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Steel All Over the World: Estimating In-use Stocks of Iron for 200 Countries

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ABSTRACT:

Industrialization and urbanization in the developing world have boosted steel demand during the recent two decades. Reliable estimates on how much steel is required for high economic development are necessary to better understand the future challenges for employment, resource management, capacity planning, and climate change mitigation within the steel sector. During their use phase, steel-containing products provide service to people, and the size of the in-use stock of steel can serve as indicator of the total service level. We apply dynamic material flow analysis to estimate in-use stocks of steel in about 200 countries and

identify patterns of how stocks evolve over time. Three different models of the steel cycle are applied and a full uncertainty analysis is conducted to obtain reliable stock estimates for the period 1700-2008.

Per capita in-use stocks in countries with a long industrial history, e.g., the U.S, the UK, or Germany, are between 11 and 16 tonnes, and stock accumulation is slowing down or has come to a halt. Stocks in countries that industrialized rather recently, such as South Korea or Portugal, are between 6-10 tonnes per capita and grow fast. In several countries, per capita in-use stocks of steel have saturated or are close to saturation. We identify the range of saturation to be 13±2 tonnes for the total per capita stock, which includes 10±2 tonnes for construction, 1.3±0.5 tonnes for machinery, 1.5±0.7 tonnes for transportation, and 0.6±0.2 tonnes for appliances and containers. The time series for the stocks and the saturation levels can be used to estimate future steel production and scrap supply.

1. Introduction

Steel is the most widely used metal and the steel sector is one of the world's largest industries with more than 4 million workers employed (World Steel Association 2012). Industrialization and urbanization boost steel demand, but once these processes reach completion and the building stock and the different infrastructures become mature, the demand for steel may fall again. Such a drop in demand happened in several western countries during the steel crisis (Tarr 1988), and has been forecast for China (Pauliuk et al. 2012) as well as for Africa, Asia, and South America (Hatayama et al. 2010). Buildings, vehicles, and other products that reach the end of their life, represent sources of post-

consumer scrap that open up opportunities for recycling. Steelmaking facilities are very capital-intensive assets with a lifetime of many decades (International Energy Agency 2008). Hence, it is difficult to adjust the production capacity when final steel demand and scrap supply are changing. Reliable estimates of future regional steel demand and scrap availability allow for better capacity planning in both primary and secondary steel production.

At present, the steel sector contributes with 9% to global energy- and process-related carbon emissions (Allwood et al. 2010). In order to identify the sector's potential contribution to climate change mitigation through increased recycling, reliable estimates on both future steel demand and scrap supply are required.

Extrapolating historic growth rates is a common approach to forecast steel production in the short- and mid-term (Ke Wang 2007; Yellishetty et al. 2010). Future steel demand can also be forecast using external GDP projections (International Energy Agency 2009; Das and Kandpal 1998; Kozawa et al. 2009; Kozawa and Tsukihashi 2009). Hidalgo et al. (2003) propose that steel use per GDP follows a curve with an inverse U-shape, which suggests that eventually, steel consumption will decouple from economic growth (van Vuuren et al. 1999).

These flow-based approaches ignore that due to the long lifetime of steel-containing products, it is not the annual consumption but the stock of steel that provides service in form of its various physical properties (Müller et al. 2007). An increasing demand for steel services creates demand for steel consumption, and the lifetime of the products in use determines the recycling potential and the need for replacement. To understand how global steel demand and the supply of old scrap will evolve in the long run, a detailed understanding of the evolution of steel stocks in both the developed and the developing world is indispensable.

Table 1: Estimates of per capita stocks of steel in use, based on Graedel (2010) and amended by recently published estimates.

Country/Region	Year	In-use stock in tonnes/cap	Source	Comment
USA	1950	8	(Brown 1954)	Top-down
USA	2002	14.3	(USGS 2005)	Top-down
USA	2004	11-12	(Müller et al. 2006)	Top-down, time series
USA	2005	10 +/- 2	(Müller et al. 2011)	Four product categories, Top-down, time series
USA, Connecticut	2006	9.3	(Eckelman et al. 2007)	Bottom-up
USA, New Haven	2005	8.8	(Drakonakis et al. 2007)	Bottom-up
China	2005	1.4	(Wang 2009)	
China	2009	2.8	(Pauliuk et al. 2012)	Top-down, time series
Urban China	2004	2.7	(Wang 2009)	
Rural China	2004	0.64	(Wang 2009)	
Beijing, China	2000	2.3	(Wang 2004)	Bottom up
Japan	2000	11.3	(Murakami 2006)	
Japan	2005	14 +1/-2	(Müller et al. 2011)	Four product categories, Top-down, time series
Japan	2000	7.4	(Daigo et al. 2007)	Top-down, time series
Japan	2006	8	(Hirato et al. 2009)	Top-down, time series
Japan, infrastructure	ca. 2005	1.5-4.5	(Hatayama et al. 2010), supplementary material	Province-specific estimate
Japan, buildings	ca. 2005	4-6	(Hatayama et al. 2010), supplementary material	
Japan, Kitikyushu	1995	7.3	(Tanikawa et al. 2002)	
Steiermark, Austria	2003	10	(Schöller et al. 2006)	Bottom-up
Australia	2005	10 +1/-2	(Müller et al. 2011)	Four product categories, Top-down, time series
Canada	2005	12 +/-2	(Müller et al. 2011)	Four product categories, Top-down, time series
France	2005	8 +/-2	(Müller et al. 2011)	Four product categories, Top-down, time series
UK	2005	8 +/-2	(Müller et al. 2011)	Four product categories, Top-down, time series

Attempts to assess the in-use stock of steel reach back as far as 1950, when Harrison S. Brown estimated the steel stock in the U.S. to ca. 8 tonnes per capita (Brown 1954). Two methods for estimating stocks have evolved since then: The bottom-up approach combines an inventory of steel-containing products (buildings, bridges, cars, etc.) with the average steel concentration in the different product categories (Müller et al. 2006). The top-down approach uses production and trade statistics to estimate the apparent consumption of steel, and a lifetime model computes the amount of steel leaving the use phase (Müller et al. 2006). The difference between inflow and outflow represents the stock change, which is accumulated over time to obtain the in-use stock. An overview on the available steel stock estimates is given in Table 1. To allow for comparison between different countries we present all figures as per capita stocks.

[Table 1 about here]

Estimates of the in-use stock of steel are available for eight countries only (Table 1). Moreover, there is considerable disagreement on the stock level between the studies on the regional or city level with those on the national level, especially for the US and Japan. This is because the estimates are taken from different studies with inconsistent system boundaries, data sources, modeling approaches, assumptions on missing data, and product categories considered. This makes it difficult to compare the estimate between different countries and to identify possible development patterns.

The objective of this work is to provide comprehensive stock data on the country level using a common methodology, to identify countries where per capita stocks may have saturated (Müller et al. 2011), and to provide a full sensitivity analysis of the estimates.

In particular we address the following questions:

1) How can the existing top-down methodology be extended to estimate stocks in countries where data on end-use of steel and product lifetime are not complete or do not exist?

2) How big are the in-use stocks of iron in different countries at present?

3) Which industrialized countries have saturated stocks and what is the range of stock saturation in these countries?

4) How accurate are our stock estimates, how reliable are the inferred saturation levels, and what uncertainties and data gaps remain?

We address question 1) in the methodology section, questions 2) and 3) in the results section, and question 4) in both the results and discussion section.

2. Methodology

2.1) System definition

We applied a multi-regional material flow analysis (MFA) model that covers the period 1700-2008 and all 288 regions defined in the UN Comtrade database for world trade (U.N. 2009) (Fig. 1). The complete model approach and all data used are described in the supplementary material. In order to determine apparent steel consumption, the numbers for crude steel production for 104 countries back to 1860 were corrected for losses in slag, forming, and fabrication as well as iron trade in all stages of the cycle. In addition, we collected pig iron production figures for 66 countries back to 1717 and corrected them for the carbon content. Pig iron is primary iron only, whereas crude steel may include secondary steel from open hearth furnaces (OHF), basic oxygen furnaces (BOF), or electric arc furnaces (EAF).
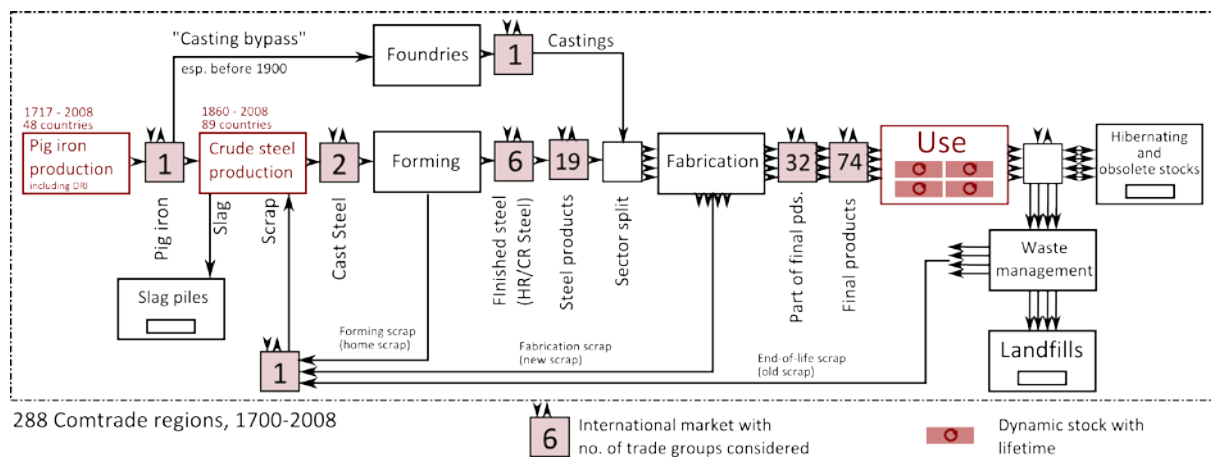

Figure 1: System definition for the steel cycle. 'DRI' = direct reduced iron. Multiple flows between processes indicate a split on the four end-use sectors transportation, machinery, construction, and products.
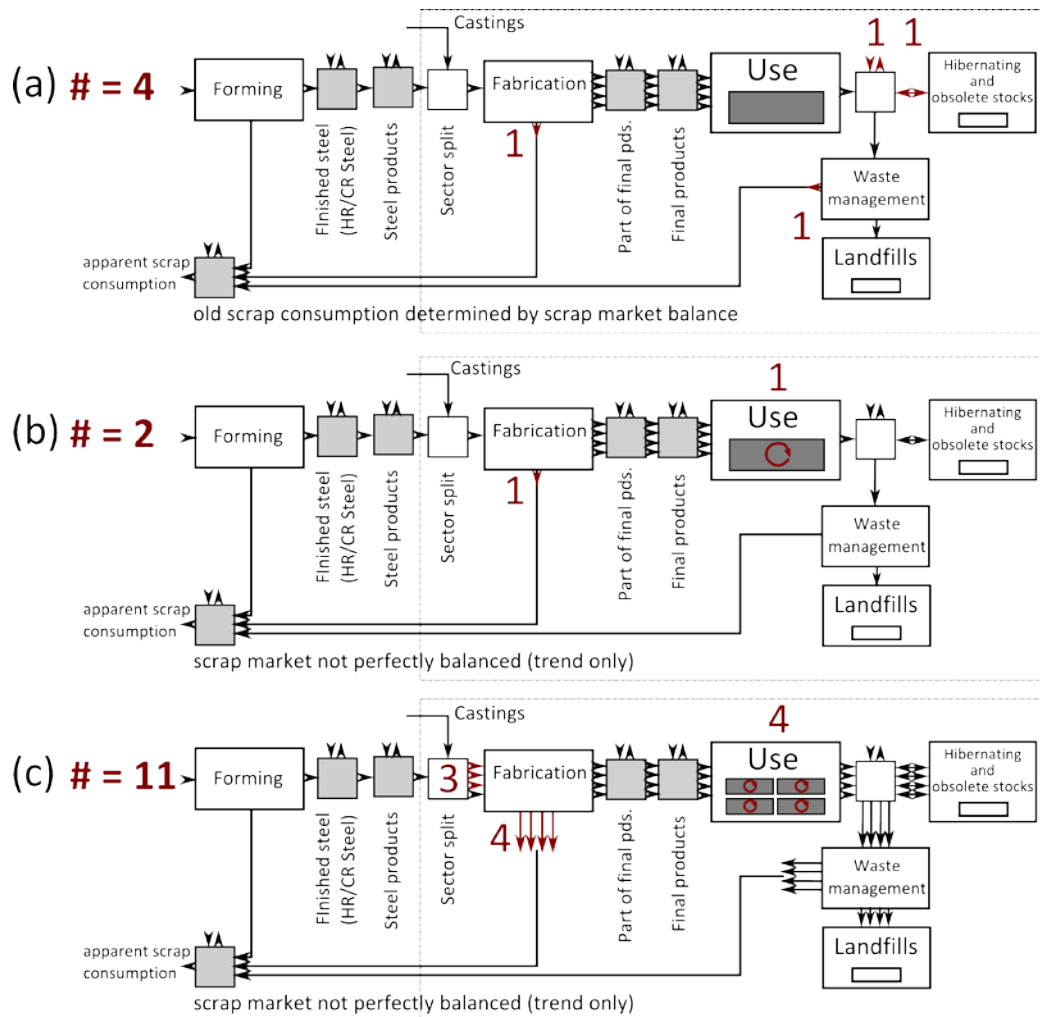
Figure 2: System definition for the three different model approaches to quantify the steel cycle. For each approach the minimum number of process parameters needed to quantify the in-use stock is indicated on the left. Multiple flows between processes indicate a split on the four end-use sectors transportation, machinery, construction, and products.

All pig iron that is not cast directly or exported goes into steelmaking (Fig.1). All crude steel is produced from either pig iron, direct reduced iron, or must have been sourced from some form of scrap. We estimated the casting output and slag losses in steel making from transfer coefficients, and used the mass balance of the pig iron market and crude steel production to determine the apparent use of steel scrap of all kinds in steelmaking (for definitions see Tables S1 and S2). Subtracting forming and fabrication scrap, which are rather well known, from the apparent total scrap consumption allowed us to determine the apparent

old scrap consumption for each country over time. This additional information was used to calibrate the stock estimates, cf. section 2.4.1.

End-of-life products may be traded, sent to dismantling and sorting, or may accumulate as hibernating or obsolete stocks. We assumed that steel in hibernating stocks such as abandoned buildings can be economically recovered at a later stage, but steel in obsolete stocks, such as foundation walls or disused pipes, was considered lost. The MFA system shown in Fig. 1 is similar to the systems used in previous studies, e.g., by Michaelis and Jackson (2000), Müller et al. (2006), (Daigo et al. 2007), and Wang et al. (2007).

2.2) Model approach

We quantified the steel cycle in three different ways (Fig. 2). For all three approaches we used the same data on production of pig iron, crude steel and cast iron as well as trade in all stages of the cycle, slag losses, and forming losses. The data, their sources, and all auxiliary calculations are contained in section S2 of the supplementary material. We explain how the dashed part of the system in Fig. 2 is quantified for each approach:

(a) We assumed that old scrap supply equals the apparent old scrap demand determined from the scrap market balance. The stock was considered homogenous and the steel cycle is perfectly closed. Four additional process parameters were required to quantify the in-use stock: The yield factor in fabrication, trade of end-of-life products, the accumulation rate of obsolete products, and the end-of-life recovery efficiency.

(b) We tracked different cohorts over time and assigned the average product lifetime to each cohort. Only two further parameters were required to determine the in-use stock: The yield loss factor in fabrication and the average product lifetime for each cohort. Estimating the different end-of-life losses allowed us to compare the scrap supply predicted by the lifetime model with the apparent scrap supply determined from the scrap market balance. In general the cycle could not be balanced, because it was not

possible to determine the exact shape of the average lifetime distribution for each cohort.

(c) This approach is a refinement of approach (b) and identical to the one previously used by Müller et al. (2011); it distinguishes between the four sectors transportation, machinery, construction, and products and applies several sector-specific parameters: We required 11 additional country-specific time series to determine the in-use stock: sector split (3, the fourth is determined from the balance), fabrication scrap rate (4), and lifetime by sector (4). Another 12 parameters were needed to quantify the entire cycle and to establish the mass balance of the scrap market: Trade of obsolete products by sector (4), formation rate of obsolete stocks by sector (4), and end-of-life recovery rate by sector (4).

2.3) Data gathering and treatment, assumptions

Table 2 gives an overview of the model parameters. A complete description of all model data is presented in the supplementary material. Next to the country-specific production statistics, we used world averages on slag losses in steelmaking, forming and fabrication losses as well as end-of-life recovery efficiency. The formation rate of obsolete construction stocks was estimated as the typical fraction of steel in subsurface construction that we assumed to remain underground after decommissioning. Little country-specific information and time series on the different loss rates was available. We therefore referred to the global average figures, and estimated their uncertainty by comparing them to the few country-specific data we had available, and performed a sensitivity analysis to determine the propagation of these errors to the stock estimates. Trade, sector split, and lifetime are discussed in sections 2.3.1-2.3.3.

The end-of-life data represent the biggest knowledge gap: Trade of obsolete products is usually not recorded (Müller et al. 2006), and we had to neglect it as no comprehensive quantitative information was available. Obsolete stocks are not recorded either and the

formation rate of 10% is a first indication only and could as well be larger. Only a handful of datasets on end-of-life recovery efficiency exists (cf. Table S13).

Table 2: Major model parameters.

Name	Values	Source
Pig iron production	66 countries, 1717-2008	cf. supplementary information S2.1
Crude steel production	104 countries, 1860-2008	cf. supplementary information S2.2
BOF/EAF slag losses	0.06	(World Steel Association 2009), cf. supplementary information S2.4
Forming scrap rate	0.09	(Cullen et al.), cf. supplementary information S2.6
Fabrication losses	0.27/0.17/0.074/0.23	(Cullen et al.), cf. supplementary information S2.7
Sector split	cf. section 2.3.2	cf. Supplementary Information S2.10
Lifetime	cf. section 2.3.3	(Müller et al. 2011), cf. Supplementary Information S2.11
Formation of obsolete stocks	0.1 of construction outflow	(Allwood et al. 2012), Fig. 3.4, cf. Supplementary Information S2.9
Separation efficiency waste management	0.82/0.87/0.82/0.58	compiled from (World Steel Association 2010) and (Graedel et al. 2011), cf. supplementary material S2.8
Trade	cf. section 2.3.1	cf. supplementary information S2.3
Trade of obsolete products	Not considered	cf. Supplementary Information S2.8

2.3.1) Trade:

We included 137 product categories from UN Comtrade to estimate trade on all stages, using the SITC1 classification starting in 1962 (U.N. 2009). UN Comtrade reports total mass flows, and we used the list of iron concentrations from the STAF-project (Wang et al. 2007) to estimate iron flows. We developed routines to fill gaps in trade data and to automatically detect and correct outliers within the 20 million datasets used. Historic trade was assumed to grow linearly from zero in 1900 to the level of 1962, when the trade statistics start. Trade data were used in three versions: i) trade flows reported by importing countries, ii) trade flows reported by exporting countries, and iii) the arithmetic mean of i and ii. We used the latter as baseline to estimate the net trade in each market and used options i and ii in the sensitivity analysis. A complete description of the trade data used is contained in section S2.3 in the SI.

2.3.2) Sector split, model approach (c):

Steel is used in a variety of applications that are often grouped to sectors like 'construction' or 'vehicles'. There are no standard sectors of final use of steel defined, and many different categorizations, which can be difficult to map onto our four end-use sectors, are used in the

literature. Another difficulty is the frequent use of classifications such as 'steel service centers', 'other', 'miscellaneous', etc. as end-use sectors, which can account for more than one third of the steel consumption and cannot be tracked further without very detailed knowledge of the steel markets in a particular country. It is often left unclear to which extent imported finished steel is covered by these statistics. Some sector split data only cover 30%-50% of the entire domestic production, which leaves a large potential for deviations. Time series are hardly available, and for many countries, there is no data available at all. In the supplementary material we discuss four very detailed splits that allowed steel flows to be mapped on the four sectors without having to make many assumptions. The aggregation of these data onto our four sectors is shown in Table 3.

Table 3: Sector split data.

Country	Year	Transportation	Machinery	Construction	Products
USA	2004	0.3	0.1	0.47	0.13
India	1995-1999 (average)	0.11	0.32	0.47	0.10
UK	1960-1965 (average)	0.25	0.29	0.31	0.15
UK	1970-2000 (average)	0.22	0.20	0.43	0.15

Instead of applying country-specific time series for the sector split that require a large number of assumptions during data preparation as in Müller et al. (2011), we assumed the sector split to be constant over time and to lie within the range given by Table 3. For all other countries than the ones in Table 3, we used the mass balance of the scrap market and an optimization routine described in section 2.4.1 to identify which of the sector splits given in Table 3 yields the lowest deviation from mass balance for each country.

2.3.3) Lifetime, model approaches (b) and (c):

Country-specific data on product lifetime are very sparse. Many lifetime estimates were obtained by observing products in the waste streams without distinguishing between different cohorts. As cohort sizes may vary a lot, these estimates may not be representative for the entire stock. As with the sector split, we used the mass balance of the scrap market and the optimization routine in section 2.4.1 to identify an optimal lifetime that yields the lowest

deviation from mass balance over time. We adopted the values used by Müller et al. (2011) as base case and investigate five alternatives (Table 4):

Table 4: Product lifetimes. Basic set and five alternatives.

Transportation	Machinery	Construction	Products	Comment
20	**30**	**75**	**15**	**base value (Müller et al. 2011)**
20	30	100	15	Construction lifetime 33% longer
20	30	50	15	Construction lifetime 33 % shorter
13	20	50	10	All lifetimes 33% shorter
27	40	100	20	All lifetimes 33% longer
10	15	38	8	All lifetimes 50% shorter

For approach (b) we defined a set of average lifetimes reaching from 20 to 70 years in steps of five years. Also here the optimization routine (cf. section 2.4.1) was applied to determine a lifetime value that minimizes mass balance violation over time. In all cases the lifetime followed a normal distribution and the standard deviation was set to 30% of the mean.

2.4) Calibration and quality control of the assumptions

2.4.1) Minimizing deviation from mass balance, model approaches (b) and (c):

In approach (a) the steel cycle is closed by definition and the apparent supply of old scrap equals the apparent consumption determined from the production statistics for pig iron, castings, and crude steel. For approaches (b) and (c) the apparent supply of old scrap is determined by using the lifetime model, and supply and consumption differ. The more accurate the data on sector split and lifetime however, the smaller the gap between consumption and supply and the better the cycle is balanced. We defined two groups of possible sectors splits (four sets, Table 3) and lifetimes (six sets, Table 4) and ran models (b) and (c) for all 24 combinations s of the two groups. We selected the combination s for which the accumulated scrap market mass balance violation is minimal:

$$abs\left(\sum_{t=1700}^{2008}\left(scrapconsumption - scrapsupply(s)\right)\right) = \min$$

An example of this routine is shown in Figure S5 in the supplementary material. The resulting sector split and lifetime estimates for 197 countries are listed in Table S23 of the supplementary material.

2.4.2) System-wide mass balance

Iron enters the anthropogenic cycle either through domestic production of pig iron or direct reduced iron, or as import of pig or cast iron, steel, products, or scrap. It leaves the cycle in form of exports of pig or cast iron, steel, products, or scrap, or it accumulates in slag piles, the in-use stock, obsolete stocks, or landfills. For each country we accumulated these flows and added the stocks to form two columns, one for all inputs and one for the disposition of steel. With perfect data the two columns should be of same size, and we generated a plot for each country to check the quality of the cycle quantification. The mismatch between the two columns reveals the overall impact of errors in trade data, discrepancies between pig iron and steel production statistics, and the absolute error of sector split and lifetime on the different stocks (Fig. 3).

2.4.3) Comparing the stock estimates for the three approaches

Comparing the stock levels for 2008 that were obtained by approaches (b) and (c) to the ones obtained by approach (a) allowed us to judge the usefulness of the determined lifetime and sector split estimates: If the levels differ a lot, there may be large systematic errors in the production and trade statistics for that country, or lifetime and sector split may have changed significantly over time.

3. Results

After having calibrated the lifetime and sector split estimates for approaches (b) and (c) according to the optimization routine, the steel cycles were compiled for all countries and all years between 1700 and 2008, and the total in-use stock was determined. A table with the 2008 stock values for all countries and approaches comes with the supplementary material

(Table S25). Fig. 3 (left) shows the apparent old scrap consumption (dark blue) and the estimated supply of old scrap from the lifetime model (medium blue) for four selected countries using model approach (c). One cannot expect the two curves to fit perfectly since the lifetime model tracked the long-term development only and a constant lifetime was used. For Germany and Thailand however, both the rise and the level of the predicted scrap flows coincided quite well with the empiric values. For the three developed countries shown, but especially for the US, the lifetime model overestimated the scrap flows for the years after 1980. We refer to the discussion section for possible reasons of that effect.

The columns on the right side of Fig. 3 show the accumulated mass balance of the country cycles for the period 1700-2008 as explained in section 2.4.2. They allowed us to compare the in-use stock of 2008 (yellow) with stocks that were lost as slag or by obsolescence over time (green), accumulated pig iron production (grey), imports (blue), and exports (orange and red). Next to showing how good the overall mass balance is met, these plots indicate to which extent the different countries relied on imports of iron throughout their history, and where the iron processed within the country ended up. For the US cycle domestic production and consumption dominated, whereas Germany showed a higher share of iron imports and almost 60% of all iron ever processed within the country has been exported. Japan lies in between the two former countries; with mostly domestic production but a large export share. Thailand showed almost no accumulated iron production, and most of the iron that ever entered the country's cycle was imported as steel and is still in use.
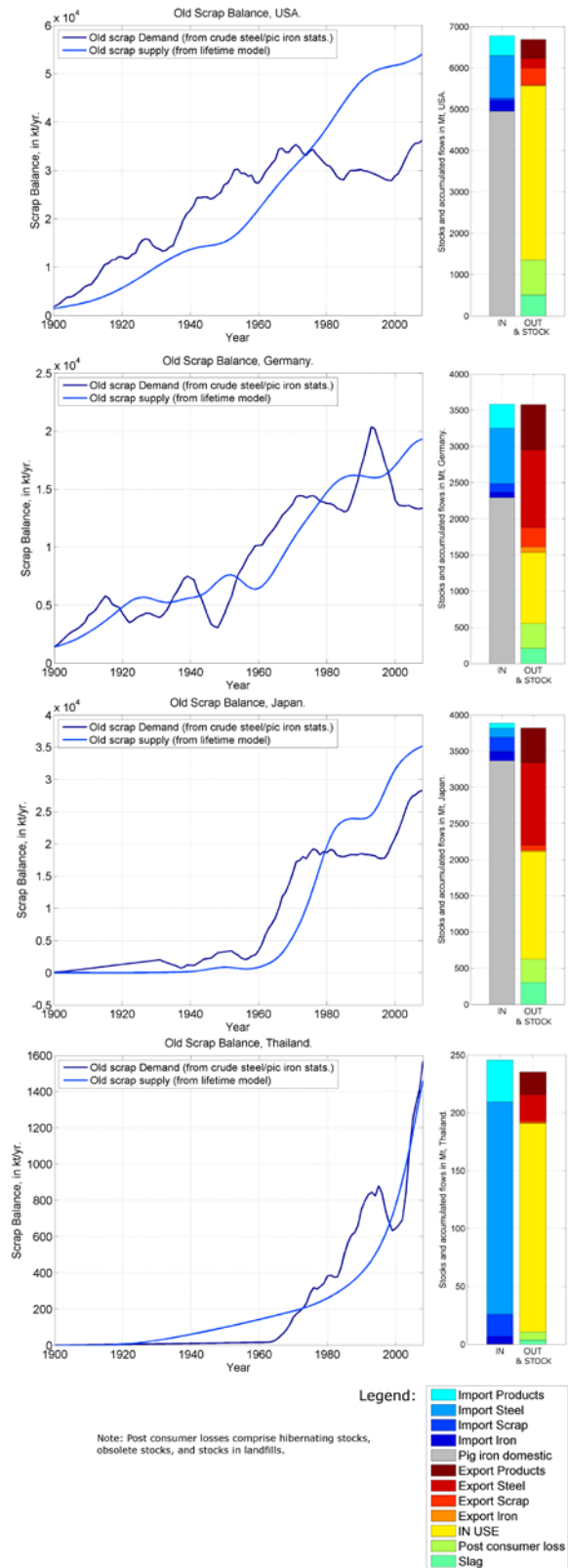
15

Figure 3: Old scrap balance and accumulated cycle balance for the period 1700-2008 for the US, Germany, Japan, and Thailand; determined by approach (c). The plots for 16 further countries are shown in the supplementary material. The unit on the left is kilotonnes per year (kt/yr), on the right it is megatonnes (Mt).
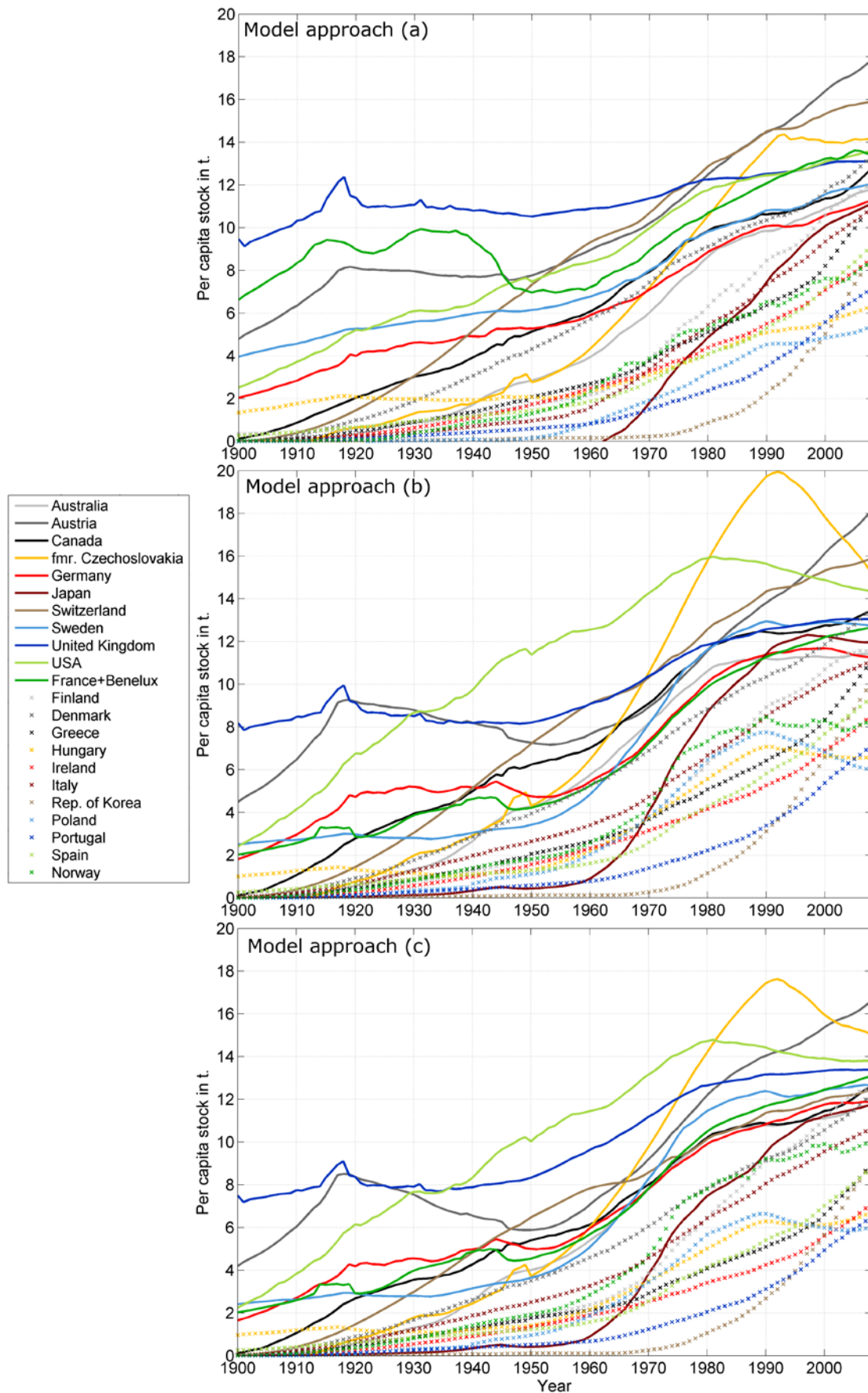
Figure 4: Total per capita in-use stock in tonnes (t) in the OECD countries for the three approaches (a)-(c), 1900-2008.

To identify patterns of in-use stock development we now focus on the larger industrialized countries. For all three approaches the stock patterns and 2008 levels were largely the same for the individual countries (Fig. 4). The most significant difference was found for the former Czechoslovakia, where the lifetime model results showed a peak in the stock curve but the mass balance approach showed saturation. A similar but less outstanding pattern applies to the former East Bloc countries Poland and Hungary, where per capita stocks stabilized or diminished after steel production dropped around 1990. This sudden drop is due to abrupt changes in the political and economic system, and the lifetime model is too inert to accurately reflect these changes. Without considering the pre-1962 trade, the stock in Belgium-Luxembourg would be between 30 and 35 tons, which is at least twice as much as in all other industrialized countries. Instead of having to assume the historic trade flows between France, Belgium, the Netherlands, and Luxembourg, we chose to aggregate these countries into the region 'France+Benelux'.

For the lifetime models (b) and (c) the per capita stocks in Australia, Canada, the former Czechoslovakia, Finland, France+Benelux, Germany, Japan, Norway, Sweden, Switzerland, the UK, and the U.S. were between 10 to 16 tonnes/capita in 2008, and the stock curves tended toward saturation, had already saturated, and some were even declining. For the mass balance approach (a) the stocks for these countries were in the same range, but there were fewer signs of saturation or even decline. This observation corresponded well with the gap between old scrap consumption and supply shown in Fig. 3; and we refer to section 4 for a discussion. For approach (a), clear signs of stock saturation and beginning saturation could be seen in the range of 10-16 tonnes per capita.

For all three approaches, Denmark, Greece, Hungary, Ireland, South Korea, Poland, Portugal, and Spain showed growing stocks at a present level of 6-12 tonnes per capita. Except for the former East Bloc countries, few signs of beginning saturation could be seen. In Denmark, Greece, Ireland, and Korea, stock accumulation even seemed to accelerate.

The stock levels for Austria and partly Switzerland were higher than for any other country, and stocks were still growing. The results for the two countries have to be handled with great care: Today's Austria has been part of several different states during the 20th century, and steel production figures before 1945 are estimates only. Switzerland had significant imports of steel when the trade records started in 1962, but the extent of trade prior to that year is an estimate only.

In the supplementary material we provide estimates for the uncertainty for all model parameters except for the iron content of pig iron (virtually constant), historic population (very accurate), and standard deviation of lifetime (coupled to lifetime).

For each single parameter change we compiled the entire cycle for all countries and determined the in-use stock. Table 5 shows the result of the sensitivity analysis for the US, the UK, Switzerland, Germany, and Japan. The time series for the US and the UK are plotted in Fig. S11.

[Table 5 about here]

The main contribution to stock errors resulted from uncertainties in the data on trade, sector split, lifetime, and post-consumer losses. Approach (a) led to more aggregated but more accurate stock estimates since sector split and lifetime data, which are unknown or come with high uncertainty for most countries, were not required for this model.

Table 5: Sensitivity of the stock estimates for the US and the UK, approaches (a) and (c), for 2008. Parameter changes which have the highest impact on stock levels are highlighted. Abbreviations: 'pp': percentage point, '—': no dependency according to model setup.

New stock value in % of the original one Base year: 2008	USA		UK		Switzerland		Germany		Japan	
	(a)	(c)	(a)	(c)	(a)	(c)	(a)	(c)	(a)	(c)
2% more pig iron	103	--	104	--	100	--	106	--	106	--
2% less pig iron	97	--	96	--	100	--	94	--	94	--
2% more crude steel	99	102	99	102	100	101	97	102	98	103
2% less crude steel	101	98	101	98	100	99	103	98	103	97
30% increase in slag rate	94	--	94	--	99	--	90	--	91	--
10% decrease in slag rate	102	--	102	--	100	--	103	--	103	--
Trade data: import only	**89**	**95**	104	103	**92**	**96**	99	99	**124**	**106**
Trade data: export only	**111**	**105**	96	97	**108**	**104**	101	101	**76**	**94**
Forming scrap +20%	101	98	101	98	100	99	102	98	102	97
Forming scrap -20%	99	102	99	102	100	101	98	102	98	103
Fabrication scrap +20%	103	97	102	97	101	97	104	97	103	97
Fabrication scrap -20%	97	103	98	103	99	103	96	103	97	103
Lifetime +25%	--	**113**	--	**115**	--	**110**	--	**117**	--	**114**
Lifetime -25%	--	**82**	--	**81**	--	**86**	--	**79**	--	**79**
end-of-life recovery-eff.: +5pp	105	--	106	--	101	--	109	--	106	--
end-of-life recovery-eff.: -10pp	**88**	--	**86**	--	97	--	**78**	--	**86**	--
Obsolete stocks formation: -3pp	103	--	103	--	101	--	105	--	103	--
Obsolete stocks formation: +10pp	**89**	--	**88**	--	97	--	**81**	--	**88**	--
Sector split: construct. +9pp, rest -3pp	--	**110**	--	**111**	--	**107**	--	**112**	--	**112**
Sector split: construct. -9pp, rest +3pp	--	**90**	--	**89**	--	**93**	--	**88**	--	**88**
Foundry share decline rate -30%	97	103	96	105	100	100	94	103	98	102
Foundry share decline rate +30%	102	98	102	97	100	100	104	98	101	99
Historic trade start: 1900 -> 1875	99	100	93	99	**117**	105	**89**	100	94	100
Historic trade start: 1900 -> 1925	101	100	108	101	**83**	94	**111**	100	105	100

In the supplementary material (Figs. S7-S10) we present our estimates on the per capita stocks broken down by sector of end-use for the OECD countries, determined by approach (c). We identified those countries where steel stocks have saturated or are close to saturation, and determined the mean saturation levels and standard deviations by sector (Table 6).

Table 6: Identified saturation levels in tonnes per capita for mature steel stocks.

Transportation	1.5 ± 0.7
Machinery	1.3 ± 0.5
Construction	10 ± 2
Appliances and other	0.6 ± 0.2
Total	**13 ± 2** (rounded from 13.4 ± 2)

4. Discussion

4.1. What did we learn about the current in-use stock levels?

The more mature stocks were found within the range of 10-16 tonnes per capita (Table S25), which is in the higher range of the values from previous studies (Table 1). For the UK, France, and Japan we found stocks to be a factor 1.5-2 larger than some of the previous estimates. The reasons for this difference lie in different assumptions on lifetimes, post-consumer losses, and the amount of steel going into construction.

The mass balance consistent top-down approach (a) determined stocks without relying on lifetime and sector split data. For the vast majority of countries, the results matched well with those obtained from approaches (b) and (c), after sector splits and lifetimes were estimated with the optimization routine. Since the 1970ies, old scrap consumption in several industrialized countries may have been lower than what follows from the lifetime model. As a consequence, in-use stocks may be higher, or significant amounts of steel accumulated in obsolete stocks or were exported. More steel than previously assumed may have gone into construction, where it accumulated.

Even if the stock estimates are conducted carefully, they can lead to very different results due to the large uncertainties in the data, as the example of Japan shows (Table 1). In this study we could not overcome some central data limitations, especially for the post-consumer processes, but we showed how the accuracy of the stock estimate can be assessed and how the data assumptions can be validated by plotting both the cycle-wide mass balance and the accumulated mass balance (Fig. 3), and by using the different estimation approaches.

4.2) What did we learn about stock saturation?

There is evidence for saturating per capita stocks in all four categories and the total stocks, no matter which approach is used. The industrialized countries with the longest tradition in steel making showed the highest stock levels, which in most cases have reached a state of slow

growth, saturation, or even decline. The whole picture is more diverse, however: In some countries, stocks continue to grow at levels where stocks in other countries saturate or decline. The lifetime model with a constant lifetime seems to have overestimated the scrap flows in several developed countries for the period after 1980, which resulted in lower stock levels and more countries with saturating stocks than for the compilation approach without lifetime. When looking into the three non-construction categories, the picture is very diverse: Stocks rose, declined, and grew at very different paces and levels (Figs. S7, S8, and S10). Only in construction a more concordant trend could be seen: Stocks in construction tended to grow to a range of 10-13 tonnes per capita (Fig. S9).

Export of obsolete products, which was neglected here, may have further reduced the in-use stock in developed countries in the past. Since this was not included in the model and still, saturation could be observed, we are confident that saturation of per capita in-use stocks of steel exists in many developed countries at or slightly below the levels given in Table 6.

4.3) How accurate are our estimates and what knowledge gaps remain?

By moving from a lifetime model to an approach where the outflow is estimated from apparent scrap consumption, the two parameters that contribute most to the uncertainty of the previous stock estimates, i.e., sector split and lifetime, could be eliminated from the model. This procedure improved the accuracy of the total stock levels calculated, and the results can in turn be used to calibrate the estimates from the lifetime and sector-specific models. For developed countries, the three modeling approaches yielded the same total stock values within a range of ±1 tonnes or better. End-of-life recovery efficiency, the formation rate of obsolete stocks, and trade at all stages of the cycle contributed most to the uncertainty of the mass-balance-based estimates. The first two parameters may vary significantly over time and countries, but only snapshots and rough estimates were available.

In some industrialized countries, such as the U.K., the U.S., and Japan, a constant product lifetime underestimated the scrap flow for the years before around 1980 and overestimated it for years thereafter. This can have several reasons, which we address in turn:

<ol type="i" start="1">
The lifetime within different sectors changes over time
The sector split changes over time
Increased formation of obsolete stocks and export of obsolete products
Change in the yield rates in forming and fabrication
Uncertainties in trade data

i) Since not even comprehensive data on product lifetime for a fixed cohort for different countries and sectors exist, it seems unrealistic to gather time series with changing lifetime values and distribution for all sectors.

ii) The same problem applies to sector split data. Though data are available for some countries and years (cf. the supplementary material, Hatayama et al. (2010), and Müller et al. (2011)), the reported splits could not be matched with our categories without having to make further assumptions, and sometimes, only ca. 50% of the domestic steel production is covered. It is often left unclear whether imported semi-finished and finished steel is included or not. In theory, it would be possible to choose time series for lifetime and sector split in a way that the scrap flow derived from the lifetime model equals the apparent scrap consumption from the mass balance of the scrap market (Fig. 3), but that choice would not be unique, as 3 sector split values and four lifetimes have to be derived from a scalar mass balance. Instead, we developed the optimization routine and the mass balance consistent approach (a) to overcome that limitation.

iii) Based on the data on end-of-life recovery efficiency and iron content of building substructures, we assumed that ca. 30% of the steel leaving use is lost either to landfills or to obsolete stocks. The latter consist of disused pipes, substructures of abandoned buildings, quay walls, etc., and may be even higher than estimated here. Hence, a fraction of steel that is presently classified as in-use stock may actually represent obsolete stocks and may be difficult to access for recycling. Export of used equipment or vehicles is another way how steel can leach out of a country's cycle. Trade of used or obsolete products is not covered by current trade statistics if the value is below a certain threshold (Müller et al. 2006). A detailed

bottom-up study that includes estimates on obsolete stocks in the above mentioned structures may help shed light on this often neglected aspect of steel use.

iv) Comprehensive country-level data for all industry and fabrication loss rates are not available. Instead of trying to increase the spatial and temporal resolution of the available global average figures, we compared them with a set of country-specific data, and estimated the upper and lower range of the global figures. The so-obtained deviations are between 10% and 30% and the sensitivity analysis showed that despite these rather large errors, their impact on per capita stocks is below +/- 0.5 tonnes, which is significantly smaller than the errors related to trade and end-of-life losses.

v) The uncertainty in the trade data is due to discrepancies between the numbers reported by importers and exporters of the same product flow. This holds not only for developing or small countries, but also for some commodities in developed countries, especially passenger vehicles (SITC1_7321) and ships (SITC1_7353). More advanced trade flow refining and interpolation routines that include CIF/FOB correction and that consider differences in reliability of the reporting countries, such as presented by Gaulier and Zignago (2010), could be applied in the future to reduce the uncertainty of the stock estimates mainly in the transportation sector and the developing countries.

4.4) Conclusion

We looked at the steel cycle from different angles and tested the robustness of our stock estimates by choosing three different MFA models and estimating the error of the parameters required. Per capita in-use stocks in industrialized countries are between 6 and 16 tonnes, and many of these countries show saturation or signs of saturation in the range of 11-16 tonnes. A large uncertainty remains, as country-specific data or even time series are unavailable for many countries and parameters. The typical error of the total per capita stock in developed countries has been estimated to about ±2 tonnes. Saturation of per capita stocks could be confirmed for a number of countries and the saturation range is 13±2 tonnes. This

observation can be used to feed models on future steel utilization in both the developed and the developing world.

Supporting information available

We provide the complete system definition, the model equations, documentation of data sources and treatment, and additional results. This material is freely available via http://www.sciencedirect.com/

Funding sources

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Figure and table captions:

Figure 1: System definition for the steel cycle. 'DRI' = direct reduced iron. Multiple flows between processes indicate a split on the four end-use sectors transportation, machinery, construction, and products.

Figure 2: System definition for the three different model approaches to quantify the steel cycle. For each approach the minimum number of process parameters needed to quantify the in-use stock is indicated on the left. Multiple flows between processes indicate a split on the four end-use sectors transportation, machinery, construction, and products.

Figure 3: Old scrap balance and accumulated cycle balance for the period 1700-2008 for the US, Germany, Japan, and Thailand; determined by approach (c). The plots for 16 further countries are shown in the supplementary material. The unit on the left is kilotonnes per year (kt/yr), on the right it is megatonnes (Mt).

Figure 4: Total per capita in-use stock in tonnes (t) in the OECD countries for the three approaches (a)-(c), 1900-2008.

Table 1: Estimates of per capita stocks of steel in use, based on Graedel (2010) and amended by recently published estimates.

Table 2: Major model parameters.

Table 3: Sector split data.

Table 4: Product lifetimes. Basic set and five alternatives.

Table 5: Sensitivity of the stock estimates for the US and the UK, approaches (a) and (c), for 2008. Parameter changes which have the highest impact on stock levels are highlighted. Abbreviations: 'pp': percentage point, '—': no dependency according to model setup.

Table 6: Identified saturation levels in tonnes per capita for mature steel stocks.