



Full length article

Supply chain integration strategies and circularity in the European steel industry

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ABSTRACT

As the environmental mindset became increasingly present in the steel industry, so did the concerns with the developments of its market. In an attempt to address both sides of this challenge, this article aimed at identifying how the implementation of different Supply Chain Integration strategies oriented towards raw material self-sufficiency and resource ownership retention could affect circularity. The European steel industry was used as case study and the effects of closing material loops via Supply Chain Integration were tested by running simulations on an integrated Life Cycle Assessment and System Dynamics model. The results brought to light that different approaches can be environmentally and strategically promising, as well as able to drive improvements in raw material self-sufficiency and in resource ownership retention. Noteworthy were the adoption of vertical hedging strategies on the supply side, and of horizontal hedging strategies on end-of-life for either recycling, refurbishing or repair and maintenance services.

1. Introduction

Since the Industrial Revolution, steel has been present in almost all aspects of modern daily life (Worldsteel Association, 2012a,b; Beddows, 2014). Its life cycle begins in the iron ores extracted from open pit or underground mines and often ends as either part of long service life infrastructure or as recyclable scrap (Warrian, 2012; Vaclav, 2016).

In the last couple of decades, steelmakers worldwide have been giving increasing attention to the environmental aspects of their products' life cycles, notably in their end-of-life (EoL) stage (D'Costa, 1999). Today, approximately 70 % of European steel is recycled and most byproducts of its production process are serving as resources to other industries (Yellishetty et al., 2012; Worldsteel Association, 2017a).

And when compared to the 1980s, the average steelmaking process now consumes 50 % less energy, and helps final products such as vehicles to become less fuel intensive, to the point of being environmentally competitive enough to give plastics and aluminum manufacturers an additional reason to worry (Warrian, 2012; Worldsteel Association, 2013; Vaclav, 2016).

Nevertheless, the expansion of global markets and the geopolitical circumstances during the same period gave Chinese, Russian, Brazilian and Indian steelmakers the opportunity to grow their market shares due

to increasing urbanization and industrialization demands, all the while developed economies have seen stabilize it or decrease, as seen in Fig. 1 (Ernst and Young, 2014, 2015).

While the former focused on acquiring know-how to maximize output towards price competitiveness, the latter – most notably North American and Western European steelmakers – saw the need for restructuring as an opportunity to focus on quality and portfolio specialization (D'Costa, 1999; Worldsteel Association, 2013).

The influence of technology as a driver of competitiveness has not been left aside, though: research and development still play a major role in the steel industry, helping reduce production costs and improve efficiency (Reppelin-Hill, 1999). But the once aggressive efficiency-oriented strategies adopted during the post-War decades were gradually replaced by complex and nuanced assessments of quality and portfolio (Vaclav, 2016; Worldsteel Association, 2017b; Nuss and Blengini, 2018).

This was particularly necessary after the push by Japan, South Korea and Germany to rejoin the steel market after the Second World War, which left the United States, the United Kingdom and the remaining Western European steelmakers temporarily lagging behind (Vaclav, 2016; Yellishetty et al., 2012; Warrian, 2012).

It was when wages were raised in developed countries, however, that steelmaking for scale flourished in the developing nations

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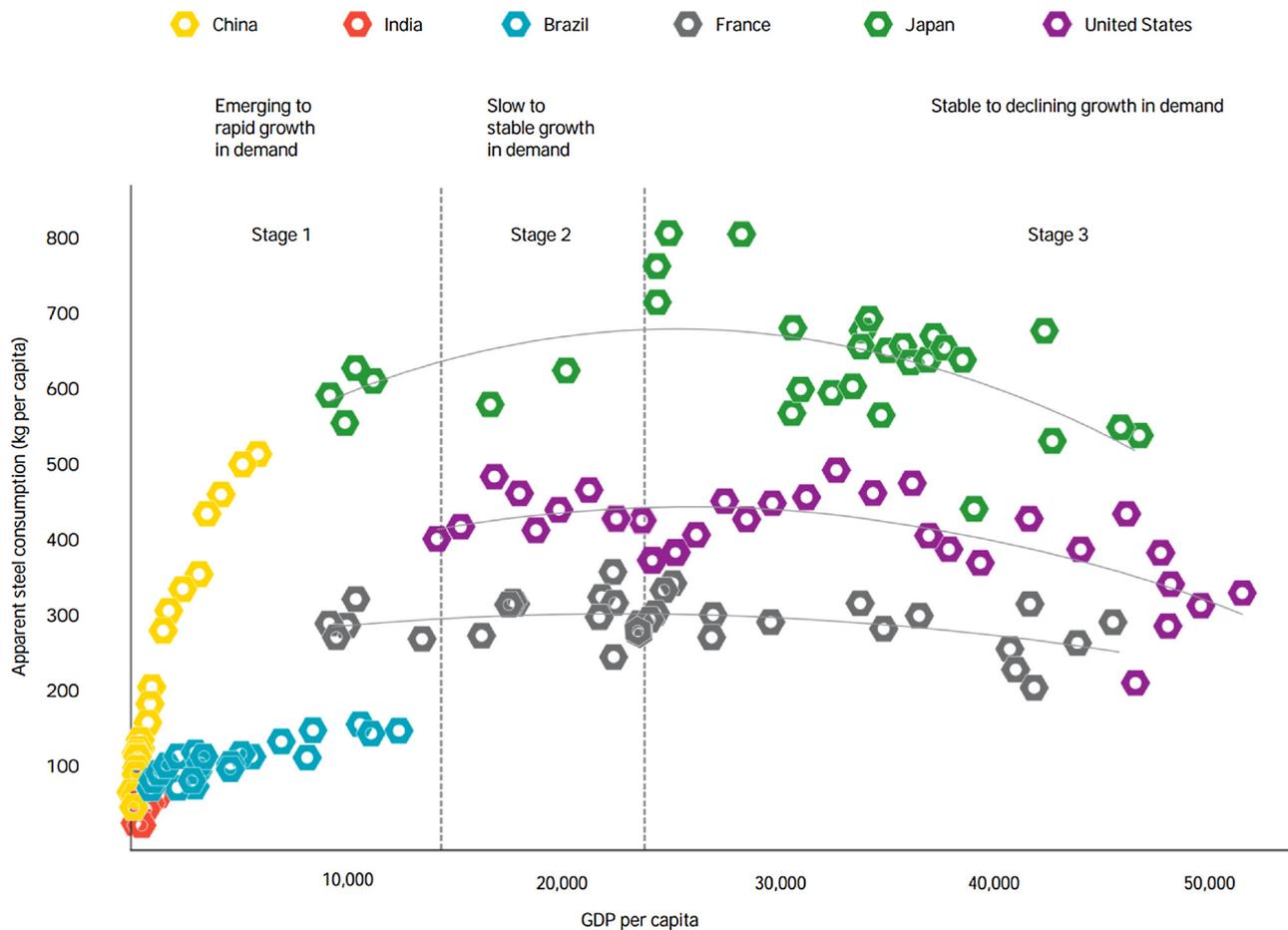


Fig. 1. Apparent steel consumption over time, as function of GDP (adapted from Ernst and Young, 2014).

mentioned above (D’Costa, 1999; Ernst and Young, 2015, 2017). But wages alone did not cause this shift: over-regulation, increasing tax burdens and prior currency exchange issues also posed as obstacles for North American and Western European steel to regain their former levels of market share, reducing their competitiveness in the global market (Yellishetty et al., 2012; Warrian, 2012).

Previously aggravated by a series of drops in prices from international competitors, North American and Western European steel products today see prices rise again and with it the uncertainty regarding the futures market (Demailly and Quirion, 2008). Consequently, investments slowed down and the deployment of financial protection strategies becomes commonplace, especially when facing China’s substantial hold on market shares (Arik and Mutlu, 2014).

Given these circumstances, one could think that North American and Western European steelmakers would then focus less on capacity and more on differentiation, especially when operating at particularly higher costs than their competition from abroad. This is often not the case, though: it is common among these steel industries for capacity to be used as strategic means to flood the market at the expense of profit, discouraging new entrants and foreign exporters – a move deemed by many specialists as economically unsustainable (Beddows, 2014; Ernst and Young, 2015).

With that in mind, and having realized that cutting costs on manpower alone could stir the European political scene against the steel industry, Supply Chain Integration (SCI) became an increasingly important strategy for European steelmakers to avoid compromising shareholder value (Warrian, 2012).

Thus far, the use of SCI strategies by European steelmakers has given special attention to resource ownership retention and raw material self-sufficiency, both of which are capable of mitigating risks

associated with production and sourcing by closing material loops along the supply chain (Ernst and Young, 2015).

In light of these developments, this article aimed to identify how the implementation of different SCI strategies focused on raw material self-sufficiency and resource ownership retention potentially affect circularity. To do so, five different scenarios that close material loops within European boundaries were tested by running simulations in the integrated Life Cycle Assessment (LCA) and System Dynamics (SD) model developed by Pinto et al. (2019) – further described in Section 2.

1.1. Supply chain integration in European steel today

Supply Chain Integration is most commonly defined as the strategic collaboration within a supply chain, among its stakeholders, in order to improve the management of intra- and inter-organization processes (Shou et al., 2017; Lii and Kuo, 2016; Wiengarten et al., 2016; Van der Vaart and Van Donk, 2004, 2008).

As per the North American National Research Council’s Committee on Supply Chain Integration (NRC, 2000: p. 27), “an integrated supply chain can be defined as an association of customers and suppliers who, using management techniques, work together to optimize their collective performance in the creation, distribution, and support of an end product”.

SCI initiatives aim at effectiveness and efficiency throughout the chain, encompassing decisions regarding material flows, resource management, services, information and capital (Bowersox et al., 1999; Sengupta et al., 2006). These initiatives often driven by the main manufacturer in the supply chain, which can choose to focus on integrating processes with its supplier side, with its customer side, or both, always depending on what said company perceives as its key

strategic assets (Bowersox et al., 1999; Wiengarten et al., 2016; Shou et al., 2017).

To properly address costs, performance and risks, the integration itself requires intense exchange and cooperation with the involved stakeholders and subcontractors and can be approached in three different manners (Vickery et al., 2003; Wiengarten et al., 2016; Van der Vaart and Van Donk, 2008; Gunasekaran and Ngai, 2004):

- a) Horizontal integration – in which information, strategies, decisions and flows are shared but ownership and management of each company in the supply chain remain independent or decentralized;
- b) Vertical integration – in which capital, ownership and management are also shared or centralized by means of mergers, acquisitions and equity efforts; or
- c) Hedging – which can occur either vertically or horizontally, but focuses mostly on ensuring profitability across markets, by having different branches of a supply chain’s operation be more or less active than others so as to adjust to market variations.

European steelmakers are often the key manufacturers in their respective supply chains and tend to focus on supplier side integration – mostly vertically – due to the commoditization of steel in the global market. Still, it is not uncommon to see European steelmakers with horizontal customer side integration, especially when providing goods to the automotive or to the heavy transportation industry (Meixell and Gargeya, 2005).

Hedging integration occurs mostly vertically and most commonly on the supplier side, with European steelmakers controlling many different operations abroad in order to compensate for ore prices, logistical expenditures, currency exchange rates and geopolitical circumstances when deemed necessary (Gardner and Buzacott, 1999).

Table 1 summarizes examples of different integration approaches used in the supply chains of steelmakers operating in Europe, as made available on their respective institutional websites.

Vertical or vertical hedging SCI strategies that go beyond European borders and involve assets in developing nations happen mostly for the transfer of unspecialized portfolio capacity or for the decentralization of sourcing (D’Costa, 1999). The capacity and the capital that remain in Europe then tend to be gradually converted into specialized products better aligned with horizontal integration on the customer side, or into higher added-value products that contribute to the reduction of overall steel intensity (Chevalier, 1995; Yellishetty et al., 2012; Shou et al., 2017).

Although hedging-oriented integration would be theoretically preferable to vertical integration due to the latter’s vulnerability to prices, logistics, resource availability and international trade agreements, many successful examples of these types of integrations currently exist. In specific cases, even companies based in developing countries have managed to find profitability in the other direction: by vertically integrating into Europe (D’Costa, 1999; Ernst and Young, 2014, 2015; Beddows, 2014).

On what regards horizontal integration, there seems to be a *quasi-*

unanimity on the argument that it is largely preferable on the customer side – as corroborated by results from the industry –, but that nowadays it would be naïve to focus on this side alone (Worldsteel Association, 2013; Beddows, 2014; Chevalier, 1995; Świerczek, 2014).

In order to exemplify the multiple possible outcomes of different SCI approaches, Fig. 2 shows the results of steelmakers during the 2009–2013 period in relation to their raw material self-sufficiency. In it, one can see that industries whose shareholders opted for vertical integration but did not necessarily find a recipe for success, regardless of capital mobilization (e.g. MMK and Sail).

It also shows that industries that were strategically oriented towards high added-value products and portfolio specialization can generate very different results even when focusing on horizontal integration with some of their customers (e.g. ThyssenKrupp and Hyundai Steel).

Among the outliers – CSN, JSPL, CAP and Severstal –, only Severstal’s operating margins can be associated with integration strategies favoring self-sufficiency, as seen in Table 1. The remaining outliers had their operating margins boosted by unorthodox business practices or favorable local political circumstances. In all of these cases, nevertheless, since 2013, their respective landscapes have changed and their operating margins have gone down towards the global average.

Additionally, the role of governments can be either constructive or destructive, especially towards vertical integration. Trade policies and mining concessions can make or break the cost effectiveness of geographically decentralizing a steel supply chain, potentially requiring subsidies during the capital mobilization phase (Worldsteel Association, 2013; D’Costa, 1999; Wiengarten et al., 2016).

Even though integrating a supply chain on the customer side may require investments that can substantially affect liquidity, cash flow and indebtedment, governments tend to have lower impact on them, often limited to final product taxation (Ernst and Young, 2014, 2017; Beddows, 2014).

To ensure that the discussions brought to light thus far do not drift away from environmental and resource related concerns, the next section introduces the concept of circularity as derived from Circular Economy (CE) and positions it as a driver for SCI to close material loops in European supply chains.

1.2. SCI towards circularity: closing material loops

Circular Economy aims to promote a transition from linear supply chains towards ones imbued with circularity, arguing that every economic activity should consider (Park et al., 2010; Ellen McArthur Foundation, 2014a, 2015a, 2016, 2017; Haas et al., 2015; Winans et al., 2017):

- a) using wastes and byproducts as inputs;
- b) switching to renewable and clean energy sources;
- c) managing the environmental costs and effects of the operation;
- d) safely reinserting end-of-life materials into either other economic activities or back into the biosphere; and
- e) designing outputs in such a way that facilitates collection,

Table 1
Examples of supply chain integration in steel supply chains.

	Mining	Steelmaking	Metalworking	Customer	End-of-Life or By-product
ArcelorMittal	Own + VI + VH	Own + VI + VH	Own	HI	Slag (Own)
SSAB	VH	Own + VI + VH	Own + VI	HI	Repair (VI) + Slag (Own)
SIJ Group	–	Own + VI	Own + VI	–	Scrap (VI)
Severstal	Own + VI	Own + VI	Own + VI	–	–
Hyundai Steel	VH	Own + VI	Own + VI	HH + HI	Slag (Own)
Voestalpine	VH	Own + VI	Own + VI	HI	Slag (Own)
ThyssenKrupp	VH	Own	Own	HI	Slag (Own)
Tata Europe	VH + VI	Own + VI + VH	VI	HH + HI	Slag (Own)

VI = Vertical integration; VH = Vertical hedging; HI = Horizontal integration; HH = Horizontal hedging.

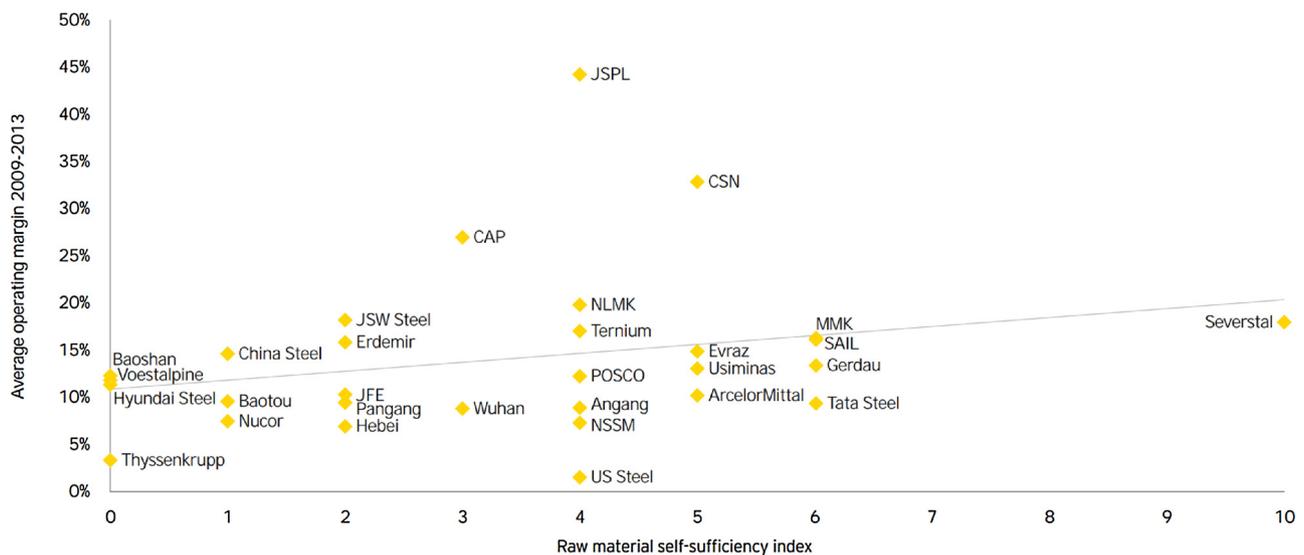


Fig. 2. EBITDA margin vs Self-Sufficiency (Ernst and Young, 2014).

separation, recycling, refurbishing, repair for reuse, redistribution, maintenance and sharing throughout their lifespans.

CE begins by classifying material resources as either biological nutrients or technical nutrients. Biological nutrients originate in and should eventually reintegrate the biosphere; technical nutrients, on the other hand, are those biological ones that were transformed by economic activities and that circulate in the economy until a product's end-of-life phase. At this point it would be ideal to have it return to its biological form and rejoin nature harmlessly (Pearce and Turner, 1989; Seager and Theis, 2002; Korhonen, 2004; Ellen McArthur Foundation, 2012, 2013, 2014b; Liao et al., 2012; Tukker, 2015; Geissdoerfer et al., 2017).

Fig. 3 illustrates these principles as applied to the steel industry. In it, it is possible to see that despite the traditional linear flow of manufacturing steps, there are multiple opportunities for technical nutrients to remain longer in circulation.

One way of looking at CE is by understanding how materials enter, flow and eventually leave the economy (European Commission, 2018). Whenever a material is reinserted into the economy during its use/consumption phase or its end-of-life phase, its flow is considered to have become circular – instead of linear (Zore et al., 2018; Niero and Kalbar, 2019).

The more a material is imbued with circularity, the more value it provides during its lifespan and the less pressure is put on nature for new resources (Pauliuk, 2018; Niero and Kalbar, 2019). Material such as steel have theoretically infinite circularity due to their recyclability characteristics, still, its full potential is yet to be achieved (Worldsteel Association, 2015a; Ellen McArthur Foundation, 2013).

Since in 2012 the European Union and its members have committed to using CE as their driving economic model, continuously increasing attention to resource-efficient measures that lead to regenerative progress towards nature is to be expected (UNEP, 2011; European Commission, 2012; Su et al., 2013; Kahle and Gurel-Atay, 2014; Ellen McArthur Foundation, 2015b; Gregson et al., 2015).

With this in mind, improving circularity can be achieved by developing Closed Loop Supply Chains (CLSC), focusing precisely on recapturing the value of materials after their consumption or use (Govindan and Soleimani, 2016; Gaur et al., 2017; Hosoda and Disney, 2018; Lewandowski, 2016).

To do so, CLSCs can monitor and manage the flows of materials during their use/consumption and EoL phases in order to direct them back to different stakeholders in a supply chain – using reverse logistics

(RL) (Jayaram and Tan, 2010; Cardoso et al., 2013). They can also define the most effective means to reinsert those materials back into the operation, be it via reuse, repair, refurbishment or recycling (Islam and Huda, 2018; Golroudbary and Zahraee, 2015; Prosman et al., 2017).

Furthermore, deciding whether to centralize, decentralize or out-source different steps of reverse logistics can have significant impact on lead-times, raw material self-sufficiency, resource ownership retention, environmental performance, and even on demand-related risks (Braz et al., 2018; Miao et al., 2017; Bhattacharyya et al., 2017; Wang et al., 2018; Cannella et al., 2016; Hey, 2017; Xu and Wang, 2018).

Fig. 4 not only summarizes the SCI strategies introduced in the previous section, but also presents where in the European steel supply chain the authors of this article see integration strategies aimed at circularity taking place to close material loops, learning from both ends of the strategic spectrum.

As discussed earlier, vertical or hedging integration strategies tend to be more effective in dealing with raw material self-sufficiency and resource ownership retention (Van der Vaart and Van Donk, 2004). Thus, choosing these approaches would better address material loops that go as far back as possible in the European steel supply chain, to the point of fully or partially replacing primary inputs (Wang et al., 2018; Prosman et al., 2017).

Considering that the recycling and refurbishing of end-of-life steel products and the recycling of steelmaking byproducts often occur outside of the steelmakers' realm of direct control, vertically integrating such activities could give steelmakers increased ownership of a raw material alternative to iron ore (Prosman et al., 2017; Wang et al., 2018). In the long-term, it could even push the operation away from iron ore as a whole due to either technical or economic scarcity of high-grade iron ores (Pinto et al., 2019) and, depending on the characteristics of the installed capacity, potentially risk overall output and force portfolio migration (Prosman et al., 2017; Wang et al., 2018).

However less conducive to directly increasing ownership and self-sufficiency, hedging these activities would enable ore-based operations to have a finer control over inputs from scrap or byproducts, which could allow for efficiency or cost related adjustments depending on market circumstances. Nevertheless, the more horizontal the hedging integration, the stronger third-party reverse logistics become as a decision-making factor and the least favorable its environmental performance (Cannella et al., 2016; Xu and Wang, 2018; Cardoso et al., 2013).

When it comes to the collection, sorting, repair for reuse, maintenance, and redistribution of technical nutrients – as seen in Fig. 3 –

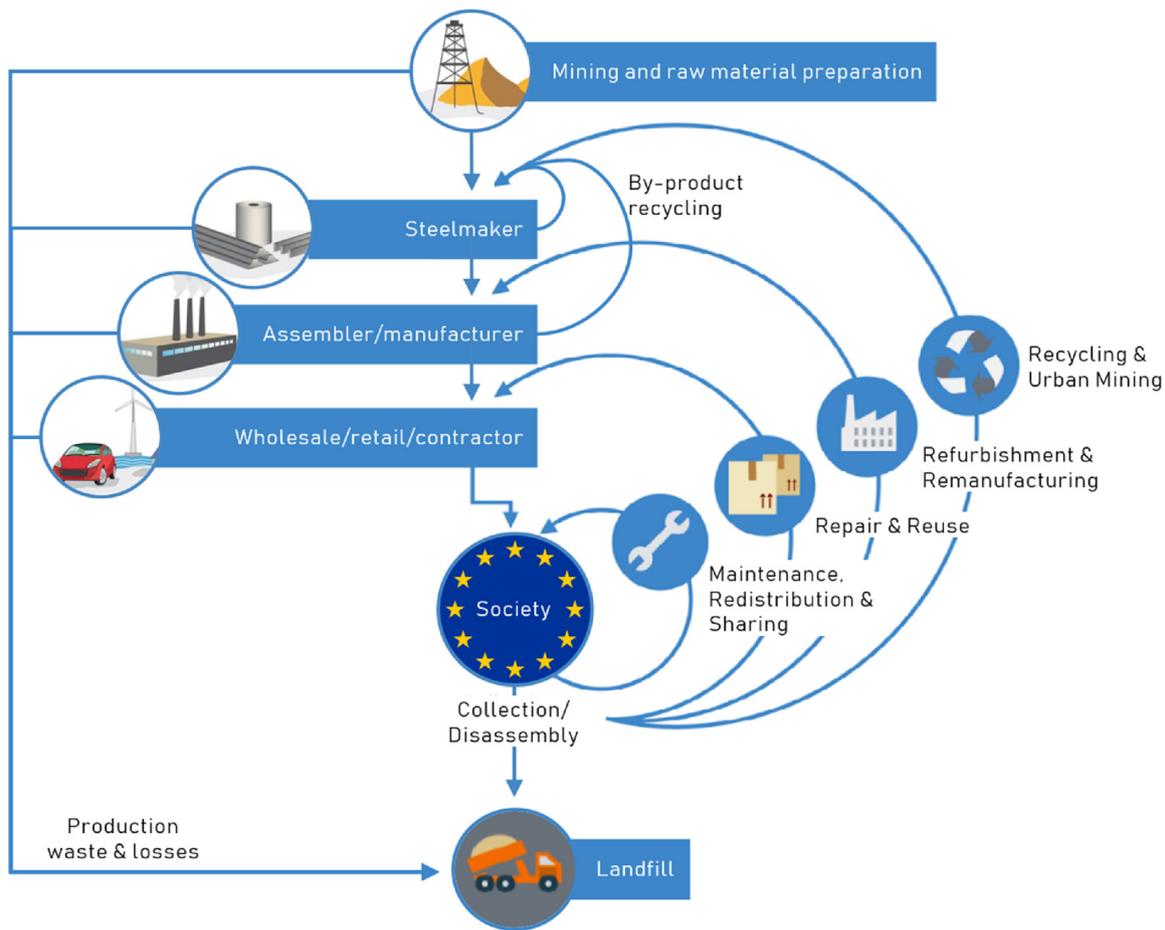


Fig. 3. Circular Economy framework applied to the steel industry (Pinto et al., 2019).

steel products in end-of-life do not configure a direct input to steel-making, but in fact reducers of overall steel demand (Pinto et al., 2019). Furthermore, business-wise, these activities stray away from the main scope of steelmaking and closer to the service sector. As such, vertical or hedging integration strategies for these processes would pose as significant investments with questionable returns (Schultmann et al., 2006; Bhattacharyya et al., 2017; Golroudbary and Zahraee, 2015).

Horizontally integrating these services, however, could be strategically advantageous from the perspective of long-term resource ownership retention, reverse logistics and environmental performance. Although not directly controlling these activities, a steelmaker could (a)

better keep track of its steel as it moves through the economy – ideally recycling it back into the same operation –, (b) reduce reverse logistics costs by having influence or leverage over its decision-making, and (c) actively manage the amounts of EoL steel that flows between servicing and steelmaking (Wang et al., 2018; Schultmann et al., 2006; Bhattacharyya et al., 2017; Islam and Huda, 2018).

Even when direct competitive advantage cannot be obtained due to regulatory frameworks regarding pricing, the benefits of resource ownership retention for a theoretically infinitely recyclable material are clear from the environmental perspective. It is to say that, if CE would rather reduce the overall consumption of natural resources, it would be

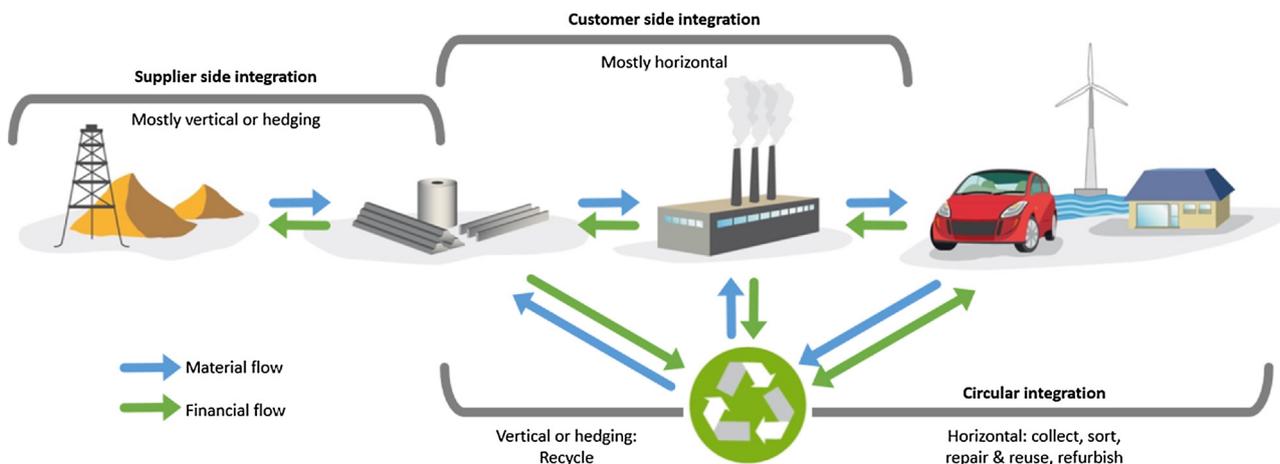


Fig. 4. Supply chain integration approaches considered by the authors.

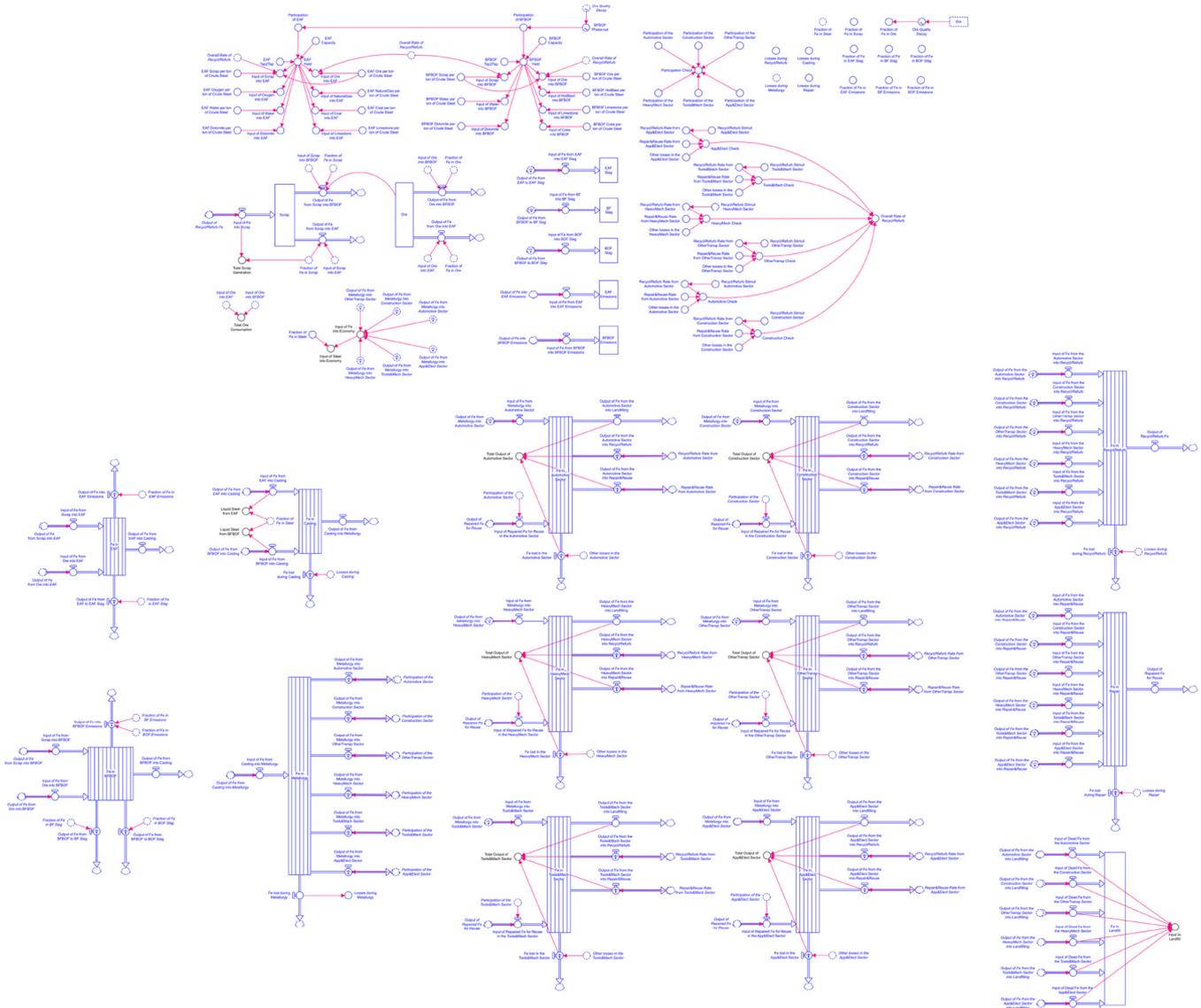


Fig. 5. Iron module's flow chart interface diagram.

strategically interesting to have as much control as possible over the circulation of the resources already supplied to the economy so as to accrue the most value before reinsertion into the biosphere is necessary (Schenkel et al., 2015; Ellen McArthur Foundation, 2015a).

2. Methodology

Given the ensemble of aforementioned developments facing the European steel industry, the authors deemed the following question worthy of exploration: how can the implementation of different Supply Chain Integration strategies focused on resource ownership retention and raw material self-sufficiency affect circularity?

In order to answer this question, the authors looked inside the Industrial Ecology toolbox and identified Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) as potential methodological candidates. However, neither LCA nor MFA independently provided a holistic view of the dynamics at play in the European Steel Industry in the long-term.

In the search for a solution, the authors identified multiple situations in which LCA and System Dynamics (SD) could benefit from working together and decided to pursue this approach. A more detailed description of this integration attempt – from conception to delivery –

can be found in Pinto et al. (2019) – an open access publication.

The present article made use of said integrated LCA and SD model developed by the authors in Pinto et al. (2019), which has been verified to successfully address the two main methodological dilemmas that existed so far when attempting to use LCA and SD together: data aggregation levels and data output formats. This was made possible by bringing the entire LCA methodology into the SD modelling environment, resulting in a model not only capable of reproducing the results of previous studies that used LCA or SD independently, but also of creating a win-win integration in which both benefit from each other (Pinto et al., 2019).

Unlike the aforementioned publication – in which the goal was to use the European Steel Industry as a case study to validate and verify the model's capabilities and reliability –, however, the present article focused on performing simulations and testing the effects of different Supply Chain Integration strategies as means to close material loops in European steel supply chains.

2.1. Case study and model

The European Steel Industry was once again chosen as case study due to its ongoing transition towards environmentally friendlier

Table 2
Summary of data inputs.

Type	Variable	Unit	Sources
EAF Inputs	Scrap, Oxygen, Natural Gas, Coal, Limestone, Dolomite, Water, Ore	kg/kg of steel	Shamsuddin (2016); Worldsteel Association (2012a, b, 2017b, c), European Union (2011); Madias (2013); Cullen et al. (2012);
BFBOF Inputs	Ore, Hot Blast, Scrap, Water, Limestone, Coke, Dolomite	kg/kg of steel	Yellishetty et al. (2011); EUROFER (2017a)
Typical Chemical Compositions of the Inputs	Scrap, Ore, Coke, Natural Gas, Coal, Dolomite, Limestone, Hot Blast	%	MINDAT (2018); WEBMINERAL (2018)
Typical Compositions of Steel Alloys, as Outputs	UNS S30400, UNS S31600, UNS S43000, UNS S17400, UNS S32205, UNS S40900	%	Bringas (2004)
Typical Slag Composition Ranges	EAF Slag, BF Slag, BOF Slag	%	Yildirim and Prezzi (2011); Adegoloye et al. (2016); EUROSLAG (2018)
Typical Composition Ranges of Emissions to the Atmosphere	EAF Emissions, BF Emissions, BOF Emissions	%	Ferreira and Leite (2015); Ramírez-Santos et al. (2018); Uribe-Soto et al. (2017); Schubert and Gottschling (2011)
Stocks in Use	Automotive, Construction, Tools & Machinery, Appliances & Electronics, Heavy Mechanical Equipment, Other Transportation	tons	Pauliuk et al. (2013); European Commission (2017)
Participation of Economic Sectors in Steel Demand		%	Worldsteel Association (2017b)
Typical Lifespan and Service Life of Steel per Economic Sector		years	Cooper et al. (2014), European Commission (2017)
Recycling and Refurbishment Rates per Economic Sector (<i>business as usual</i>)		%	NFDC (2012); EUROSTAT (2018); Björkman and Samuelsson (2014); BIR (2015); Panasiyk et al. (2016); EUROFER (2017b); CEDED (2017); Terörde (2006); Eckelman et al. (2014)
Repair and Reuse Rates per Economic Sector (<i>business as usual</i>)		%	NFDC (2012), EUROSTAT (2017), Dindarian and Gibson (2011); Truttmann and Rechberger (2006); Bovea et al. (2016); Kissling et al. (2013); CEDED (2017); RREUSE (2012); Eckelman et al. (2014); Terörde (2006)
Distribution and End-of-Life Losses		%	Pauliuk et al. (2017); Johnson et al. (2008)
Typical Cooling Water Reuse and Recycling Rates	EAF Cooling Water, BFBOF Cooling Water	%	Worldsteel Association (2015a,b), WSSTP (2013); Burchart-Korol and Kruczek (2015)

operations, to its importance for the European economy, and to its trade and market concerns on the rise of international competitors. The boundaries of the model were set at the EU28 zone, comprising the supply chains of all steelmakers members of the Worldsteel Association therein, which account for 84 % of the entire European Steel Industry.

The model focuses on the biophysical interactions that represent the average behavior of the European Steel Industry as per the aforementioned boundaries, and not on a specific firm. As described in Pinto et al. (2019), it was built in three steps: 1) Business Process Mapping (BPM) – using the BizAgi BPM software –; 2) Causal Loop Diagramming (CLD) – using the OmniGraffle software –; and 3) Flow Charting (FC) – using the ISEE Stella Architect software (ISEE Systems, 2018).

Furthermore, iron was set as the driving chemical element of steelmaking, steel scrap and iron ore were set as the key raw materials, and all chemical elements and raw materials present in steelmaking adopted two different levels of aggregation within the complex processes they were a part of. Cradle-to-gate processes were deconstructed to their simplest interactions and its inputs disaggregated down to chemical level, while gate-to-cradle processes were disaggregated to product level. This choice was made in order to give decision-making granularity without over encumbering macro-level analyses that could affect policy-making on end-of-life and circularity services.

Additionally, the material needs of the furnaces were used to define the amounts of raw materials pulled from their respective sources. This pulling behavior is present in the system until liquid steel becomes an intermediary output, point in which the system then pushes materials through the subsequent processes so as to represent the continuous casting operation. Additionally, attention was given to the feedbacks that close the loop (e.g. recycling, repair for reuse), so as to enable the system to operate under the definitions of CE and CLSC.

Modelling was approached modularly and each process was established as an individual LCA-based unit, capable of being displaced, rearranged or replicated with minimal interference in other processes or modules. This allowed for the model to be as scalable and flexible as possible for use by any stakeholder involved in a European steel supply chain, also reducing user interface cluttering.

In total, twenty modules were created – one for each chemical element involved in the steel supply chain –, all of which used a

functional unit (FU) of 1 ton of steel and were built to be structurally identical, distinguished only by specific flows necessary to properly represent their typical operational behaviors.

As exemplified in Fig. 5, individual productive processes were grouped into macro-processes based on their most common occurrence in the European steel industry, namely (a) EAF and (b) BFBOF – each encompassing sintering, pelletizing, degassing, alloying, desiliconization, desulfurization, homogenization or dephosphorization, whenever applicable; (c) Casting – which encompasses all shape, heat and surface treatments; (d) Metallurgy – which encompasses all forming and metalworking processes; (e) Economic Sectors – divided in Construction, Automotive, Other Transportation, Tools & Machinery, Appliances & Electronics, and Heavy Mechanical Equipment; (f) Recycling – which feeds back into the stock of scrap used as input for “a” and “b”; (g) Repair for Reuse – which feeds back into each economic sector according to their share in its demand; and (h) Losses & Landfills – which configure process-based sinks.

Furthermore, it is important to note that 1) due to the lack of available disaggregated data, emissions from mining, casting and metallurgy were attributed to the EAF and the BFBOF macro-processes accordingly; 2) dust and particulate matter generation were incorporated into the emissions; 3) no disaggregated emission data was found for end-of-life and circularity solutions; 4) energy flows were considered only in the form of amount of fossil fuels consumed, and not in the form of heat or electricity; and 5) no pricing, costing or speculative variables were considered.

Consequently, and as per design, inherent behaviors of the model structure include (a) the gradual transition from BFBOF production to EAF production as function of steel scrap availability, iron ore quality decrease and iron ore scarcity over time; (b) the gradual shift towards consuming steel scrap instead of iron ore as a function of iron content and availability, still respecting alloying and operational requirements; and (c) steel scrap downcycling over time due to alloying quality loss during repeated service lives.

2.2. Parameters and simulation runs

All data inputs used in this article encompassed the interval

Table 3
Summary of parameters used in the model.

Parameter	Value	Unit	Sources
EAF Tap-to-Tap Time ⁽¹⁾	0,8	hours	Shamsuddin (2016); Worldsteel Association (2012a,b, 2017b, 2017c), European Union (2011); Madias (2013);
EAF Furnace Capacity	100,00	tons	Cullen et al. (2012); Yellishetty et al. (2011b,a), EUROFER (2017a,b)
BFBOF Cycle Capacity	42,00	tons/batch	
BFBOF Productivity ⁽¹⁾	7	batches/h	
Share of EAF Production in the EU28	39,70	%	Worldsteel Association (2017b)
Share of BFBOF Production in the EU28	60,30	%	
Recoverable High-grade Iron Ore	82 billion	tons	Sverdrup and Ragnarsdottir (2014)
Recoverable Low-grade Iron Ore	92 billion	tons	
Recoverable Very low-grade Iron Ore	166 billion	tons	

As both delay and yield factor.

between 2001 and 2014, and were verified based on the criteria of the ILCD Handbook (European Commission, 2010) and of ISO14044:2006 (ISO, 2006), notably on what regarded input data coherence and reliability for Life Cycle Inventory and Life Cycle Impact Assessment. Furthermore, multiple sources were cross-checked – as seen in Table 2 – and each data point was compared to their equivalent in the Worldsteel Association's Life Cycle Inventory Study for Steel Products (Worldsteel Association, 2017c). The authors also considered adopting Product Environmental Footprint (PEF) standards (JRC, 2012), however, in its current state, it presented itself as a less consolidated and less disseminated methodology, with available applications focused mainly in the construction sector.

As per SD practice and as described in the previous subsection, deconstructing each complex process to its most simple interactions allowed for substantial disaggregation, therefore requiring minimal data parametrization. Any remaining input data that required parametrization had it performed according to the dimension and scale of the case study, using the parameters seen in Table 3.

The model was set to perform annual calculations during a period of 200 years and assume that the demand for steel focused on steel types UNS S30400, UNS S31600, UNS S43000, UNS S17400, UNS S32205 and UNS S40900. The yield of the EAF and the BFBOF production macro-processes was set according to their respective capacity and productivity, as well as to their share of participation in the EU28.

Within the realm of possible scenarios, the authors chose to run five simulations deemed feasible based on the existing field experience of the European Steel Industry – exemplified in Table 1. Each simulation run focused on testing a different integration strategy that could close material loops, as described in Table 4. All of the testing considered a phase-in period of 10 years (from 2020 to 2030) and runs were then compared to the BAU and analyzed in the next section.

In terms of modelling, the following structural adaptations were performed alongside variable manipulation in order to adequately run the aforementioned simulations:

- Runs 1 and 2: the flows of alloying elements from EAF and BFBOF slags that once left the boundaries of the supply chain towards third-party recycling were entirely brought into the supply chain and fed back into each operation respectively, following the yields in Table 4;
- Run 3: the flows of EoL steel from each sector that once left the boundaries of the supply chain towards third-party refurbishment or reuse were partially brought into the supply chain according to types of alloying, and fed back into metallurgy considering the yields in Table 4;
- Runs 4 and 5: the flows of repaired and maintenance serviced steel products from third-party services towards each sector remained outside of the supply chain's modelling boundaries but were subjected to being deterred or stimulated by the productive variables of the steelmakers, according to the rates in Table 4.

Finally, all runs – including the *business-as-usual* (BAU) one – were subjected to validation by statistical regression, one-factor-at-a-time (OFAT) analysis, mass and energy balancing, and comparison to historical data and trends.

3. Results and discussion

3.1. Vertical integration of slag recycling for recovery

As previously discussed in Pinto et al. (2019) and seen in Fig. 6, the model reproduces the long-term trends present in the data, pointing to a transition from operations based on iron ore (i.e. Blast Furnace and Basic Oxygen Furnace - BFBOF) – to those based on scrap (i.e. Electric Arc Furnace - EAF), as well as the consequent impact that such a transition would impose onto these sources of iron.

From performing simulation runs 1 and 2 it was perceived that both vertically integrating and vertically hedging slag recycling into the steelmaking operation would result in reduced consumption of iron ore, as seen in Fig. 7. In both runs, the endogenous feedback behavior of the model has also shown that the stimulus to recycle slag increases as a function of its yield, being also inversely proportional to the decay of iron content in the ore over time.

The results were naturally more substantial when regarding BFBOF operations, but better results were achieved by vertically hedging the slag recycling process. Doing so would enable multiple sources of BFBOF slag to be used as input (e.g. multiple furnace operations in a same supply chain); unlike in vertical integration, in which slag recycling would be dedicated to each operation.

More iron was recovered by the vertically integrated slag recycling solution than by the vertically hedged one – as seen in Fig. 8 –, pointing to better potential for increasing raw material self-sufficiency. Nevertheless, the flexibility to supply different furnace operations and to be supplied by multiple sources of slag favors the adoption of a vertical hedging approach if the strategic priority is to have resource ownership retention increased throughout the supply chain.

From the perspective of iron ore availability, runs 1 and 2 were also promising, as seen in Fig. 9. In both cases, the threshold of high-grade ore technical scarcity was pushed forward in time, from year 2054 (BAU) to 2062 (vertical integration) and 2072 (vertical hedging). This gives BFBOF operations prolonged viability for either raw material self-sufficiency or resource ownership retention strategies, especially considering that currently most slags are directed to third-parties for either recovery or reuse in other applications, such as built infrastructure. Furthermore, the better the slag recycling yield becomes over time, the more it could contribute as an iron input, thus lowering the pressure on ore and improving these results further.

EAF operations were affected only marginally by runs 1 and 2, mostly because (a) its operation relies minimally, if at all, on iron ore; (b) even high yield recycled slags have lower iron content than most steel scraps; and (c) the increasing availability of steel scrap already reinforces the behavior of moving away from ore.

Table 4
Summary of simulation runs.

Run	Object	Proposition	Circularity driver	SCI approach	Deployment	Variables
1	Slag	Integrate slag recycling into furnace operations, instead of transferring it to third-party recyclers	Recycling for recovery	Vertical	Direct source of iron replacing ore	Recycling yields ¹ : EAF: 20 to 60% BF: 10 to 20% BOF: 20 to 40%
2	End-of-Life steel products	Integrate steel refurbishment and repair back into metallurgy, instead of having it be performed by third-party services	Refurbishment and reuse	Vertical hedging	Hedged source of iron against steel	Yields ^{1,2} : 0 to 30%
3		Integrate third-party EoL services, stimulating or deterring its operation	Repair and maintenance	Horizontal	As tracked repaired steel	20% deterred 20% stimulated

¹ As iron content output to input ratio, linear increase during the phase-in period.

² As performed within the steelmaker's supply chain, being the remainder still performed by a third-party.

It is important to mention that slag recycling requires the management of impurities (e.g. sulfur, silicon and phosphorus) as well as of other alloying elements (e.g. chromium, zinc, copper and nickel). All of these elements could be interesting materials to be recovered along with iron, or to be individually redirected as byproducts to completely different sectors. Closing the material loops of these elements could also create new business opportunities for steelmakers, such as a new unit dedicated to supplying unnecessary or excessive elements to other industries, a business model already in place often outside of the steelmakers' boundaries.

Focusing on iron alone would provide the most benefits for sectors such as Construction, Heavy Mechanical Equipment, and Tools & Machinery, not only for their considerable demand – which vertically hedging BFBOF slag recycling in bulk could better support –, but also due to their lower alloying requirements. This could pose as a potential policy on either national or European level. Furthermore, vertical hedging in this context can also serve as a sound strategy for financial hedging against ore futures in a European steel market facing pressure from external players from developing nations.

Sectors like Automotive, Appliances & Electronics, and Other Transportation (especially aviation and aerospace), on the other hand, could benefit from vertically integrated EAF slag recycling focused on recovering not only iron, but mostly the specific elements necessary as raw materials for precision alloying (e.g. niobium, molybdenum and cobalt). Due to the lower demands for specialty alloys, this approach would be more suitable for individual supply chains than for a European or national policy.

3.2. Horizontal hedging of refurbishment or reuse of EOL steel

In what regards to simulation run 3, the results depicted in Fig. 10 highlight the potential impact of horizontally hedging EoL steel as an alternative to new steel, notably on the consumption of ore and scrap, but also in the reduced steel output. The more a same material circulates in the economy before actually being discarded, the less new materials are required, therefore the more important it becomes to retain resource ownership in order to accrue more value from it as it circulates, and not only by inputting it into the economy at first.

EAF operations were impacted over twice as much as BFBOF, mostly due to their direct dependence on the availability of recycled scrap, which declined as a function of the prolonged circulation of iron in the economy. Still, this impact was far from being capable of reversing the trend towards the shift from BFBOF to EAF operations, even if by reducing ore consumption the lifespan of BFBOF operations was lengthened. Horizontal hedging in this context would also support financial measures regarding the futures of scrap, but less so regarding the futures of ore.

As seen in Fig. 11, the amount of iron retained in the supply chain increases, even if hedged horizontally. Therefore, bringing in or creating new repair and refurbishment providers within a steelmaker's supply chain gives it the strategic possibility to influence the flow of repairs vs refurbishments and to create new dynamics of exchange with its metalworking or assembler stakeholders.

This opens the door for an integrated supply chain to deploy new downstream service-based operations aimed at providing upstream manufacturing-oriented benefits, a managerial behavior often seen in agricultural management, but not as often in inorganic commodities management. Depending on how geographically close and operationally aligned this horizontal hedging is implemented alongside the other stakeholders in the supply chain, benefits might even extend to reverse logistics.

Having analyzed this run, the authors noticed that, particularly in this case, steelmakers with strong customer side relations in sectors that are more dependent on specialty alloys could potentially benefit even further from a vertical hedging approach, instead of a horizontal one. Focusing on the retention of scarcer alloying elements such as cobalt,

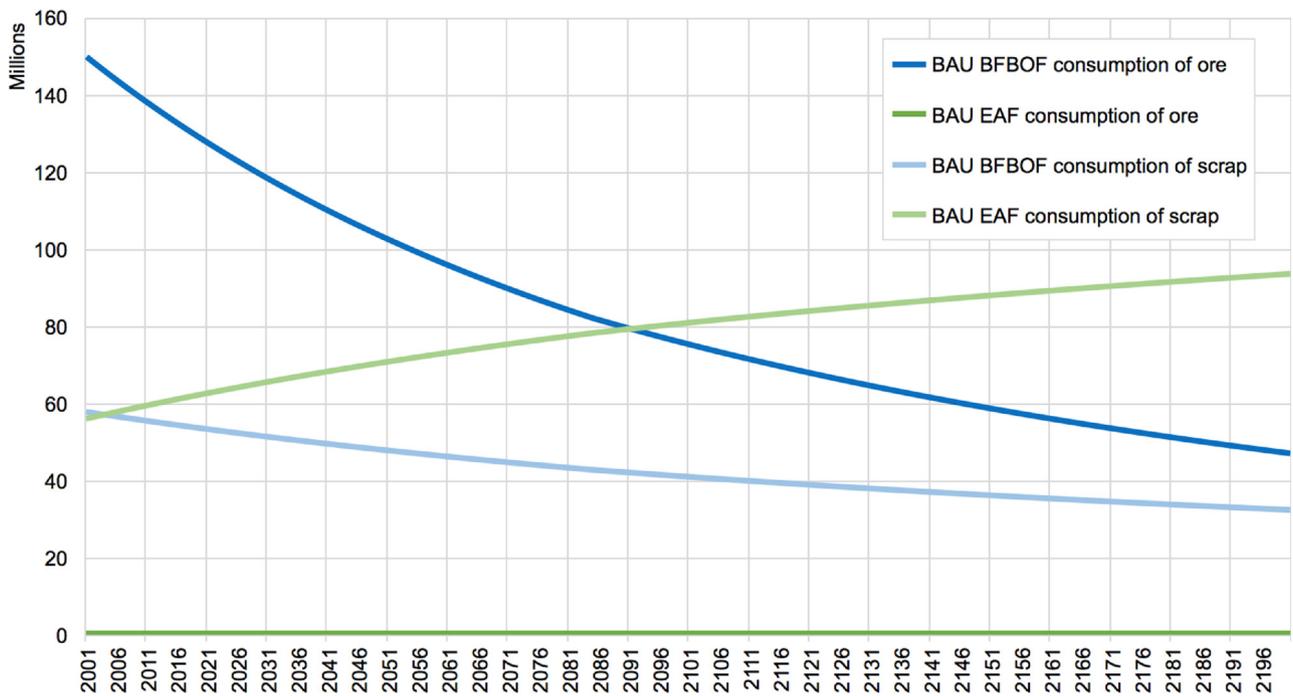


Fig. 6. Evolution of iron input consumption (tons) over time, per type of production.

molybdenum and niobium within their supply chains, steelmakers could potentially increase the competitiveness of their alloys aimed at the Automotive, Appliances & Electronics and Aerospace sectors, while simultaneously covering the risks of their futures by increasing raw material self-sufficiency.

3.3. Horizontal integration of repair and maintenance of EOL steel products

Finally, simulation runs 4 and 5 presented horizontal integration as a double-edged sword strategy for EoL steel maintenance and repair. Whether via planned obsolescence of the final products or by controlling the deployment of warranty coverage – among many other strategic possibilities –, having enough horizontal influence to deter circularity (run 4) would increase the demand for new steel and, therefore,

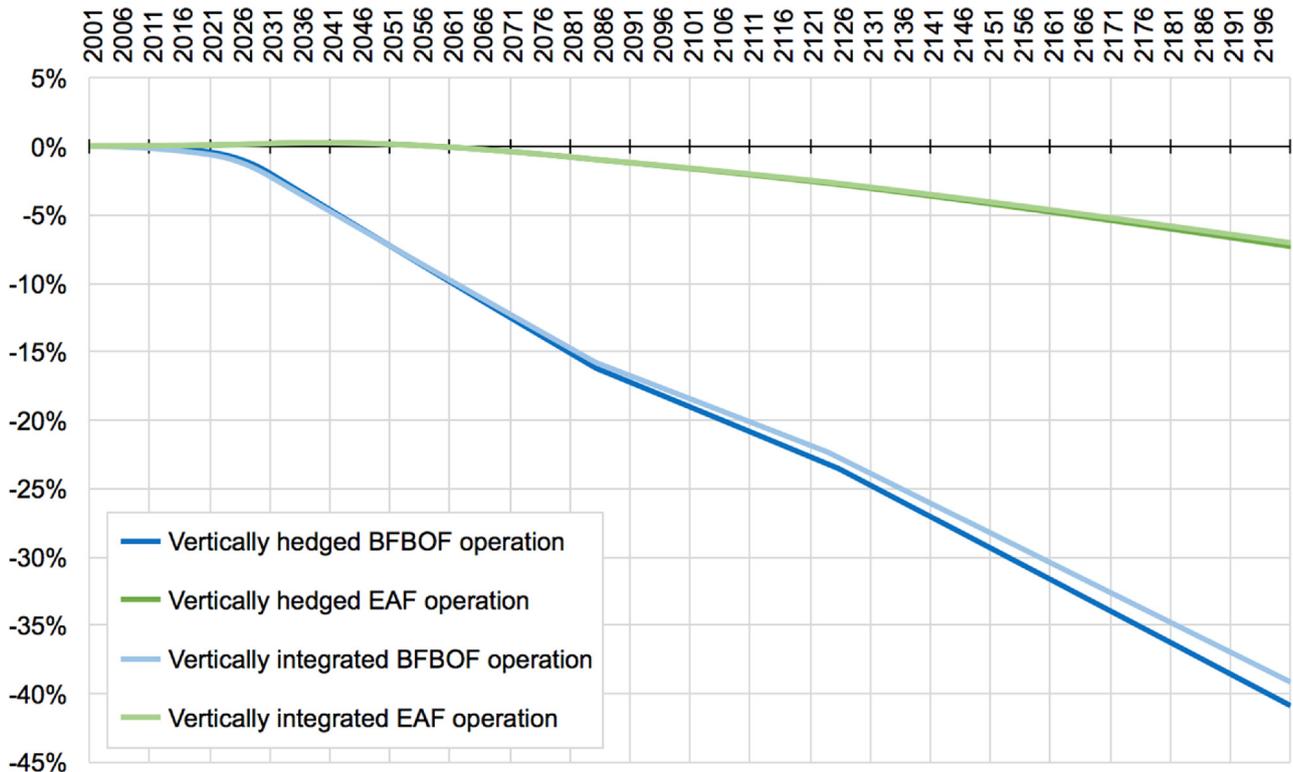


Fig. 7. Impact of simulation runs 1 and 2 on iron ore consumption over time.

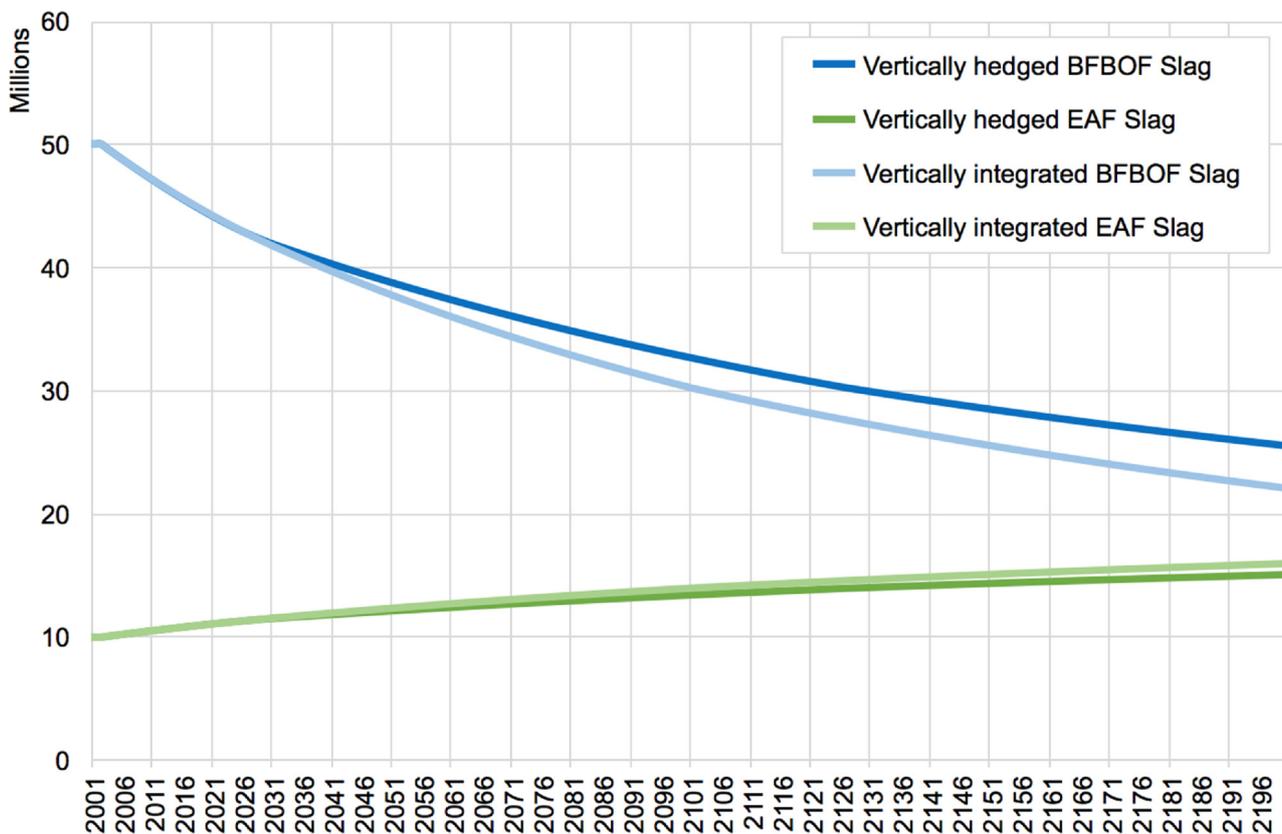


Fig. 8. Recoverable iron in slag (kg) as a result of simulation runs 1 and 2.

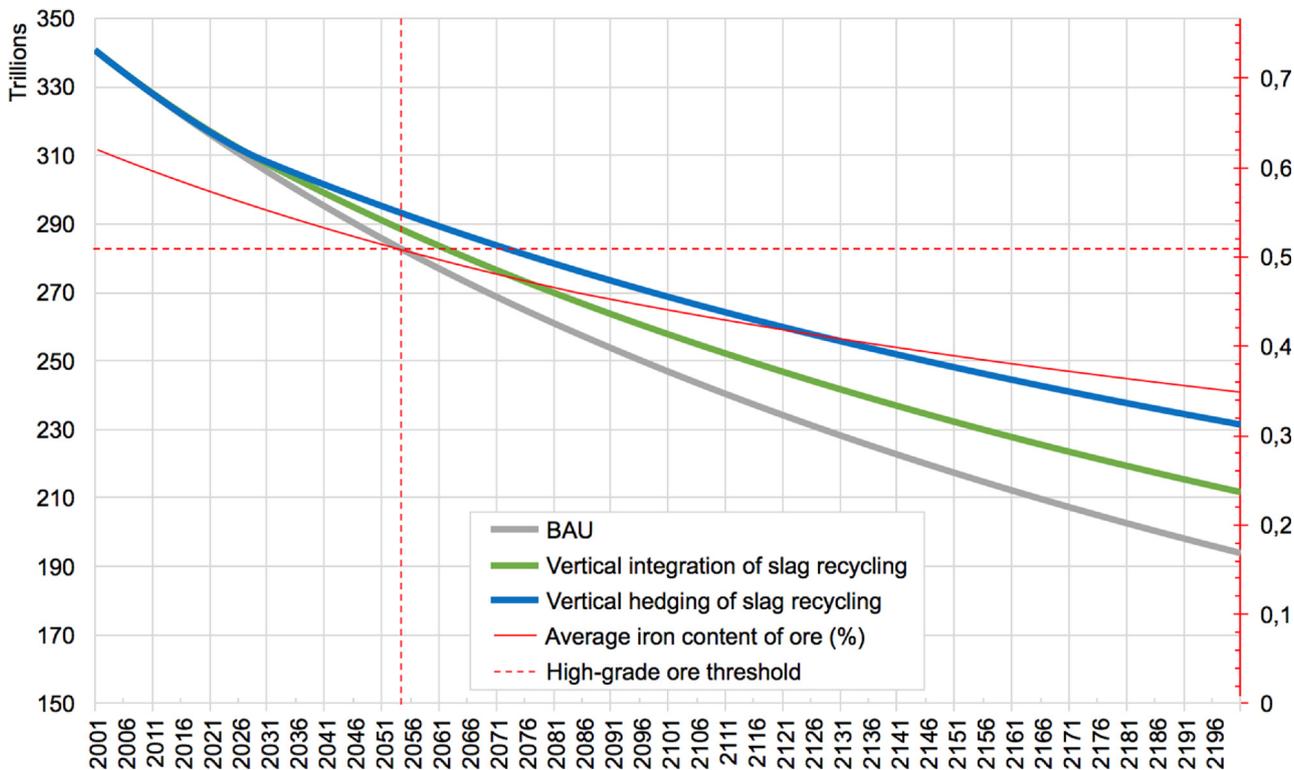


Fig. 9. Worldwide technically extractable ore reserves (kg) comparison.

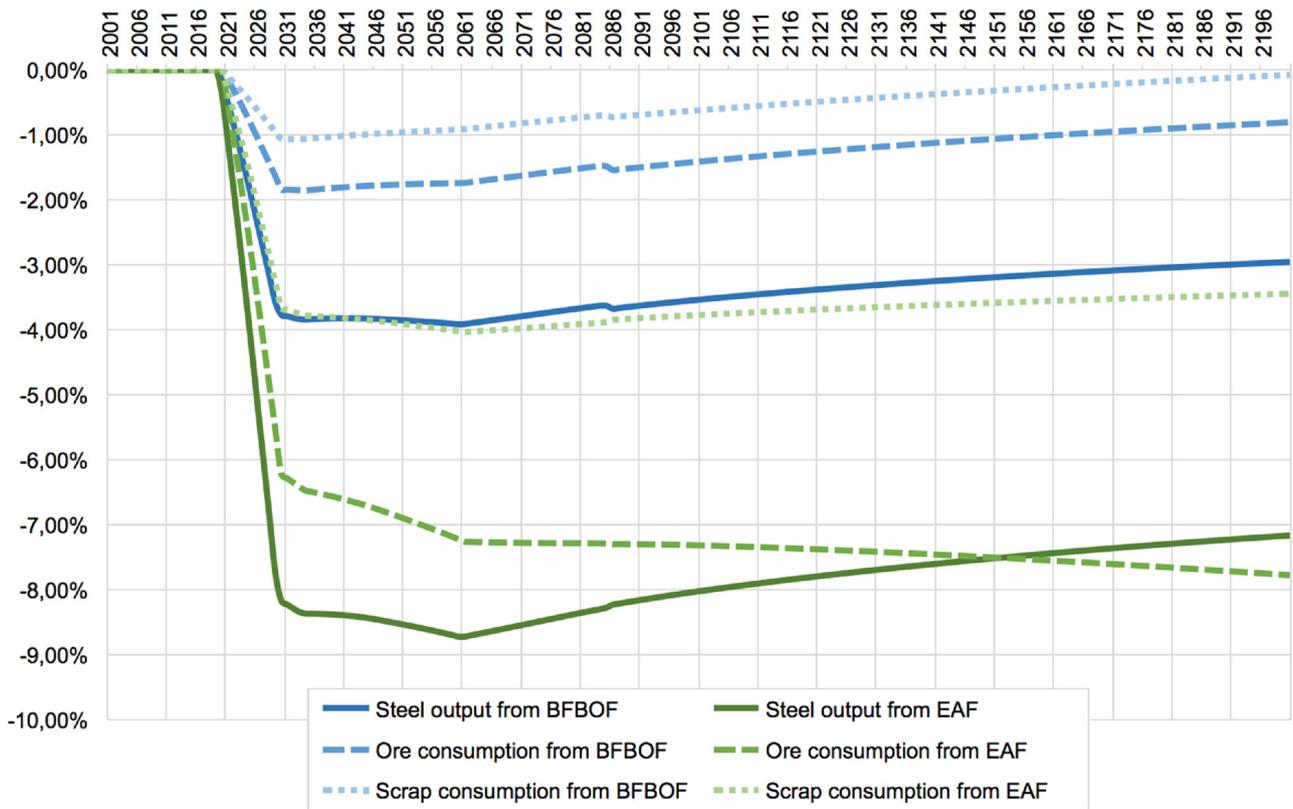


Fig. 10. Impact of simulation run 3 on steel output and ore and scrap consumption.

the consumption of ore and scrap, as seen in Fig. 12. Naturally, the very opposite would occur when stimulating circularity (run 5) by, for example, centralizing or monopolizing maintenance and repair.

The potential for this integration approach to backfire would always be present because, although influence and control can be exerted on third-party EoL service providers that are integrated to the steelmaker's

supply chain, nothing can be done regarding those that are not. Therefore, the benefits of either deterring or stimulating circularity as means of feeding back the desired outcomes to the steelmaker can in fact create a *bullwhip* effect. Choosing to close material loops this way would require close attention to return times, backlogged demand and competitor behavior.

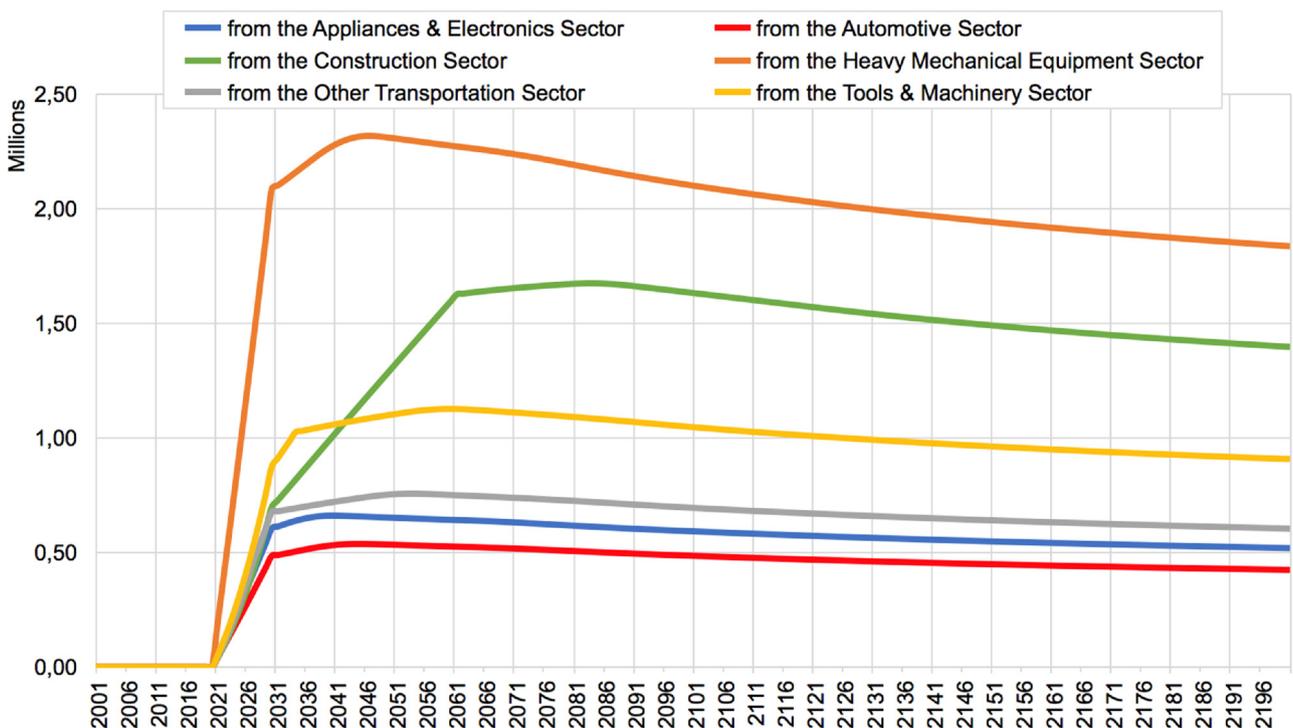


Fig. 11. Iron retained within the supply chain (kg) as a result of simulation run 3.

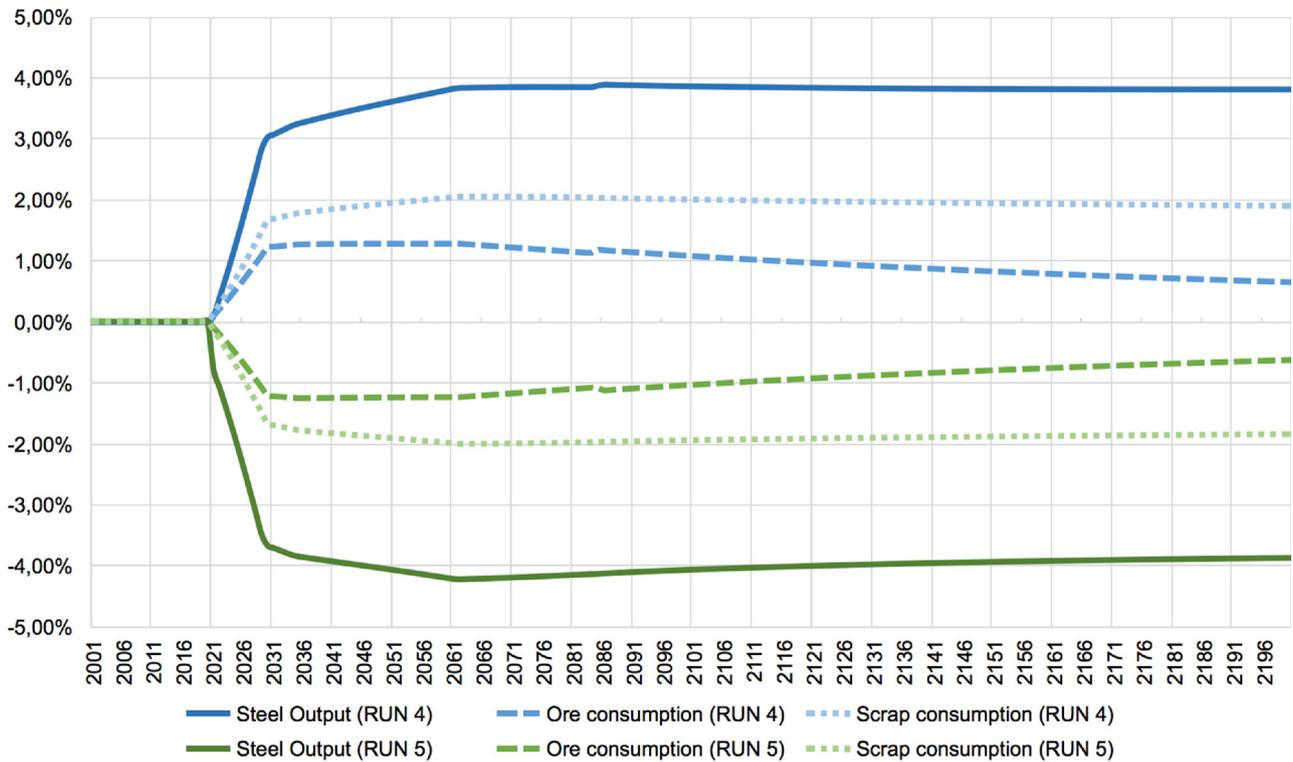


Fig. 12. Impact of simulation runs 4 and 5 on supply side dynamics.

It is to say that, in run 4, undersupplied demand for EoL maintenance and repair services would be picked up by the competitors outside of the integrated third-party providers' boundaries. In run 5, the same EoL services if oversupplied by the integration would have a delayed feedback and either flood the market with renewed steel or even scrap, or increase intermediary stocks throughout the supply chain due

to reduced flow output.

These behaviors are easier to visualize by analyzing Figs. 12 and 13 simultaneously, as it is possible to see that the impacts on the supply side dynamics would be twice as high and begin about a decade earlier than the impacts on the EoL side.

Fig. 13 also shows that, after the phase-in period, a new equilibrium

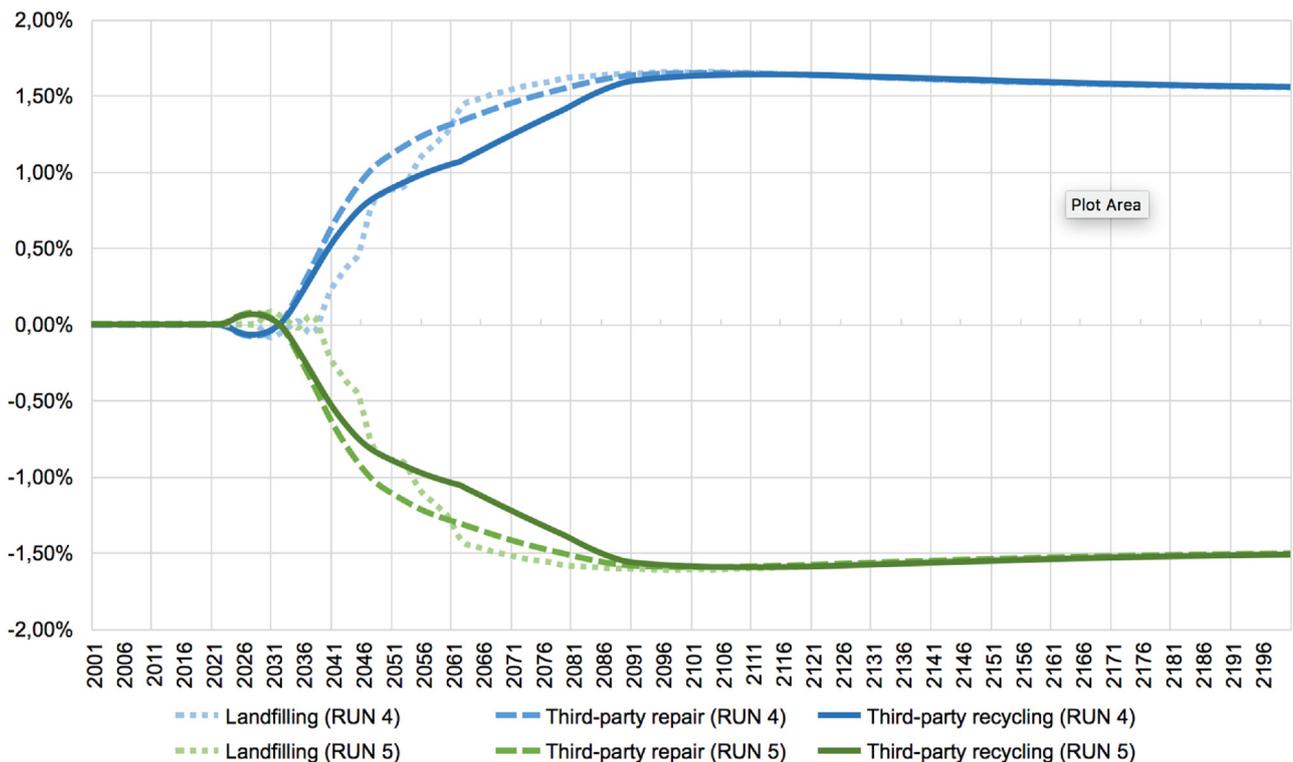


Fig. 13. Impact of simulation runs 4 and 5 on End-of-Life dynamics.

would eventually be achieved in the long-term, circa 2100, moment in which landfilling, third-party repair and third-party recycling converge onwards. As the market readjusts to either a circularity-deterrent or a circularity-stimulated strategy, two questions for further investigation arose: which strategy would be economically worth its risks for steel-makers? And which would better suit the economic or environmental interests of the nation or of Europe?

To answer these questions, one could look at the Automotive sector as an example of how decoupling resource ownership from maintenance and repair services can allow for EoL horizontal integration. Nevertheless, it configures a completely different business model mostly unrelated to steelmaking and subject to different market dynamics.

In summary, it would be preferable for most integrated steelmaking supply chains to either:

- a) include these EoL services as part of the product in the form of support and warranty, as it is often done already by either manufacturers or assemblers;
- b) develop a new business unit within its control and dedicated to these dynamics, as per the Automotive example;
- c) implement the proposition from run 3 alone and focus on increasing circularity, a strategy potentially more aligned with environmentally-oriented policies; or
- d) to align the propositions of runs 4 and 5 to those of run 3, so as to ensure that any EoL steel of which value can no longer be accrued by reinsertion into the manufacturing actually remains within the boundaries of the supply chain for repair and maintenance services; a strategy more likely to economically benefit steelmakers.

4. Conclusions and recommendations

Simulation runs 1 and 2 showed that both vertically integrating and vertically hedging slag recycling would reduce iron ore consumption, push the technical scarcity of high-grade ores further into the future, and that the stimulus to recycle slag in general would grow as a function of its yield.

If the strategic priority is resource ownership retention, vertical integration would perform better for iron recovery and allow for better yields in other alloying elements, especially when supplying clients that demand specialty alloys. As a policy, vertical integration would therefore be more applicable in very local or specific situations, being mostly of interest for individual supply chains as an investment opportunity.

Vertical hedging, on the other hand, would perform better as a raw material self-sufficiency strategy due to its results in long-term bulk supply, notably for BFBOF operations supplying clients that do not require specialty alloys. Vertically hedging slag recycling would also pose as an interesting tool for financial hedging against ore futures and, as a policy, it seemed more suitable for national and European scales than its counterpart.

Simulation run 3 brought to light that horizontally hedging the refurbishment or reuse of EoL steel is an interesting strategy for resource ownership retention. By influencing the flow of repairs or refurbishments vs a linear flow, a significant impact can be made on the demand for new steel, on steel output and on the consumption of both scrap and ore, potentially altering the dynamics with metalworking or assembler stakeholders as a consequence.

EAF operations were the most affected by the reduced availability of scrap in the long-term and, although it would not be enough to reverse the electrification trend, financial protection against scrap futures would play a large role in this context. Such hurdles could be overcome with the development of integrated downstream service-based operations to support upstream manufacturing, potentially making horizontal hedging even more fruitful. The results of run 3 went beyond the expectations of the authors and also pointed to a vertical hedging approach as potentially even more interesting, specifically for steelmakers

with close customer side relations with clients dependent on specialty alloys.

Simulation runs 4 and 5 highlighted the paradoxical nature of horizontally integrating EoL steel maintenance and repair services into the steelmaking supply chain. Neither resource ownership retention nor raw material self-sufficiency were substantially benefitted. Whether using the horizontal influence to deter or to stimulate these services, a bullwhip effect becomes an ever-present risk.

Mitigating this risk would require carefully monitoring the behaviors and reactions of service competitors, so that oversupply does not clog intermediary stocks and undersupply demand does benefit competitors' market shares. Although the Automotive industry already manages this type of challenge with warranty and leasing practices, doing so alongside other sectors would have the higher likelihood of benefitting steelmakers if it allowed for serviced steel to be hedged against recycled steel, as per run 3, ensuring a win on the manufacturing side even if a loss takes place on the service side.

Overall, understanding the potential effects of SCI approaches to resource ownership retention and raw material self-sufficiency through the lens of circularity created new branches of strategic decision- and policy-making discussion in the European steel industry.

The authors believe that going further into these analysis by empirically addressing the capital requirements for different SCI investments, the implications to reverse logistics and the specific environmental impacts that result from such strategic shifts could substantially improve the results already presented thus far.

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References

- Adegoloye, G., Beaucour, A.L., Ortola, S., Noumowe, A., 2016. Mineralogical composition of EAF slag and stabilized AOD slag aggregates and dimensional stability of slag aggregate concretes. *Constr. Build. Mater.* 115, 171–178. <https://doi.org/10.1016/j.conbuildmat.2016.04.036>.
- Arik, E., Mutlu, E., 2014. Chinese steel market in the post-futures period. *Resour. Policy* 42-C, 10–17. <https://doi.org/10.1016/j.resourpol.2014.08.002>.
- Beddows, R., 2014. *Steel 2050 - How Steel Transformed the World and Now Must Transform Itself*. Kingsbridge, Devonian ISBN 0993038107.
- Bhattacharyya, S., Choudhary, A., Shanka, R., 2017. A decision model for a strategic closed-loop supply chain to reclaim end-of-life vehicles. *Int. J. Prod. Econ.* 195, 273–286. <https://doi.org/10.1016/j.ijpe.2017.10.005>.
- Bir, 2015. *World Steel Recycling In Figures*. Bureau of International Recycling, Brussels.
- Björkman, B., Samuelsson, C., 2014. Recycling of steel. In: Worrell, E., Reuter, M. (Eds.), *Handbook Of Recycling*. Elsevier ISBN 9780123965066.
- Bovea, M.D., Ibáñez-Forés, V., Pérez-Belis, V., Quemades-Beltrán, P., 2016. Potential reuse of small household waste electrical and electronic equipment: methodology and case study. *Waste Manag.* 53. <https://doi.org/10.1016/j.wasman.2016.03.038>.
- Bowersox, D.J., Closs, D.J., Stank, T.P., 1999. *21st Century Logistics: Making Supply Chain Integration a Reality*. Council Of Logistics Management Professionals, Oak Brook ISBN 9780965865326.
- Braz, A.C., Mello, A.M., Vasconcelos Gomes, L.A., Nascimento, P.T., 2018. The bullwhip effect in closed-loop supply chains: a systematic literature review. *J. Clean. Prod.* 202, 376–389. <https://doi.org/10.1016/j.jclepro.2018.08.042>.
- Bringas, J.E., 2004. *Handbook Of Comparative World Steel Standards*. ASTM International ISBN 0803133626.
- Burchart-Korol, D., Kruczek, M., 2015. Water scarcity assessment of steel production. *Metalurgija* 54, 276–278.
- Cannella, S., Brucoleri, M., Framinan, J.M., 2016. Closed-loop supply chains: what reverse logistics factors influence performance? *Intern. J. Prod. Econ.* 175, 35–49. <https://doi.org/10.1016/j.ijpe.2016.01.012>.
- Cardoso, S.R., Barbosa-Póvoa, A.P., Relvas, S., 2013. Design and planning of supply chains with integration of reverse logistics activities under demand uncertainty. *Eur. J. Oper. Res.* 226–3, 436–451. <https://doi.org/10.1016/j.ejor.2012.11.035>.
- CEDED, 2017. *Material Flows of The Home Appliance Industry*. European Committee Of Domestic Equipment Manufacturers.

- Chevalier, J., 1995. *L'économie industrielle des stratégies d'entreprises*. Montchrestien, Paris ISBN 978-2-7076-1211-3.
- Cooper, D.R., Skelton, A.C.H., Moynihan, M.C., Allwood, J.M., 2014. Component level strategies for exploiting the lifespan of steel in products. *Resour. Conserv. Recycl.* 84, 24–34. <https://doi.org/10.1016/j.resconrec.2013.11.014>.
- Cullen, J.M., Allwood, J.M., Bambach, M.D., 2012. Mapping the global flow of steel: from steelmaking to end-use goods. *Environ. Sci. Technol.* 46, 13048–13055. <https://doi.org/10.1021/Es302433p>.
- D'costa, A.P., 1999. *The Global Restructuring of the Steel Industry – Innovations, Institutions and Industrial Change*. Routledge, Oxon ISBN 0415148278.
- Demailly, D., Quirion, P., 2008. European emission trading scheme and competitiveness: a case study on the iron and steel industry. *Energy Econ.* 30–34, 2009–2027.
- Dindarian, A., Gibson, A.P., 2011. Reuse of EEE/WEEE in UK: review on functionality of EEE/WEEE at the point of disposal. *Sustain. Syst. Technol. Conf.* <https://doi.org/10.1109/Isst.2011.5936867>.
- Eckelman, M.J., Ciacci, L., Kavlak, G., Nuss, P., Reck, B.K., Graedel, T.E., 2014. Life cycle carbon benefits of aerospace alloy recycling. *J. Clean. Prod.* 80, 38–45. <https://doi.org/10.1016/j.jclepro.2014.05.039>.
- Ellen Mcarthur Foundation, 2012. *Towards the Circular Economy – An Economic and Business Rationale for an Accelerated Transition*. Ellen Mcarthur Foundation, Cowes.
- Ellen Mcarthur Foundation, 2013. *Towards the Circular Economy – Opportunities for the Consumer Goods Sector*. Ellen Mcarthur Foundation, Cowes.
- Ellen Mcarthur Foundation, 2014a. *A New Dynamic – Effective Business in a Circular Economy*. Ellen Mcarthur Foundation, Cowes.
- Ellen Mcarthur Foundation, 2014b. *Towards the Circular Economy – Accelerating the Scale-up Across Global Supply Chains*. Ellen Mcarthur Foundation, Cowes.
- Ellen Mcarthur Foundation, 2015a. *Growth Within – A Circular Economy Vision for a Competitive Europe*. Ellen Mcarthur Foundation, Cowes.
- Ellen Mcarthur Foundation, 2015b. *Delivering the Circular Economy – A Toolkit for Policymakers*. Ellen Mcarthur Foundation, Cowes.
- Ellen Mcarthur Foundation, 2016. *Intelligent Assets – Unlocking the Circular Economy Potential*. Ellen Mcarthur Foundation, Cowes.
- Ellen Mcarthur Foundation, 2017. *The Circular Economy – A Wealth of Flows*. Cowes, Ellen Mcarthur Foundation.
- Ernst & Young, 2014. *Global Steel 2014 – Planning to Profit From Opportunity and Preparing for Future Demand*. Eym.
- Ernst & Young, 2015. *Global Steel 2015/16 – Globalize or Customize – Finding the Right Balance*. Eym.
- Ernst & Young, 2017. *The Rising Threat of Substitution: Mining & Metals*. Ey Industries – Mining and Metals (Retrieved February 12). <http://www.ey.com/GI/En/Industries/Mining—Metals/The-Rising-Threat-Of-Substitution—Mining-And-Metals>.
- Eurofer, 2017a. *European Steel in Figures*. Eurofer, Brussels.
- Eurofer, 2017b. *Steel, The Backbone of Sustainability in Europe*. Eurofer, Brussels.
- European Commission, 2010. *ILCD Handbook: General Guide for Life Cycle Assessment – Detailed Guidance*. Joint Research Centre – Institute For Environment and Sustainability, Luxembourg.
- European Commission, 2012. *Manifesto for a Resource-Efficient Europe*. European Resource Efficiency Platform, Brussels.
- European Commission, 2017. *Study on the Review of the List of Critical Raw Materials*. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Luxembourg.
- European Commission, 2018. *On a Monitoring Framework for the Circular Economy*. Communication From the Commission to The European Parliament. Strasbourg.
- European Union, 2011. *Improved Eaf Process Control Using On-line Offgas Analysis – Offgas*. European Union, Luxembourg.
- EUROSLAG, 2018. *European Association of Metallurgical Slag Producers*. (Accessed: 05 September). <https://www.euroslag.com>.
- EUROSTAT, 2018. *Data Reporting on Quantity, Hazardousness and Shipments of Waste*. (Accessed: 05 September). <http://ec.europa.eu/eurostat/Web/Waste/Data>.
- Ferreira, H., Leite, M.P.G., 2015. A life cycle assessment study of iron ore mining. *J. Clean. Prod.* 108a, 1081–1091. <https://doi.org/10.1016/j.jclepro.2015.05.140>.
- Gardner, D.T., Buzacott, J.A., 1999. Hedging against uncertainty in new technology development: the case of direct steelmaking. *IEEE Trans. Eng. Manag.* 46–52, 177–189. <https://doi.org/10.1109/17.759146>.
- Gaur, J., Subramoniam, R., Govindan, K., Huisingh, D., 2017. Closed-loop supply chain management: from conceptual to an action oriented framework on core acquisition. *J. Clean. Prod.* 167, 1415–1424. <https://doi.org/10.1016/j.jclepro.2016.12.098>.
- Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultnik, E.J., 2017. The circular economy – a new sustainability paradigm? *J. Clean. Prod.* 143, 757–768. <https://doi.org/10.1016/j.jclepro.2016.12.048>.
- Golroudbary, S.R., Zahraee, S.M., 2015. System dynamics model for optimizing the recycling and collection of waste material in a closed-loop supply chain. *Simul. Model. Pract. Theory* 53, 88–102. <https://doi.org/10.1016/j.simpat.2015.02.001>.
- Govindan, K., Soleimani, H., 2016. A review of reverse logistics and closed-loop supply chains: a journal of cleaner production focus. *J. Clean. Prod.* 142–1, 371–384. <https://doi.org/10.1016/j.jclepro.2016.03.126>.
- Gregson, N., Crang, N., Fuller, S., Holmes, H., 2015. Interrogating the circular economy: the moral economy of resource recovery in the EU. *Econ. Soc.* 44, 218–243. <https://doi.org/10.1080/03085147.2015.1013353>.
- Gunasekaran, A., Ngai, E.W., 2004. Information systems in supply chain integration and management. *Eur. J. Oper. Res.* 159–2, 269–295. <https://doi.org/10.1016/J.Ejor.2003.08.016>.
- Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy? An assessment of material flows, waste production, and recycling in the European Union and the World in 2005. *J. Ind. Ecol.* 19–5, 765–777. <https://doi.org/10.1111/Jiec.12244>.
- Hey, Y., 2017. Supply risk sharing in a closed-loop supply chain. *Intern. J. Prod. Econ.* 183–A, 39–52. <https://doi.org/10.1016/J.Ijpe.2016.10.012>.
- Hosoda, T., Disney, S.M., 2018. A unified theory of the dynamics of closed-loop supply chains. *Eur. J. Oper. Res.* 269–1, 313–326. <https://doi.org/10.1016/J.Ejor.2017.07.020>.
- ISEE Systems, 2018. *Stella Architect*. (Accessed: 5 May). <https://www.iseesystems.com/Store/Products/Stella-Architect.aspx>.
- Islam, M.T., Huda, N., 2018. Reverse logistics and closed-loop supply chain of waste electrical and electronic equipment WEEE/E-waste: a comprehensive literature review. *Resour. Conserv. Recycl.* 137, 48–75. <https://doi.org/10.1016/J.Resconrec.2018.05.026>.
- ISO, 2006. *ISO 14044 - Environmental Management, Life Cycle Analysis, Requirement and Orientations*. International Standardization Organization, Geneva.
- Jayaram, J., Tan, K., 2010. Supply chain integration with third-party logistics providers. *Int. J. Prod. Econ.* 125, 262–271. <https://doi.org/10.1016/J.Ijpe.2010.02.014>.
- Johnson, J., Reck, B.K., Wang, T., Graedel, T.E., 2008. The energy benefit of stainless steel recycling. *Energy Policy* 36, 181–192. <https://doi.org/10.1016/J.Enpol.2007.08.028>.
- JRC, 2012. *Joint Research Centre - Institute for Environment and Sustainability - European Commission. Product Environmental Footprint (Pef) Guide*, Ispra July.
- Kahle, L.R., Gurel-Atay, E., 2014. *Communicating Sustainability For The Green Economy*. M.E. Sharpe, New York ISBN 0765636816.
- Kissling, R., Coughlan, D., Fitzpatrick, C., Böni, H., Luepschen, C., Andrew, S., Dickenson, J., 2013. Success factors and barriers in re-use of electrical and electronic equipment. *Resour. Conserv. Recycl.* 80, 21–31. <https://doi.org/10.1016/J.Resconrec.2013.07.009>.
- Korhonen, J., 2004. Industrial ecology in the strategic sustainable development model: strategic applications of industrial ecology. *J. Clean. Prod.* 12–8, 809–823. <https://doi.org/10.1016/J.Jclepro.2004.02.026>.
- Lewandowski, M., 2016. Designing the business models for circular economy – towards the conceptual framework. *Sustainability* 8, 43–51. <https://doi.org/10.3390/Su8010043>.
- Liao, W., Heijungs, R., Huppes, G., 2012. Thermodynamic analysis of human–environment systems: a review focused on industrial ecology. *Ecol. Modell.* 228, 76–88. <https://doi.org/10.1016/J.Ecolmodel.2012.01.004>.
- Lii, P., Kuo, F., 2016. Innovation-oriented supply chain integration for combined competitiveness and firm performance. *Intern. J. Prod. Econ.* 174, 142–155. <https://doi.org/10.1016/J.Ijpe.2016.01.018>.
- Madias, J., 2013. *Electric furnace steelmaking*. In: Seshadri, S. (Ed.), *Treatise On Process Metallurgy*. Elsevier ISBN 9780080969879.
- Meixell, M.J., Gargeya, V.B., 2005. Global supply chain design: a literature review and critique. *Transp. Res. Part E Logist. Transp. Rev.* 41–6, 531–550. <https://doi.org/10.1016/J.Tre.2005.06.003>.
- Miao, Z., Fu, K., Xia, Z., Wang, Y., 2017. Models for closed-loop supply chain with trade-ins. *Omega* 66–B 308–326. <https://doi.org/10.1016/J.Omega.2015.11.001>.
- Mindat, 2018. *Mineralogy Database*. (Accessed: 05 September). <https://www.Mindat.Org/>.
- NFDC, 2012. *The Recycling And Reuse Survey*. UK National Federation Of Demolition Contractors, Herts.
- Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: a proposal to advance the assessment of circular economy strategies At the product level. *Resour. Conserv. Recycl.* 140, 305–312. <https://doi.org/10.1016/J.Resconrec.2018.10.002>.
- NRC, 2000. *Surviving Supply Chain Integration: Strategies For Small Manufacturers*. Committee On Supply Chain Integration. National Research Council. National Academy Press, Washington, D.C ISBN 9780309173414.
- Nuss, P., Blengini, G.A., 2018. Towards better monitoring of technology critical elements in Europe: coupling of natural and anthropogenic cycles. *Sci. Total Environ.* 613–614, 569–578. <https://doi.org/10.1016/J.Scitotenv.2017.09.117>.
- Panaszyk, D., Laratte, B., Remy, S., 2016. Steel stock analysis in europe from 1945 to 2013. *Conference On Life Cycle Engineering, Procedia Cirp* 48, 348–351. <https://doi.org/10.1016/J.Procir.2016.04.084>.
- Park, J., Sarkis, J., Wu, Z., 2010. Creating integrated business and environmental value within the context of China's circular economy and ecological modernization. *J. Clean. Prod.* 18–15, 1494–1501. <https://doi.org/10.1016/J.Jclepro.2010.06.001>.
- Pauliuk, S., Wang, T., Müller, D.B., 2013. Steel all over the world: estimating in-use stocks of iron for 200 countries. *Resour. Conserv. Recycl.* 71, 22–30. <https://doi.org/10.1016/J.Resconrec.2012.11.008>.
- Pauliuk, S., Kondo, Y., Nakamura, S., Nakajima, K., 2017. Regional distribution and losses of end-of-life steel throughout multiple product life cycles – insights from The Global Multiregional Matraxe Model. *Resour. Conserv. Recycl.* 116, 84–93. <https://doi.org/10.1016/J.Resconrec.2016.09.029>.
- Pauliuk, S., 2018. *Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations*. *Resour. Conserv. Recycl.* 129, 81–92. <https://doi.org/10.1016/J.Resconrec.2017.10.019>.
- Pearce, D.R., Turner, K.R., 1989. *Economics of Natural Resources and the Environment*. John Hopkins University Press, Baltimore ISBN 9780801839870.
- Prosmann, E.J., Waehrens, B., Liotta, G., 2017. Closing global material loops: initial insights into firm-level challenges. *J. Ind. Ecol.* 21–3, 641–650. <https://doi.org/10.1111/Jiec.12535>.
- Pinto, Julian, T.M., Sverdrup, Harald, U., Diemer, Arnaud, 2019. Integrating life cycle analysis into system dynamics: the case of steel in Europe. *Environ. Syst. Res.* 8–15. <https://doi.org/10.1186/S40068-019-0144-2>.
- Ramírez-Santos, A., Castel, C., Favre, E., 2018. A review of gas separation technologies within emission reduction programs in the iron and steel sector: current application

- and development perspectives. *Sep. Purif. Technol.* 194, 425–442. <https://doi.org/10.1016/j.seppur.2017.11.063>.
- Reppel-Hill, V., 1999. Trade and environment: an empirical analysis of the technology effect in the steel industry. *J. Environ. Econ. Manage.* 38–3, 283–301. <https://doi.org/10.1006/Jeem.1999.1085>.
- RREUSE, 2012. *Challenges to Boosting Reuse Rates in Europe*. RREUSE, Brussels.
- Schenkel, M., Caniels, M.C.J., Krikker, H., Van Der Laan, E., 2015. Understanding value creation in closed loop supply chains – past findings and future directions. *J. Manuf. Syst.* 37–3, 729–745. <https://doi.org/10.1016/j.jmsy.2015.04.009>.
- Schubert, E.S., Gottschling, R., 2011. *Co-Generation: A Challenge For Furnace Off-Gas Cleaning Systems*. Southern African Pyrometallurgy Institute.
- Schultmann, F., Zumkeller, M., Rentz, O., 2006. Modeling reverse logistic tasks within closed-loop supply chains: an example from the automotive industry. *Eur. J. Oper. Res.* 171–3, 1033–1050. <https://doi.org/10.1016/j.ejor.2005.01.016>.
- Seager, T.P., Theis, T.L., 2002. A uniform definition and quantitative basis for industrial ecology. *J. Clean. Prod.* 10–3, 225–235. [https://doi.org/10.1016/S0959-6526\(01\)00040-3](https://doi.org/10.1016/S0959-6526(01)00040-3).
- Sengupta, K., Heiser, D.R., Cook, L.S., 2006. Manufacturing and service supply chain performance: a comparative analysis. *J. Supply Chain. Manag.* 42–4, 4–15. <https://doi.org/10.1111/J.1745-493x.2006.00018.X>.
- Shamsuddin, M., 2016. *Physical Chemistry Of Metallurgical Processes*. Wiley Kindle Edition, Hoboken ISBN 978-1-119-07833-3.
- Shou, Y., Li, Y., Park, Y., Kang, M., 2017. Supply chain integration and operational performance: the contingency effects of production systems. *J. Purch. Supply Manag.* <https://doi.org/10.1016/J.Pursup.2017.11.004>. In Press.
- Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China: moving from rhetoric to implementation. *J. Clean. Prod.* 42, 215–227. <https://doi.org/10.1016/j.jclepro.2012.11.020>.
- Sverdrup, H., Ragnarsdottir, K.V., 2014. *Geochemical Perspectives: Natural Resources in a Planetary Perspective*. European Association of Geochemistry, Toulouse. <https://doi.org/10.7185/Geochempersp.3.2>.
- Świerczek, A., 2014. The impact of supply chain integration on the ‘Snowball Effect’ in the transmission of disruptions: an empirical evaluation of the model. *Int. J. Prod. Econ.* 157, 89–104. <https://doi.org/10.1016/j.ijpe.2013.08.010>.
- TeröRde, F., 2006. *Stainless Steel Recycling, Data And Scenarios, Availability Of Scrap*. ISSF.
- Truttman, N., Rechberger, H., 2006. Contribution to resource conservation by reuse of electrical and electronic household appliances. *Resour. Conserv. Recycl.* 48–3, 249–262. <https://doi.org/10.1016/j.resconrec.2006.02.003>.
- Tukker, A., 2015. Product services for a resource-efficient and circular economy - a review. *J. Clean. Prod.* 97, 76–91. <https://doi.org/10.1016/j.jclepro.2013.11.049>.
- Van Der Vaart, T., Van Donk, D.P., 2004. Buyer focus: evaluation of a new concept for supply chain integration. *Int. J. Prod. Econ.* 92–1, 21–30. <https://doi.org/10.1016/j.ijpe.2003.10.002>.
- Van Der Vaart, T., Van Donk, D.P., 2008. A critical review of survey-based research in supply chain integration. *Int. J. Prod. Econ.* 111–1, 42–55. <https://doi.org/10.1016/j.ijpe.2006.10.011>.
- Vickery, S.K., Jayaram, J., Droge, C., Calantone, R., 2003. The effects of an integrative supply chain strategy on customer service and financial performance: an analysis of direct versus indirect relationships. *J. Oper. Manag.* 21, 523–539. <https://doi.org/10.1016/J.Jom.2003.02.002>.
- UNEP, 2011. *Towards a Green Economy - Pathways to Sustainable Development and Poverty Eradication*. United Nations’ Environmental Programme, Geneva.
- Uribe-Soto, W., Portha, J., Commenge, J., Falk, L., 2017. A review of thermochemical processes and technologies to use steelworks off-gases. *Renew. Sustain. Energy Rev.* 74, 809–823. <https://doi.org/10.1016/j.rser.2017.03.008>.
- Vaclav, S., 2016. *Still The Iron Age*. Butterworth-Heinemann, Elsevier, Oxford ISBN 9780128042359.
- Wang, N., He, Q., Jiang, B., 2018. Hybrid closed-loop supply chains with competition in recycling and product markets. *Int. J. Prod. Econ.* <https://doi.org/10.1016/j.ijpe.2018.01.002>. In Press.
- Warrian, P., 2012. *A Profile of the Steel Industry - Global Reinvention for a New Economy*. Business Expert Press, New York ISBN 1631573845.
- Webmineral, 2018. *Mineralogy Database*. (Accessed: 05 September). <http://Webmineral.Com/>.
- Wiengarten, F., Humphreys, P., Gimenez, C., 2016. Risk, risk management practices, and the success of supply chain integration. *Int. J. Prod. Econ.* 171–3, 361–370. <https://doi.org/10.1016/j.ijpe.2015.03.020>.
- Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. *Renew. Sustain. Energy Rev.* 68–1, 825–833. <https://doi.org/10.1016/j.rser.2016.09.123>.
- Worldsteel Association, 2017c. *Methodology Report Life Cycle Inventory Study For Steel Products*. Worldsteel Association, Brussels.
- Worldsteel Association, 2015a. *Steel in the Circular Economy – A Life Cycle Perspective*. Worldsteel Association.
- Worldsteel Association, 2017a. *Steel Markets*. Worldsteel Association (Accessed: 30 January 2017). <http://www.worldsteel.org/Steel-By-Topic/Steel-Markets/Buildings-And-Infrastructure.html>.
- Worldsteel Association, 2013. *Sustainable Steel – Policy and Indicators 2013*. Worldsteel.
- Worldsteel Association, 2012a. *Sustainable Steel: At The Core Of A Green Economy*. Worldsteel Association.
- Worldsteel Association, 2012b. *The White Book of Steel*. Worldsteel.
- Worldsteel Association, 2015b. *Water Management in the Steel Industry*. Worldsteel Association.
- Worldsteel Association, 2017b. *World Steel in Figures*. Worldsteel Association.
- WSSSTP, 2013. *Research and Technology Development Needs for Water and Steel*. Water Supply and Sanitation Technology Platform, Brussels.
- Xu, L., Wang, C., 2018. Sustainable manufacturing in a closed-loop supply chain considering emission reduction and remanufacturing. *Resour. Conserv. Recycl.* 131, 297–304. <https://doi.org/10.1016/j.resconrec.2017.10.012>.
- Yellishetty, M., Mudd, G., Mason, L., Mohr, S., Prior, T., Giurco, D., 2012. *Iron Resources and Production – Technology, Sustainability and Future Prospects*. CSIRO & Monash University, Sydney ISBN 978-1-922173-46-1.
- Yellishetty, M., Mudd, G., Ranjith, P.G., Tharumarajah, A., 2011b. Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects. *Environ. Sci. Technol.* 14–6, 650–663. <https://doi.org/10.1016/J.Envsci.2011.04.008>.
- Yellishetty, M., Mudd, G.M., Ranjith, P.G., 2011a. Availability, addiction and alternatives: three criteria for assessing the impact of peak minerals on society. *J. Clean. Prod.* 19, 78–90. <https://doi.org/10.1016/j.jclepro.2010.12.006>.
- Yildirim, I.Z., Prezzi, M., 2011. Chemical, mineralogical, and morphological properties of steel slag. *Adv. Civ. Eng.* <https://doi.org/10.1155/2011/463638>.
- Zore, Z., Cucek, L., Kravanja, Z., 2018. Synthesis of sustainable production systems using an upgraded concept of sustainability profit and circularity. *J. Clean. Prod.* 201, 1138–1154. <https://doi.org/10.1016/j.jclepro.2018.07.150>.