford et al. (2011).

Using the logic described above, the yields for all fabrication processes are estimated, while ensuring the overall yield equals 85% to match the fabrication scrap value of 186Mt (see table S2, flow [9]).

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Abbreviations

BF	Blast furnace
BOF	Basic oxygen furnace
CR	Cold rolled
CRC	Cold rolled coil
CRM	Cold rolling mill
DRI	Directly reduced iron
DR	Direct reduction (process)
EAF	Electric arc furnace
EF	Electric furnace (=EAF)
EOL	End-of-life scrap (post-consumer scrap)
FIC	Foundry iron casting
GP	Galvanising plant
HR	Hot rolled
HRC	Hot rolled coil
HSM	Hot strip mill
IC	Ingot casting
OBC	Oxygen blown furnace (=BOF)
OCP	Organic coating plant (non-metallic)
OHF	Open hearth furnace (and other)
PLM	Plate mill
PRM	Primary mill
RBM	Rod and bar mill
SEM	Section mill
SM	Secondary metallurgy
SR	Smelt reduction
SP	Scrap preparation
SPC	Steel product casting
STP	Seamless tube plant
TM	Tinmill plant
TWP	Tube welding plant