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How will tramp elements affect future steel recycling in Europe? – A dynamic material flow model for steel in the EU-28 for the period 1910 to 2050

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A B S T R A C T

Global steel production has undergone massive growth since WWII. In recent decades, however, affluent regions such as the US and the EU-28 have been experiencing a saturation of the steel market. Stagnant steel production volumes and increased post-consumer scrap volumes are the consequence. The increasing shares of post-consumer scrap provide the opportunity to increase the scrap rate (share of utilized scrap) in crude steel production. However, steel recycling has a major limiting factor: the content of specific tramp elements.

In the present study, a dynamic material flow model for steel is used to compare available scrap with crude steel demand on a quantitative and qualitative level (tramp element content of Cu, Ni, Mo, Cr and Sn). The results show that post-consumer scrap increases from 80 Mt/yr (65% of all scrap available) in 2020 to more than 100 Mt/yr (75% of all scrap available) in 2050. Based on the model, the development of the yearly surplus of low purity scrap (for which there is a higher supply than demand) was assessed via material pinch analysis. The low purity scrap surplus rises further, from today's 20 Mt/yr (2020) to 43 Mt/yr in 2050. Assuming that the current handling of scrap continues, the maximal scrap rate is shown to lie at around 55%, while the potential scrap rate (without quality constraints) could reach 75%. The dilution of low purity scrap with high purity resources would allow the utilization of all scrap until 2040 if the current collection scheme remains in place.

1. Introduction

Steel is not only one of the most commonly used commodities, but is also applied widely in all end-use sectors. On a global scale, the steel industry has experienced extensive growth in recent decades (World Steel Association, 2020), which has been mainly driven by emerging regions, such as Asia (Hatayama et al., 2010). In affluent economies, steel in-use stock is mostly saturated (Hatayama et al., 2010; Müller et al., 2011; Pauliuk et al., 2013b), which results in stagnant steel consumption rates in these regions. This stagnation makes scrap increasingly relevant as raw material for steel production. The usage of scrap for crude steel production is not only beneficial from a resource point of view, but also helps reduce CO_2 emissions (Broadbent, 2016) and brings other environmental benefits, such as lower eutrophication, acidification and photochemical oxidation, in comparison to steel production from primary resources (Hu et al., 2014; López et al., 2020).

Steel flows have been extensively investigated on various levels, in varied degrees of detail and in different timeframes (retrospectively and in terms of forecasting: e.g., Cooper et al. (2020); Cullen et al. (2012); Hatayama et al. (2010); Müller et al. (2011); Pauliuk et al. (2013b, 2013a); Zhu et al. (2019)). However, analyses of steel flows on an European level are rather rare (e.g., Dworak and Fellner (2021); Passarini et al. (2018)).

In recent decades, quantitative analyses of steel flows have been extended to include qualitative aspects. To do so, the presence of impurities in steel and steel scrap (tramp elements such as Cu, Ni, Mo, Cr or Sn), their impact on recycling and possible technical interventions to deal with such impurities have been investigated (e.g., Daehn et al. (2019); Daigo et al. (2021); Noro et al. (1997); Sampson and Sridhar (2013); Savov et al. (2003); Spitzer et al. (2003)). However, only very few studies are available which quantify the scrap flows and associated tramp element flows and put the scrap availability in relation to crude steel demand (e.g., globally for Cu (Daehn et al., 2017), retrospectively for the former EU-28 (Dworak and Fellner, 2021), and for Japan (Daigo

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et al., 2017; Igarashi et al., 2007; Oda et al., 2010)). What the results of these studies have in common is that they indicate a surplus of low purity scrap, which requires dilution with primary steel in order to be recycled. On a global scale, this surplus might arise in the near future (see Daehn et al. (2017)). In Japan and Europe it is already prevalent, as highlighted by Igarashi et al. (2007) and Dworak and Fellner (2021). At present, this existing surplus is largely balanced by the export of scrap as both the European Union and Japan are net exporters of steel scrap (+16 Mt/yr and +8 Mt/yr). For the US the situation is similar.

The extent to which this current surplus of low purity scrap might increase in the future, and thus further limit the domestic recycling of steel scrap in affluent economies, has not been investigated so far.

Hence, the objective of the present paper is to assess the long-term development (until 2050) of steel scrap generation and its composition with regards to the total contents of tramp elements (Cu, Sn, Cr, Ni and Mo) in the European Union and to compare the domestic steel scrap supply with the crude steel demand in terms of both quantity and quality. To do so, a dynamic top-down material flow model for steel (taking steel impurities into account) is developed and applied for the territory of the former EU-28 and the period from 1910 to 2050. In order to enhance the significance of the results, the model is partially validated with bottom-up data, which represents an advance relative to the existing dynamic steel models.

2. Material and methods

2.1. Model structure

The proposed system boundaries correspond to the geographical border of the former EU-28 over the time period of 1910 to 2050. The start of the timeframe is chosen to take stock accumulation and resulting post-consumer scrap for sectors with long lifetimes into account. The flows in the model are balanced, based on the law of mass conservation. Fig. 1 displays the simplified steel flow model (covering carbon steel and cast iron and steel, but not considering stainless steel) for the former EU-28. Stainless steel is not considered since the accompanying elements in these sorts are seen as resources for alloying rather than as tramp elements. Hence, stainless steel is managed differently. Furthermore, the average share of stainless steel in relation to total steel production is less than 10% for the period considered. It contains 7 processes ((1). Crude steel production, (2). Production and trade of intermediate products, (3). Fabrication of finished products, (4). Trade in finished steel products, (5). Consumption, (6). Waste Management and (7). Scrap market) and 16 flows of steel and steel scrap (CrS - Crude steel, IP - Intermediate steel products, FSP - Finished steel products, PoCSg - Post-consumer scrap generated, PoCSr - Post-consumer scrap recovered, Sr - Scrap recycled, PFS - Production & forming scrap, FS - Fabrication scrap, NIS - Net-import of ingots & semis, RM - Raw materials, NIFSP - Net-import of finished steel products, EEoLP - Export of end-of-life products, NISc - Net-import of scrap, CI - Cast Iron, NIIP - Net-import of intermediate steel products, NEUFSP - Net End Use of finished steel products). Process 1 (Crude steel production) and Process 7 (Scrap market) are not balanced and are therefore located outside of the system boundaries. For the sake of completeness, however, they are shown in Fig. 1. The steel flow model is largely based on the work of Dworak and Fellner (2021). All blue flows are based on statistical data or determined via the application of transfer coefficients. Transfer coefficients are used to partition specific inputs to specific outputs. In this study, the transfer coefficients are applied to determine specific steel intermediate products to the end-use sectors, and also to determine the fabrication scrap based on steel product and end-use sector specific material efficiencies. A detailed description of their derivation is given in Dworak and Fellner (2021). The current work focuses on the determination of the red flows, especially on the amount and composition of PoCSr as well as the in-use stock. The steel flow model is built up in multiple layers. On the one hand, the flows of specific intermediates can be mapped throughout the system. Further, each intermediate steel product is split up into the corresponding end-use sectors. Altogether 19 intermediates (casts - Cast Steel (c CS), Cast Iron (c CI); flats - Electrical Strip (f ES), Tin Plated (f TP), Plate (excl. plates used for welded tubes) (f P), Cold Rolled Coil galvanized (f CRCg), Cold Rolled Coil coated (f CRCc), Cold Rolled Coil (f CRC), Hot Rolled Coil galvanized (f HRg), Hot Rolled Narrow Strip (excl. Strips used for welded tubes) (f HRNS), Hot Rolled Coil (f HRC); tubes - Welded Tubes (t WT), Seamless Tubes (t ST); bars - Wire Rod (b WR), Reinforcing Bar (b RB), Hot Rolled Bar (b HRB); shapes - Heavy Section (s HS), Light Section (s LS), Rail Section (s RS)) and 4 end-use sectors with altogether 10 sub-end-use sectors (Construction - Buildings (C Bu), Infrastructure (C In); Industrial Equipment - Mechanical Engineering (I ME), Electrical Engineering (I EE); Transport – Cars (T Ca), Trucks (T Tr), Other Transport (T OT); Metal Goods - Other Metal Goods (MG OMG), Appliances (MG Ap), Packaging (MG Pa)) are distinguished according to similar studies (Cullen et al., 2012; Zhu et al., 2019).

This multilevel approach allows quality classes to be assigned to the

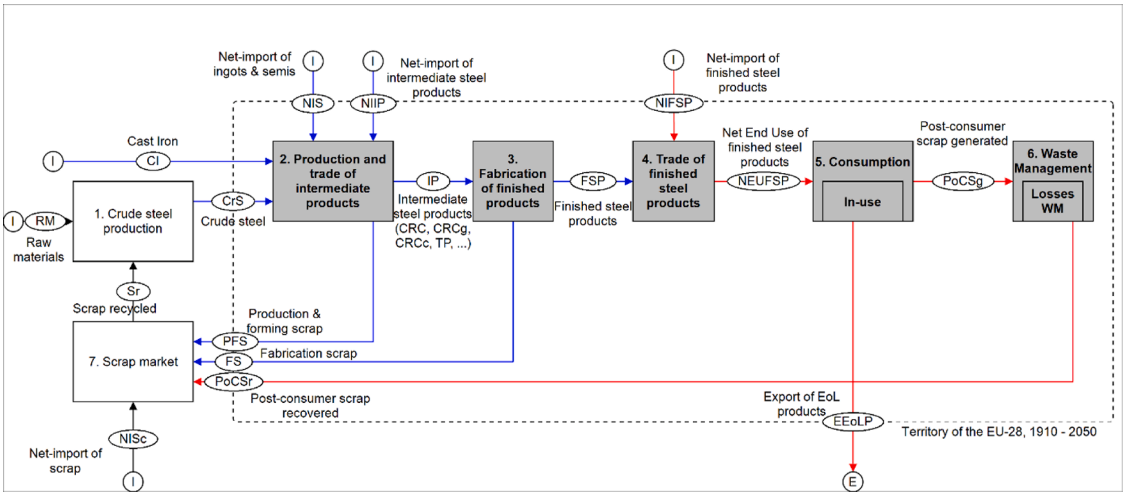

Fig. 1. Simplified MFA system for assessing steel and scrap flows in the former EU-28 (the red flows are determined in this study via dynamic modelling, whereas the blue flows are based on statistics and transfer coefficients (Dwoark and Fellner, 2021)); processes 1 and 7 are within the borders of the former EU-28, but not considered/balanced within the framework of the present study and are therefore located outside the system boundary; In-use: steel stock in use, Losses WM: Losses in waste management system to e.g. landfills. In addition to steel, the flows of cast iron were considered as well.

specific steel intermediates with regards to allowed levels of impurities depending on the assigned end-use sector. Four classes of steel and steel scrap are distinguished (Q1-Q4) based on total content of the tramp elements Cu, Sn, Cr, Ni and Mo (Daigo et al., 2010; Dworak and Fellner, 2021), plus an additional quality class for cast products (Q0). Following this principle, we can estimate the quality of all flows and stocks within the system boundaries.

Based on the domestic fabrication of the final steel products (FSP) and the trade thereof (NIFSP, where the same sectoral composition as for FSP for the corresponding year is assumed), the domestic end-use of finished steel products (NEUFSP) is determined. End-of-life products (EoLP) are determined on the basis of Weibull life-time functions, depending on the corresponding end-use sector. Taking the export of end-of-life products (EEoLP) into consideration, which is especially relevant regarding cars, the post-consumer scrap generated (PoCSg) can be determined. Further processing in the waste management system leads to losses, which are considered equally distributed within each sector (meaning, of all steel intermediates exiting the sector in the corresponding year, the same share is regarded as loss and the sectoral composition is identical in PoCSg and PoCSr). The output of the waste management system is the PoCSr, which then becomes available for recycling or trade.

2.2. Input data

The input data was compiled from various data sources, which are briefly described in the following. The blue flows in Fig. 1 are mostly based on statistics and transfer coefficients (for details see Dworak and Fellner (2021)).

2.3. Historical data and basic input data

Intermediate steel products (IP): The starting point of the calculation for the period from 1946 to 2017 is the reported production data of IP (adapted from Dworak and Fellner (2021)). From 1910 up to 1945, shares of steel intermediates were assumed to correlate with the average shares of the years 1946–1950, which is definitely a gross simplification as two world wars significantly influenced steel use during this time. Nonetheless, the overall impact of this simplification on the present and future scrap supply is negligible. The total amount of steel production of the EU correlates with world steel production (Kelly and Matos, 2014), again using the relation between EU-28 and world steel production for the period from 1946 to 1950 for scaling.

Production and forming scrap (PFS): Quantities of PFS were taken from Dworak and Fellner (2021), who applied time- and production route dependant PFS rates to estimate the quantities of the crude steel production (CrS) and the amount of PFS.

Final steel products (FSP) and fabrication scrap (FS): We applied transfer coefficients dependant on (i) time, (ii) end-use sector and (iii) steel intermediate to determine FSP. Material efficiencies, likewise dependant on time, end-use sector and steel intermediate, were applied to determine FS. Both transfer coefficients and material efficacy are based on Cullen et al. (2012) and calibrated according to Dworak and Fellner (2021).

Net-import of finished steel products (NIFSP) and net end use of finished steel products (NEUFSP): Quantities of traded final steel products were derived from the UN Comtrade database (UN Comtrade, 2020) and the corresponding steel contents were adopted from the World Steel Association (World Steel Association, 2018). For the NIFSP, the same composition as for FSP (in terms steel qualities) for the corresponding year is assumed. Detailed information about the determination of the trade flows is provided in the Supplementary Information. By balancing *Process 4. Trade of finished steel products*, the net end use of finished steel products NEUFSP was determined.

End-of-life products (EoLP equals the sum of EEoLP and PoCSg and is not shown as a separate flow): As mentioned above, EoLP was determined by applying Weibull lifetime-functions to the NEUFSP. Weibull functions are quite well suited for use as lifetime-function as they are finite (no negative values) and their form is easily adjustable (width and skewness, e.g. (Melo, 1999)). Even though some studies aim to estimate the variance of lifetimes over the years in general (e.g. via the volume correlation model (Gauffin et al., 2015)), data on the variation of lifetimes for specific sectors is rarely available. For the sake of consistency and simplicity, we decided to keep the lifetime functions for the different sectors constant over time. The parameters applied for the lifetime functions are summarized in Table 1.

In-use stock (In-use): The initial steel stock in 1910 was assumed to be zero, which is a simplification as Klinglmair and Fellner (2011) and Pauliuk et al. (2013a) have shown in their work that the per capita steel stock in the Austro-Hungarian Empire and Western Europe amounted to approximately 1.2 and 2 t/cap in 1910. Nonetheless, this simplification is justified by the fact that the stock present 100 years ago is of minor significance for the steel stocks today and thus also for steel scrap generation today. Nevertheless, the model might underestimate the in-use stock for the first few decades.

Export of end-of-life products (EEoLP): Unknown whereabouts in the Transportation sector (Cars and Trucks) is a well-known issue in the former EU-28 (e.g. manifested in the ELV-directive (EC, 2000)). In this model, vehicles (cars or trucks) with unknown whereabouts (possibly due to illegal export, vehicle theft, or vintage vehicles kept by car enthusiasts on private properties (Oeko-Institut e.V., 2017)) are considered via a constant rate. The determined share of end-of-life vehicles with unknown whereabouts is a little above 30% of the deregistered and not re-registered or reported as end-of-life vehicles in waste statistics. The corresponding reports do not discriminate between cars and trucks. We assumed that 30% of steel contained in all end-of life cars and 70% of steel contained in all end-of-life trucks is of unknown whereabouts. The rates applied are also provided in Table 1.

Post-consumer scrap generated (PoCSg): By subtracting the corresponding EEoLP from the EoLP, the PoCSg was determined.

Post-consumer scrap recovered (PoCSr): To determine PoCSr, the corresponding losses through processing in waste management were determined by means of sector-specific recovery rates. We chose to decrease the recovery losses between 2010 and 2050 to account for efforts to improve recovery rates. To do so, we assumed that the rate of losses decreases linearly until 2050 by 30% in comparison to the losses in 2010. Only for the Transport sector (Cars and Trucks) is more specific data available. Therefore, based on these data, the recovery rate of steel from shredded EoL cars and trucks is adjusted at several points in time (2006, 2009, 2018, 2030). Detailed sources and derivation of the values

Table 1

Input parameters for the dynamic MFA model; lifetimes derived based on (Dahlström et al., 2004; Davis et al., 2007; Gauffin et al., 2015; Hatayama et al., 2010; Huuhka and Lahdensivu, 2016; Melo, 1999; Michaelis and Jackson, 2000; Müller et al., 2011, 2006; Neelis and Patel, 2006; Oda et al., 2013; Pauliuk et al., 2013a; Wang et al., 2007); EEoLP derived based on (Oeko-Institut e.V., 2017); recovery rate based on (EC, 2000; Pauliuk et al., 2019; UBA and BMU, 2019). The recovery rate is constant up until 2010 and then liniarly intropolated to increased recovery rate (30% less losses), except for Cars and Trucks (for details see Supplementary Information).

End-use sector	Lifetime	EEoLP	Recovery rate	
	Average lifetime	Rate	Up to 2010	2050
C Bu	65	–	82%	87%
C In	65	–	82%	87%
T Ca	17	30%	82%	98%
T Tr	17	70%	82%	98%
T OT	55	–	82%	87%
I ME	17,5	–	87%	91%
I EE	15	–	87%	91%
MG OMG	14	–	58%	71%
MG Ap	14	–	58%	71%
MG Pa	1	–	58%	71%

are provided in the Supplementary Information. The recovery rates applied are provided in Table 1.

2.4. *Future projection of steel and scrap flows*

The projection is based on the mean value of the period 2003 to 2017 to account for the intense fluctuations in recent years. A stagnant crude steel production rate was assumed based on the fact, that steel production rates are more or less stagnant for the last decades in Europe. It was assumed that the quantity of each specific flow (in every layer) stays in the same relation (no significant changes in composition of flows).

Three simple scenarios for the future development of steel use in the former EU-28 are considered. They assume either a moderate growth in steel use of 0.5% per year (Scenario “growth”), a constant steel use (Scenario “zero growth”) or a reduction in steel use of 0.5% per year (Scenario “de-growth”). Modelling based on stock saturation, which is a common approach for dynamic models, comes with high uncertainties, especially in lights of expected societal changes (e.g., transformation to a low carbon society). To evade additional uncertainties, and for simplicity reasons, only the above-mentioned scenarios are considered.

A stock-driven model for dynamic steel MFA as, for instance, applied by Pauliuk et al. (2013a) and Hu et al. (2010) was not considered as too many factors (e.g. implementation of shared economy in the Car sector, increase in public transport due to climate mitigation targets, development of infrastructure, etc.) make assessments of future stocks of steel in the different sectors highly uncertain. Therefore, we decided to use a flow-driven model as was also applied by Igarashi et al. (2007).

2.5. *Steel quality assessment*

2.5.1. *Quality assessment of steel products and new scrap (production and forming scrap, fabrication scrap)*

The quality assessment was adopted from Dworak and Fellner (2021). Four quality classes (Q1-Q4) of steel are defined on the basis of the total content of five major tramp elements (Cu, Sn, Cr, Ni and Mo), and an additional class for cast iron and cast steel products (Q0) was introduced. The classes are assigned based on the steel intermediate and the designated end-use sector (for details, see Dworak and Fellner (2021)). As (Dworak and Fellner, 2021) argue, the data availability regarding tramp elements is not sufficient to follow another, more precise, approach.

2.5.2. *Quality assessment of post-consumer scrap*

The post-consumer scrap was categorized using three different options:

Option A: The post-consumer scrap generated was assigned a sector-specific quality class (for instance, scrap from EoL cars was assigned quality Q4 due to the potential contamination with copper during EoL processing). For the sectoral assignment of the steel qualities to the different EoL products, literature data was applied (Q1: Metal Goods – Packaging, Q2: none, Q3: Transportation, Industrial Equipment, Metal Goods (except Packaging), Q4: Construction; based on (Daehn et al., 2017; Daigo et al., 2017, 2005; Eurofer, 2016; Hatayama et al., 2014; Igarashi et al., 2007; Savov et al., 2003; Schrade et al., 2006), for details see Supplementary Information). Option A considers contamination which might occur during use or during waste management when no enhanced sorting or decontamination procedure is in place. It represents in many respects the “worst case scenario” regarding the post-consumer scrap quality investigated in this paper.

Option B: The assignment of quality classes of steel scrap to the different EoL products was based on the average content of tramp elements $c_{Tramp,av}$ present in the steel of the sector. Contamination of the steel scrap via other metals (e.g., copper cables) during dismantling and processing of EoL products have been disregarded for option B. In determining the average content of tramp elements in the sector-specific steel mix of EoL products, normal distribution for the tramp elements in each quality class was assumed.

$$\overline{c_{Tramp,x}} = \frac{\sum_{i=1}^{n} c_{Tramp,ix} \cdot IM_{ix}}{\sum_{i=1}^{n} IM_{ix}}$$

With

$\overline{c_{Tramp,x}}$Average content of tramp elements in the steel mix of the respective sector [%]

$c_{Tramp,ix}$Content of tramp elements in the steel intermediate i for the product x [%]

IM_{ix}Mass of steel intermediate i for the product x [Mt/yr]

Option C: For this option, total disassembly of steel products, subsequent alloy/steel quality sorting and no contamination is assumed. This means that the post-consumer scrap can be sorted into the different steel intermediates (and their respective qualities) used to manufacture the finished steel products. This option represents a hypothetical “best case scenario” regarding the post-consumer scrap quality investigated.

2.6. *Sensitivity analysis*

To evaluate the robustness of the model, a sensitivity analysis was performed. The surplus of low purity scrap (Q3 & Q4, tramp element content higher than 0.25%) in relation to crude steel demand serves as the major results, whose changes are to be assessed. The sensitivity was analysed for the following four groups of parameters:

- Sector split: for the future prediction (2019–2050) we assumed varying splits of two end use sectors (Construction and Transport). We considered a variation of ±10% (relatively) for Construction and Transport (marked as “C+”, “C-”, “*T*+”, “T-”), each separately, while the remaining sectors splits were scaled accordingly.
- average lifetime (shape of lifetime function was kept constant): a variation of the average life time ±20% (marked as “upper” and “lower”) was applied.
- Export rate of end-of-life products: the export rate of EoL products was varied by ±20% relative to the base value (marked as “upper” and “lower”).
- recovery rate of post-consumer scrap generated: a reduction in losses of 20% relative to the base value (marked as “upper”) was assumed. As the efficiency of the waste management system in the future will rather increase than decrease, only an increase in recovery rates was considered.

The sensitivity analysis was conducted for each year modelled (1910–2050). Due to rather poor data (only rough estimates via projection) and not yet accumulated in-use stock, the results of the first few decades are not meaningful. Therefore, and for reasons of relevance, the sensitivity analysis will be discussed only from the year 1980 onwards.

2.7. *Material pinch analysis*

Pinch analysis was originally established to minimize energy demand in industries (Linnhoff and Hindmarsh, 1983) by taking into consideration the fact that different processes require different heat and pressure levels. It was further developed and has been used for some decades now to analyse material flows (Daehn et al., 2017; Ekvall et al., 2014; Hatayama et al., 2012, 2009). In this context the method takes into account that different materials and processes require different purities. In this study a semi-quantitative material pinch analysis (analogue to the work of Dworak and Fellner (2021)) is applied to compare the annually available scrap with crude steel demand in terms of the required purity. The results of this semi-quantitative analysis show to what extent the quantity and composition of the scrap (regarding tramp elements) meets the demand for crude steel.

2.8. *Model validation*

In order to increase the reliability of the model, specific stocks and flows were independently validated with bottom-up data. In particular, bottom-up stock assessments were conducted for cars and for reinforcement bars in buildings. Both together account for up to 18% of the total steel stock. A top-down approach was chosen for the validation of scrap quantities becoming available.

2.8.1. *Bottom-up stock assessment for buildings and cars*

For the Transport sector (subsector Cars) official registration numbers (eurostat, 2021) were used to validate the stock in the end-use sectors. The car weight was derived via estimated average weights of the reported weight classes (less than 1000 kg, from 1000 kg to 1249 kg, from 1250 kg to 1499 kg, 1500 kg or over). For each weight class the average weight was assumed (less than 1000 kg: 950 kg; from 1000 kg to 1249 kg: 1125 kg; from 1250 kg to 1499 kg: 1375 kg; 1500 and over: 2100 kg). A steel content of 65% (based on (Todor and Kiss, 2016)) was applied. The uncertainty of the stock determined in this manner was estimated at ±10%. This bottom-up based assessment of steel stock in the car fleet was then compared with the dynamically modelled stock of the Car sector.

The in-use stock of reinforcement bars was determined based on average concrete use and steel use in reinforced concrete based on newly built and demolished buildings. Most data were taken from Nemry et al., 2008).

A detailed description of data sources and the procedures applied for the bottom-up stock assessments is provided in the Supplementary Information.

2.8.2. *Comparison with reported scrap data*

The outcome of the dynamic MFA model (basically the scrap quantities generated) was validated by reported scrap quantities becoming available. Therefore, the total scrap quantities determined by the dynamic model, including production and forming scrap, fabrication scrap and post-consumer scrap, were compared with officially reported data on scrap generation. For the latter, the reader is referred to the work of (Dworak and Fellner, 2021), who assessed the scrap becoming available based on data provided by Eurostat (1946–1966) and Worldsteel (1967–2017).

3. Results

3.1. *Quantitative analysis*

3.1.1. *Scrap*

Over the period investigated (1910–2050), the total amount of available scrap (sum of production & forming scrap, fabrication scrap and post-consumer scrap recovered) constantly increases from about 20 Mt/yr in the beginning of the 20th century to 130 Mt/yr in 2050. In the first few decades (from 1910 onwards), post-consumer scrap may be underestimated as the in-use stock was assumed to be zero at the beginning of dynamic modelling in 1910.

As shown by Dworak and Fellner (2021), production & forming efficiency increased tremendously between the 1970s and the 1990s, which led to a decrease in production and forming scrap (from about 50% of the total scrap available in the 1950s to 12% from the 2020s onwards). The share of fabrication scrap is more or less constant (the share varies between 20% and 30%, trending toward 20% since the 2020s). Nevertheless, the amount of total scrap available is constantly increasing due to the vastly increasing post-consumer scrap recovered (PoCSr). PoCSr quantities rose from about 10 Mt/yr in 1960 (about 20% of the overall scrap quantity) to 80 Mt/yr in 2020 (or 65% of total amount) and will further increase to more than 100 Mt/yr (slightly less than 75%) in 2050 (see Fig. 2), which is in line with results of (Oda et al., 2013).

3.1.2. *In-use stock*

The in-use stock constantly increases, although with less and less intensity. In the zero-growth scenario, the expected plateau is not yet reached (around 2075 the stock would be saturated). While an in-use stock of 3000 Mt (6.7 t/cap) can be quantified in 1980, it rises up to 4700 Mt (9.5 t/cap) in 2010 and 5300 Mt (10.5 t/cap) in 2050, which is in line with results of Müller et al. (2011) and Pauliuk et al. (2013b, 2013a).

3.2. *Export of end-of-life products*

Based on the applied rates of export of end-of-life vehicles (30% for cars, 70% for trucks), the share of steel exiting the system this way is about 5% to 8% of the post-consumer scrap generated (PoCSg). The amount rises constantly up to 2020, when it peaks at around 7 Mt/yr.

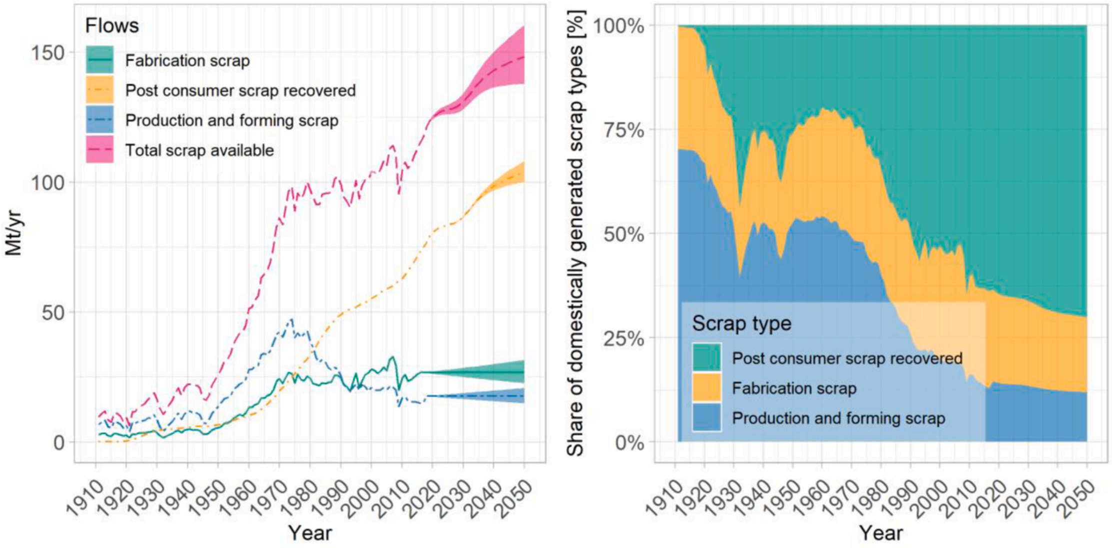

Fig. 2. left: Modelled quantities of flows scrap becoming available, categorized into forming & production scrap, fabrication scrap and post-consumer scrap as well as the total amount (sum of all scrap cathegories). The ribbon indicates the three scenarios (upper bound: growth; line: zero growth; lower bound: de-growth); right: Shares of scrap types: production & forming scrap, fabrication scrap and post-consumer scrap.

Until 2050, a slight decrease in the steel exported by EEoLP to 6 Mt/yr is expected due to the production peak of cars in the early 2000s.

3.3. Steel qualities and sector shares – scrap, stock and crude steel

3.3.1. New scrap (production & forming scrap, fabrication scrap)

For the period 1946 to 2017, the quantities and qualities of new scrap (production & forming scrap, fabrication scrap) were adopted from Dworak and Fellner (2021). The composition for the preceding period (1910–1945) was projected back with shares based on the period 1946–1950 covered by the investigation of Dworak and Fellner (2021). Hence, the shares of steel qualities Q1, Q2, Q3 and Q4 present in new scrap during the period 1910–1945 are 17%, 31%, 23% and 29%, respectively. Similarly, for future prediction, shares of the different qualities are based on the average shares of the years 2003 to 2017. Hence, for the period 2018–2050 the shares of Q1, Q2, Q3 and Q4 in new scrap are 53%, 25%, 11% and 10%, respectively.

3.3.2. In-use stock

Sector split: The major part of the steel in-use stock is allocated in the Construction sector (Buildings and Infrastructure). The high share of the steel stock present in the Construction sector of about 70% in the late 1970s will further increase to over 80% in 2050. This sector is also the driver for the overall stock increase due to its rather long lifetimes. The stock in the remaining sectors rises in varying degrees of intensity until the late 2000s, whereas afterwards they either slightly decrease or subsequently flatten, depending on their lifetime. Only the subsector Other Transport is characterized by a further stock increase due to its comparatively long average lifetime (55 years). The share of the overall steel stock amongst the Industrial Equipment, Metal Goods and Transport sectors decreases from 11%, 10% and 8%, respectively, in the 1980s to 6% (Transport and Industrial Equipment) and 5.5% (Metal Goods).

Quality: The steel qualities (impurity levels) assigned to the in-use stock are based on the quality of the steel intermediates comprising the final steel products. The share of Q0 (cast products) constantly decreases, from 14% (350 Mt/yr) in the mid 1970s to 6% (300 Mt/yr) in 2050. Steel of the lowest purity level (Q4) assumes the largest share in the total in-use stock by 2050 (about 30%). From then on, steel quality Q2 becomes dominant; both amount to about 1600 Mt. The share of Q3 steel relative to the overall stock is rather stable at about 15%. Nonetheless, stock quantities of Q3 almost double from the 1980s (500 Mt) to 2050 (850 Mt). Q1's share in the stock increases most, rising from 5% (80 Mt) in 1960 to 19% (1000 Mt) in 2050. In general, a shift from lower purity steel (Q3 & Q4, tramp element content higher than 0.25%) to higher purity steel (Q1 & Q2, impurities below 0.25%) can be observed for the in-use stock.

3.3.3. Post-consumer scrap

Up to the 1990s, all sectors deliver constantly increasing amounts of PoCSr. The biggest share can be attributed to the Mechanical Equipment sector, which yields the highest amount of PoCSr up until the mid-2000s. The share of Industrial Equipment in PoCSr constantly decreases, from 40% in 1950 to less than 20% of the total PoCsr in 2050. From 2010 onwards, the Construction sector (Buildings and Infrastructure) becomes the dominant source of PoCSr. In 2050, it is forecasted that more than 50% of PoCSr originates from Construction. The Transport sector (Car, Truck and Other Transport) accounts for a constant share of around 10% up until the 1980s, after which the share increases and reaches the highest value in the 2010s, with slightly more than 15%. By 2050, its share will again decrease to around 10%.

The share of cast products constantly decreases from 25% in 1970 to 6% in 2050. As scrap from cast products (Q0) is considered separately and the amount is the same for all options, the following results focus on the remaining qualities (Q1-Q4) only.

For Option A, the sector-specific quality classification of post-consumer steel scrap, the vast majority of PoCSr is low purity scrap. Only separately collected food packaging can be recovered at quality class Q1 (see Fig. 3). The other streams of post-consumer scrap becoming available are classified as Q3 and Q4, whereas the share of Q4 is constantly increasing, driven by the increasing share of PoCSr from the Construction sector. Until the mid-2020s Q3 dominates the PoCSr, after which Q4 assumes the largest share.

Option B: The results for this approach are by definition somewhere in between the results of the two other options (A and C). Still, some results are remarkable: Even though some sectors (especially C In and C Bu) receive most of the lowest steel quality class (Q4), the summed-up tramp elements of the sectors correspond to Q3. It should, however, be mentioned that the calculated average concentration is close to the threshold to Q4. The same principle applies to the higher share of Q1 in comparison to Option C. The calculated mean values for the Q1 scrap fractions are rather close to the threshold for Q2. Specific data about the concentration of the tramp elements in the different scraps is provided as a spreadsheet in the Supplementary Information.

For option C, the post-consumer scrap exits the consumption process of the same quality as the intermediate steel products comprising the final steel products. Scrap of quality Q4 is mainly delivered and subsequently yielded as scrap by the Construction sector, therefore the share of Q4 is constantly rising similar to the yield of the scrap from the Construction sector, even if less intensively. The share of Q2 is rather constant (slightly above 25%).

3.4. Comparison of scrap availability and crude steel demand

Besides the quantity and quality of available scrap, the crude steel requirements (quantity and quality) were determined in order to compare scrap availability with crude steel demand in the territory of the former EU-28. As discussed above, the PoCSr are becoming increasingly relevant as a major source for steel scrap. Crude steel demand, on the contrary, is dominated by increasing quantities of high purity steel (due to an ever-increasing demand for flats). In the upper row of Fig. 4, crude steel demand and scrap availability for Option A and Option C, with regard to their quantity and quality, are presented. From a quantitative perspective, an increasing share of the EU's crude steel demand might be produced out of scrap. In the 1990s, the potential scrap-based production rate of steel amounted to 50%, increased in 2020 to 65% and will further increase to 75% by 2050. After 2050, the potential scrap-based production rate of steel will further increase.

However, the results of material pinch analysis also clearly indicate that without implementing alloy/steel quality sorting, the quantity of low purity scrap (Q3 & Q4) exceeds the respective demand of steel from 2009 onwards. The lower part of Fig. 4 shows snapshots of the material pinch analysis for the corresponding years for Option A (upper row) and Option C (lower row). While up to 2008, the crude steel demand could take up all of the low purity scrap (tolerance greater than 0.25% of tramp elements, Q3 & Q4) becoming available in Option A, starting from 2009 the surplus of low purity scrap constantly rises, up to almost 50 Mt/yr by 2050 (which equals more than 1/3 of the overall scrap generated). By 2020, this surplus is almost exclusively composed of Q3 steel scrap. However, later on Q4 scrap also exceeds the respective crude steel demand (24 Mt/yr in 2050). When calculating the dilution potential for the tramp elements present in steel scrap (for option A), it turns out that by 2040, steel scrap generated could theoretically be diluted by the necessary quantities of crude steel from primary sources. However, later on, there is a surplus of tramp elements present in the steel cycle, which cannot be managed by simply diluting the scrap. The respective results are given in the Supplementary Information in the form of a spreadsheet.

3.5. Sensitivity analysis

The sensitivity analysis was performed in reference to the low purity (Q3 & Q4) scrap surplus on four parameters (lifetime, EEoLP, recovery

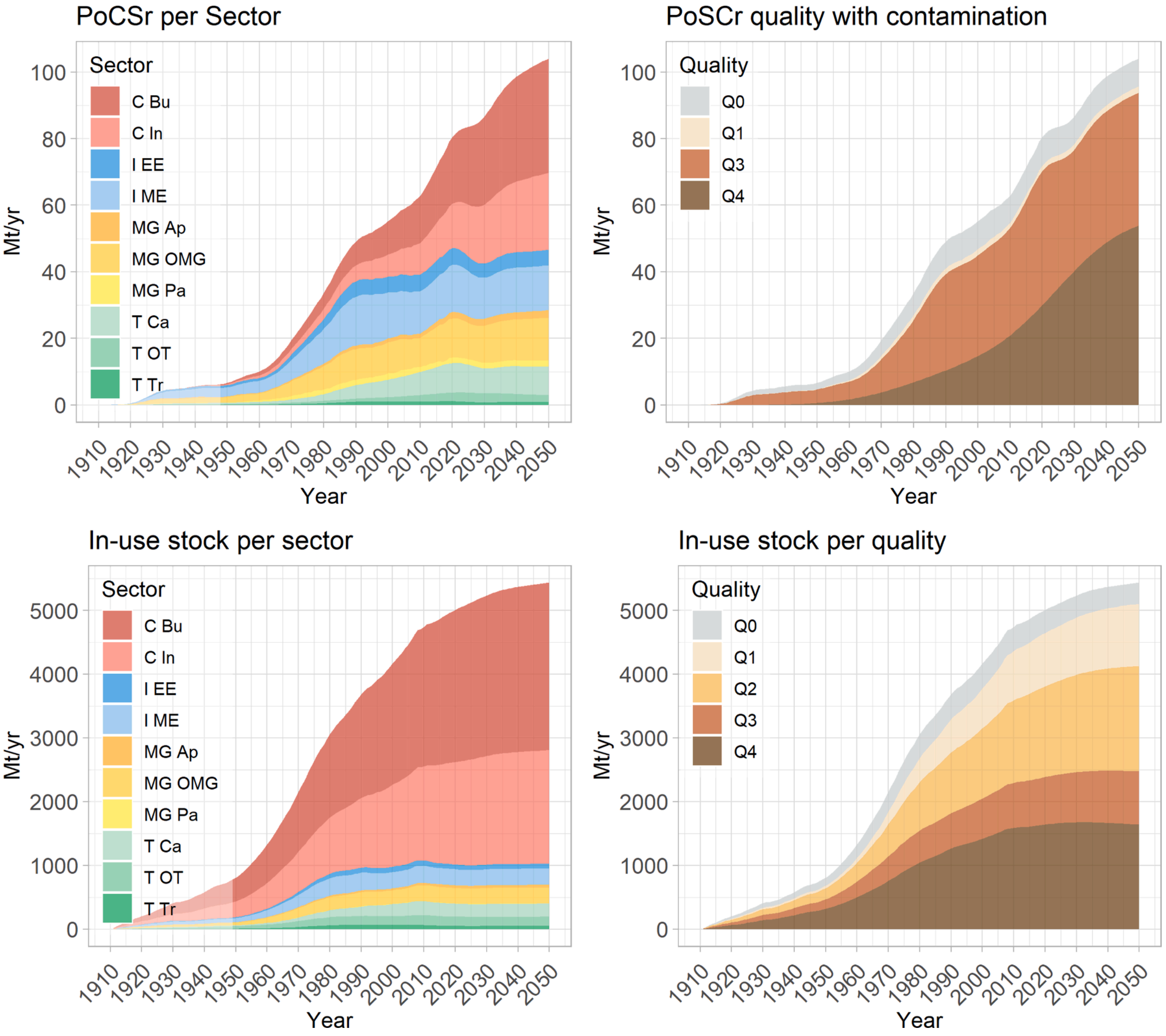

Fig. 3. Post-consumer scrap recovered (PoCSr) with sector origin (upper left), with quality classification according to Option A (purity based on sector of origin, lower right), Option B (average purity per sector based on inputs, no contamination considered, lower left), Option C (purity of input = purity of output, upper right). The steps in quality class changes can be attributed to the sharp distinction between the quality classes, which means that if the input quality of a sector changes, the whole subsector might switch to another quality class (as e.g. MG OMG from 1992 to 1993 and I ME from 2020 to 2021, with both switching from average Q2 to Q1). Abbreviations of sectors: Construction: C Bu - Buildings, C In – Infrastructure; Industrial Equipment: I ME - Mechanical Engineering, I EE - Electrical Engineering; Transport: T Ca - Cars, T Tr - Trucks, T OT - Other Transport; Metal Goods: - MG OMG: Other Metal Goods, MG Ap - Appliances, MG Pa - Packaging.

rate, sector split (forecast from 2018 onwards)) for all options. In the following, only Option A and Option C are discussed. Fig. 5 shows the sensitivity of the core results of the study (the surplus of low purity scrap Q3 & Q4) for the most influential parameters (lifetime, sector split). The sensitivity analysis indicates that the average lifetime of the different sectors has the highest impact (up to 9.3% for option A in 2015, 4% for option C in 2009, if the average lifetime is reduced by 20%) on the surplus of low purity scrap (see Fig. 5). This can be mainly attributed to the faster backflow of low purity scrap from the Construction sector. Furthermore, the steel demand in the Construction sectors is rather decisive for the surplus of low purity scrap. An increased demand in the Construction sector of 10% would reduce the scrap surplus by 2.1% and 4% (about 4 Mt/yr and 7.8 Mt/yr) in 2050, respectively, for Options A and C. In contrast, the export rate of ELV has little influence on the amount of surplus scrap. In the case of 20% less ELV exports, the surplus scrap quantities would only increase by less than 0.52% and 0.03% (about 1 Mt/yr and 0.06 Mt/yr) in 2050, respectively, for Options A and C.

3.6. Validation

The model was partially validated by comparing three of the model's stocks/flows (steel stock of cars, reinforcement bars in buildings, and available scrap) with independent data.

Steel stock in the Car sector (see Fig. 6, upper part): Bottom-up data of registered cars in the former EU-28 was compared with the steel stock modelled for the Car sector. Until 2010, the modelled stock figures are higher than the stock determined via bottom-up data. This apparent overestimation of the steel stock by the MFA model can be partly attributed to the fact that not all cars in the stock are registered (either due to interchangeable number plates or because of non-registered vehicles kept on private property).

Reinforcement bars in buildings (see Fig. 6, middle part): The modelled stock is below determined bottom-up stock, but still within the uncertainty range. The increase is similar in both datasets. The underestimation of the modelled stock can at least partly be explained by the use of other steel products (e.g., hot rolled bars or wire rod) as reinforcement in concrete.

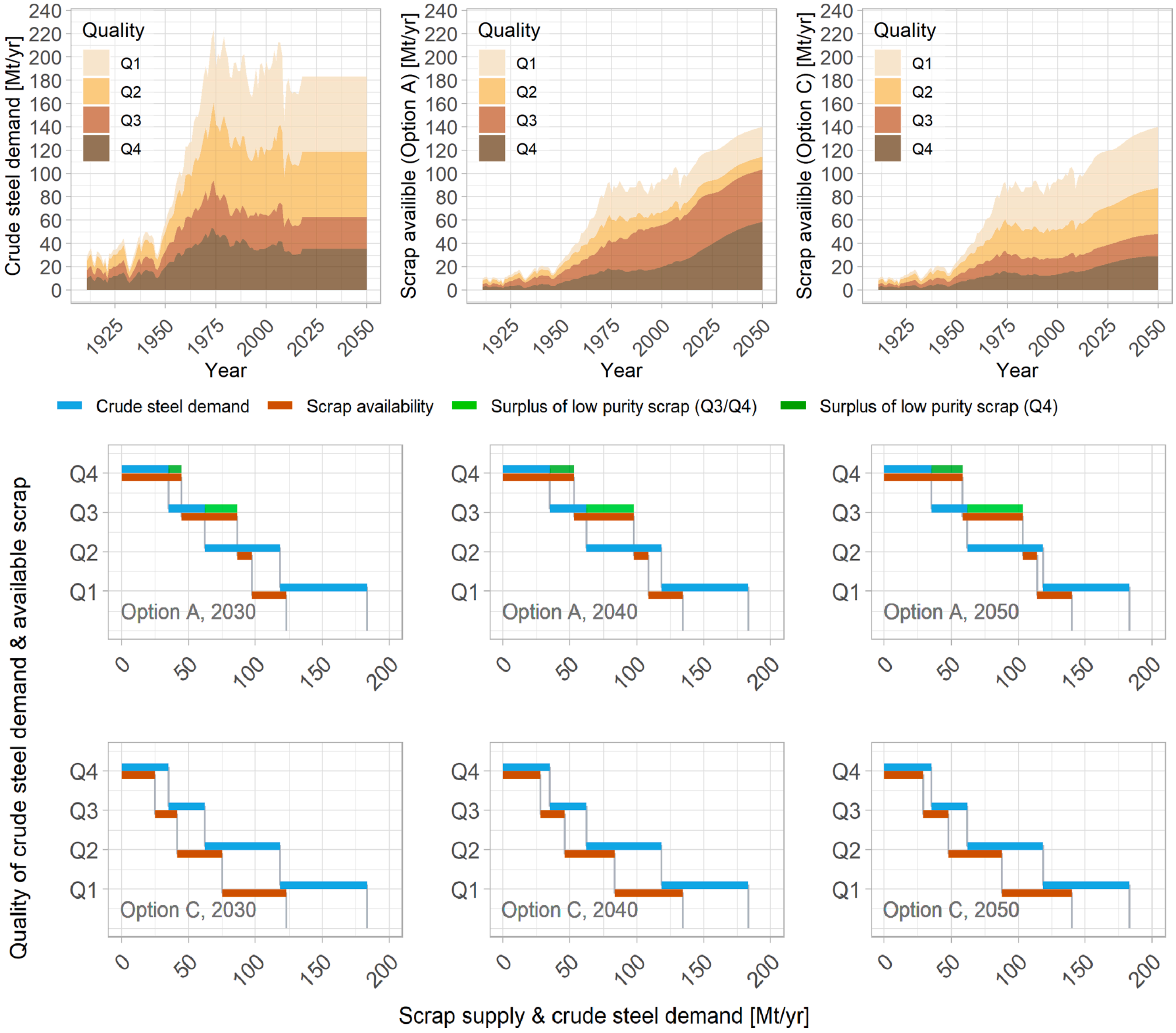

Fig. 4. upper part: Crude steel demand taking quality classes for crude steel demand into account (left), scrap available with quality classes based on Option A (middle) and Option C (right), considering Q1 to Q4, without Q0 (cast products); lower part: Material pinch analysis for the quantities and qualities (purities) of crude steel demand and available scrap in the former EU-28 for the years 2030, 2040, 2050.

Scrap availability (see Fig. 6, lower part): The increase of available scrap modelled is similar to that derived from statistics, but the model slightly underestimates the available scrap from 1950 to 1985, which can be at least partially attributed to the long average lifetimes of some steel products (up to 65 years). From 1985 to 2017, a good fit can be observed, which suggests that the model is fit for future assessment as propagated underestimates no longer influence the result.

To summarize, the approach of the various validation methods do not result in a perfect fit, but key parameters such as magnitude and the rate of change fit rather well with the model. In general, the outcomes of the comparisons verify the model approach and the data used.

4. Discussion

The top-down approach, employing the assumption of stagnant crude steel demand and constant sector splits and composition, is rather simple. It does not allow presumed saturation as well as economic and societal development to be accounted for. Still, in comparison with very sophisticated models, it performs quite well and reaches similar results in many respects. Additionally, it yields insights into future challenges regarding the quality of steel scrap and its handling:

In-use Stock: Stock assessment is not the focus of this study, but such evaluation allows - in comparison with much more sophisticated models on steel stocks (e.g., Hatayama et al. (2010); Müller et al. (2011;) Pauliuk et al. (2013b, 2013a)) - for plausibility checks. The in-use stock is dominated by steel in the Construction sector, whose share will increase even further to up to 80% (8.7 t/cap) in 2050, whereas the Metal Goods, Transportation and Industrial Equipment sectors will have similar magnitudes in 2050 (0.58 t/cap, 0.79 t/cap, 0.64 t/cap, respectively). The in-use stock will amount to about 10.7 t/cap in the former EU-28 in 2050. The stock values are below the mean results, but within the uncertainty margin for stock saturation determined in Pauliuk et al. (2013b) (Construction:10 ± 2 t/cap, Metal Goods: 0.6 ± 0.2 t/cap, Transportation: 1.5 ± 0.7 t/cap, Industrial Equipment 1.3 ± 0.3 t/cap). In comparison with other stock investigations in various regions in affluent economies (Böhmer et al., 2010; Müller et al., 2011), the results are in line with the results of total in-use stock. Furthermore, the bottom-up stock assessment for cars in use and for reinforcement bars in buildings as well as the top-down validation based on historic scrap output both validate the model results at least partially. The model also

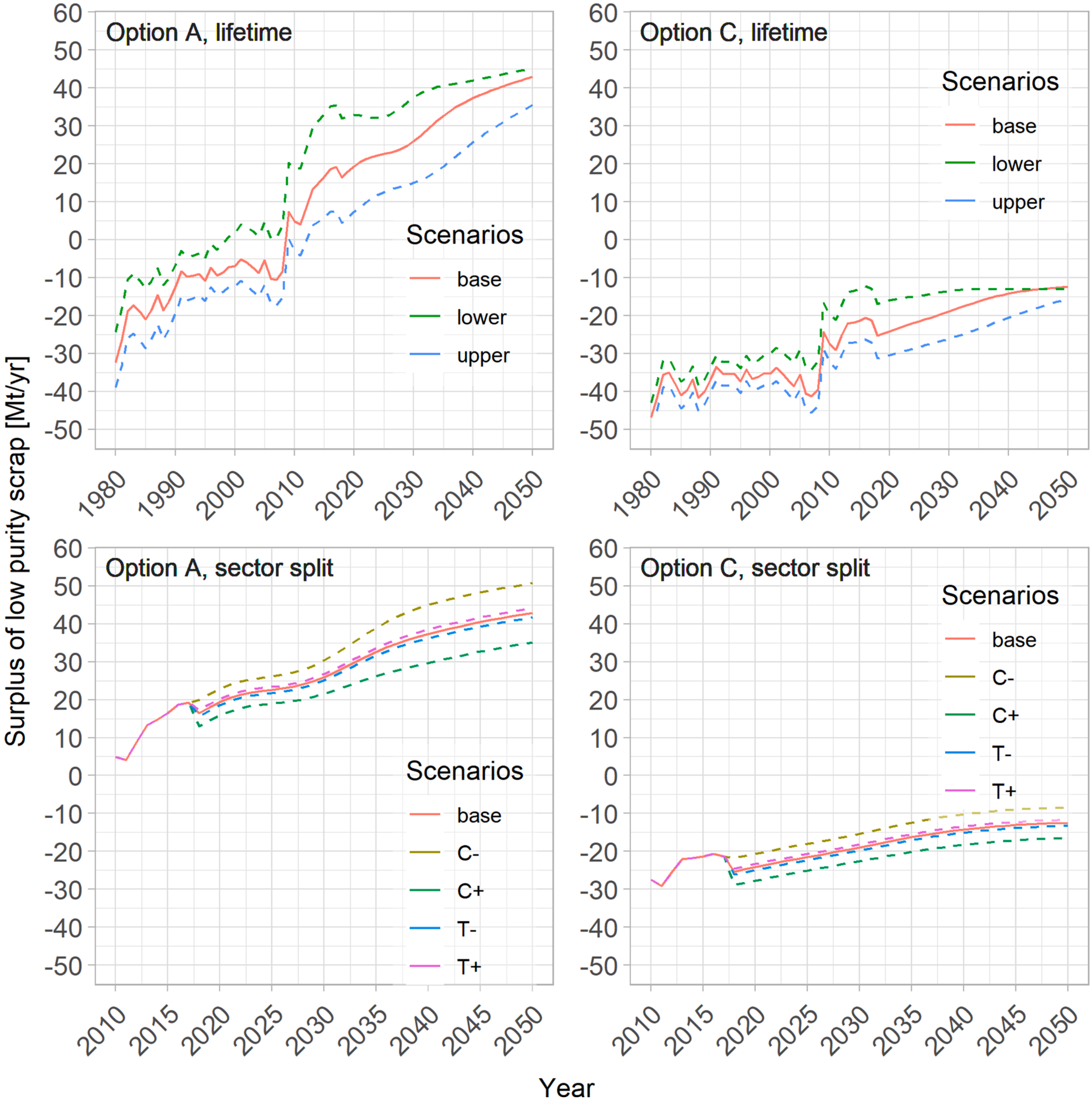

Fig. 5. Sensitivity for lifetime (±20%, upper part) and sector split (±10% for either Construction (C+/C-) or Transportation ($T+$/T-) sector, lower part) for Option A (purity of output based on sector of origin, right column) and Option C (purity of input = purity of output, left column). The reference value is the surplus of low purity scrap (Q3 & Q4, up to 0.25% of tramp elements considered) relative to the crude steel demand.

shows that for in-use stock to be saturated in the near future, crude steel demand (input into the system) and therefore steel use would have to decrease (as shown by Pauliuk et al. (2013a)). In our linear projection with constant input, the total stock (without taking population projections into account) will reach a plateau well after 2050, around 2075. That would mean a per capita stock of roughly 11 t/cap.

Scrap: The role of scrap is becoming more important. Dworak and Fellner (2021) showed with a static model that in the past (1945–2017) the composition of scrap shifted significantly from predominantly new scrap to predominantly old scrap (60% in 2017). The dynamic modelling approach comes to a similar conclusion and suggests that this trend will continue for several decades, even if less intensely (see Fig. 2). In 2050, the share of old scrap reaches close to 75%. If we assume that the efficiency in steel making and fabricating of final steel products (which means less new scrap) as well as the recovery rate (which was conservatively assumed to be low in this study) of steel from end-of-life products both increase, the old scrap ratio may be even higher. Currently, low purity scrap is mainly exported and not used in the former EU-28 (Dworak and Fellner, 2021). Similarly, scrap in the range of 10 to 20% of crude steel production is net exported from the US (according to the World Steel Association, 2017; Zhu et al., 2019). As global steel production volumes are still increasing, demand for scrap, regardless of the quality, is still high, especially in emerging economies. Therefore, the exported scrap was and is currently used to substitute primary raw materials abroad (as shown by Dworak and Fellner (2021)). But it can be expected that the demand for external low purity scrap will diminish since the emerging economies will also reach saturation at some point and generate their own post-consumer (low purity) scrap.

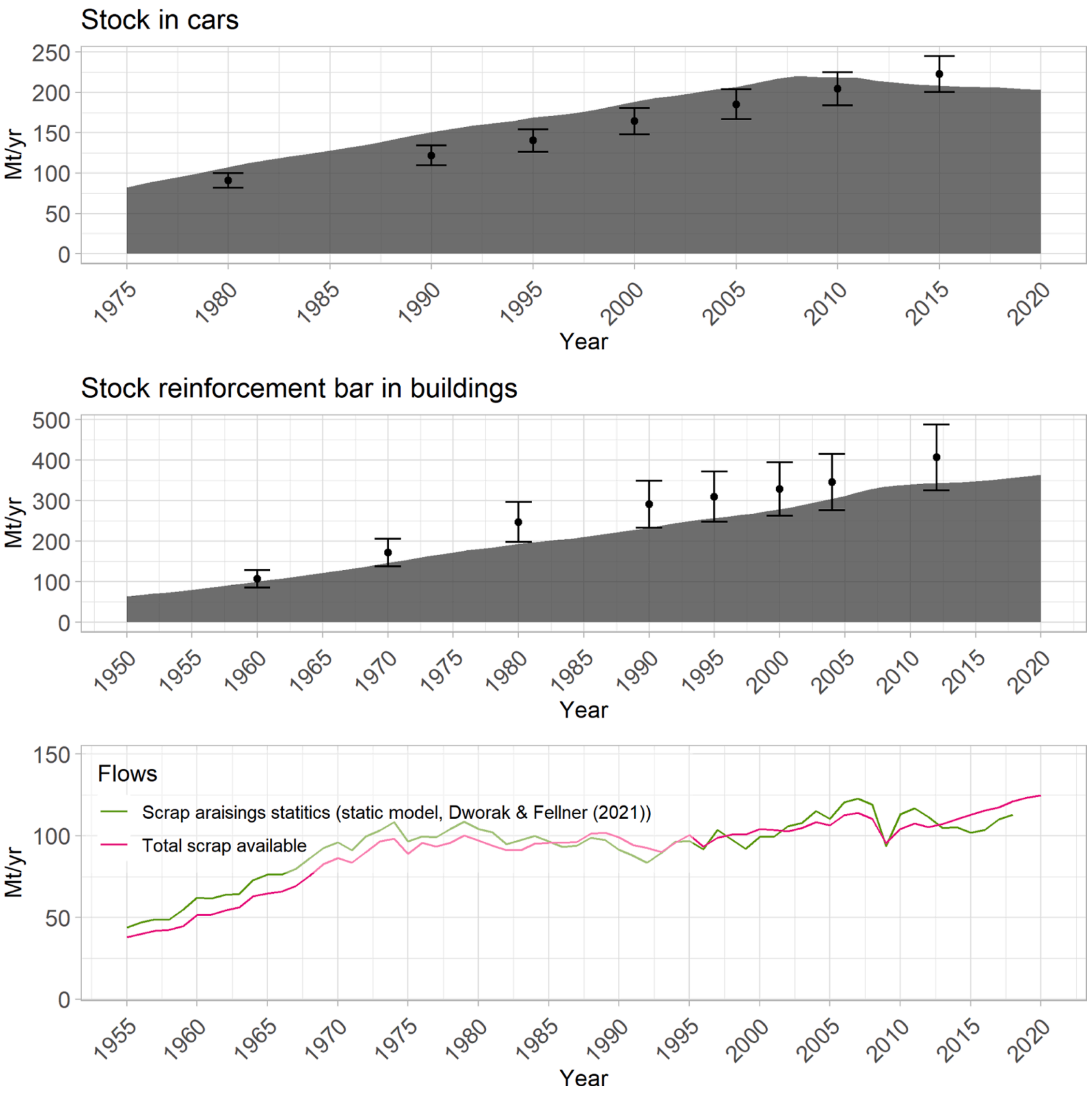

Fig. 6. Validation of model, upper part: validation of in-use stock in the Car sector, modelled stock compared with bottom-up data on cars in use; middle part: validation of in-use stock of reinforcement bars in the sector Buildings, modelled stock compared with data on housing space statistics; lower part: validation of modelled scrap available with top-down data based on scrap statistics.

Hence, the handling of steel scrap must undergo changes for it to be profitably employed in steel production. For one, by diluting available scrap with crude steel from primary sources, the surplus of low purity scrap could be balanced until 2040, potentially. Still, one of the main challenges remains the common lack of knowledge as regards the composition of single scrap batches. To potentially reach the goals of the circular economy package, alloy sorting is crucial (Daehn et al., 2019). The latter is also of importance to reduce the climate impact of the European steel industry. Utilizing the predicted 1000 Mio tons of surplus scrap (sum until 2050) domestically would reduce the EU's CO2 emissions by 560 to 2360 Mio tons (estimate based on (Damgaard et al., 2009)) and at the same time reduce the import of almost 1300 Mio tons of iron ore (estimate based on (Broadbent, 2016)). For end-of-life vehicles, alloy sorting was investigated by Ohno et al. (2015) and Willmann et al. (2017) and seems to have the potential to sort the available scrap sufficiently enough to close the steel cycle while simultaneously allowing present alloy elements to be preserved. Moreover, low purity scrap could be diluted with high purity resources (e.g., steel from primary sources, iron sponge) to exhaust the dilution potential. Proper alloy sorting would facilitate efforts in this direction as the composition of specific batches of scrap would come to be known better and could be applied accordingly. Further, several technical interventions could be considered to (i) reduce the tramp element content from the melt (e.g., sulphide slagging or vacuum distillation for Cu removal); (ii) improve processes for more tramp element tolerance (e.g., direct strip casting (Spitzer et al., 2003)) (iii) redesign materials for higher tramp element tolerance (e.g., counterbalance negative properties by adding interacting alloys (Daigo et al., 2021)).

For policymakers the results potentially imply that in order to foster a higher domestic circularity of steel, a tax on exports of scrap might need to be considered since valuable resources are more likely to be domestically recovered and alloy sorting technologies or technical innovations in the production process (reducing tramp element content in the melt) may only pay off with the help of such a measure.

5. Conclusion

We investigated the European steel cycle with a practicable dynamic MFA model to assess scrap availability until 2050 with regard to quantity and quality, and validated it partially. The top-down approach, with its assumption of stagnant crude steel demand and constant sector splits and composition, is straight forward and can be applied without taking many variables, such as presumed saturation or economic and societal developments, into account. Still, it offers robust results with the data available.

The share of post-consumer scrap is increasing in overall scrap composition (up to 75% of total scrap available). This scrap is mostly of low purity, especially if no countermeasures (e.g. alloy sorting) are put in place. Low purity scrap (tramp element content above 0.25%) is therefore gaining in importance as regards overall scrap composition (post-consumer, production & forming and fabrication scrap). The potential scrap rate (including old and new scrap) for crude steel production will reach more than 75% in 2050. Seen from a circularity point of view, this seems to be very good news. But if scrap continues to be handled as it usually is at the moment (e.g., little sorting, little dilution), the quality requirements for crude steel in the EU will not be able to be met and the European steel industry will also in future have to produce more than 45% of crude steel from primary sources to satisfy the qualitative (purity) requirements of crude steel, which is approximately the rate currently attained. This means that an increase in the scrap rate is not achievable under current practices, while simultaneously the amount of post-consumer-scrap is constantly increasing.

CRediT authorship contribution statement

Sabine Dworak: Conceptualization, Data curation, Investigation, Formal analysis, Visualization. **Helmut Rechberger:** Supervision, Writing – review & editing. **Johann Fellner:** Conceptualization, Supervision, Data curation, Writing – review & editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.106072.

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