INTEGRATING LIFE CYCLE ANALYSIS INTO SYSTEM DYNAMICS: THE CASE OF STEEL IN EUROPE

PINTO, Julian T. M. [a b c] *; SVERDRUP, Harald U. [a b]; DIEMER, Arnaud [a c]

[a] European Commission's Horizon 2020 Programme, Marie Skłodowska Curie Fellowship Actions in Excellent Research, AdaptEconII Project;

[b] Department of Industrial Engineering, University of Iceland, Reykjavik, Iceland;

[c] Centre d'Etudes et de Recherches sur le Développement International (CERDI), Université Clermont-Auvergne, Clermont-Ferrand, France;

* 26 avenue Léon Blum, 63000, Clermont-Ferrand, France. Email: julian.torres@live.it

Abstract: This article used the European steel industry as a case study to explore the potential benefits of integrating Life Cycle Analysis (LCA) into System Dynamics (SD) under the scopes of Circular Economy and Industrial Ecology. The study's aim was to verify if this integration could provide additional benefits for decision-making on the biophysical aspects of long-term materials sourcing. Nevertheless, a prior assessment of whether or not such an integration can reproduce existing literature's results generated independently by LCA and SD was deemed worthy of exploration. To do so, first, relevant literature was brought forward and both LCA and SD were subjected to a SWOT analysis. Then, a model representative of the European steel industry's supply chain was built modularly in the Stella Architect software with the support of a Causal Loop Diagram (CLD) and of Business Process Mapping. In addition to the base run, three more simulation runs were performed by the model, using data collected following LCA guidelines and standards from ILCD and ISO. Results indicated that integrating LCA into SD is feasible and capable of not only reproducing independently generated results, but also of contributing to both SD and LCA in different levels, however, further development is necessary in order to include indicators. The authors believe that this approach has potential to interest policy-makers who seek more granularity as well as industrial decision-makers searching for a broader understanding of their operation.

Keywords: Steel, Europe, System Dynamics, Life Cycle Assessment, Industrial Ecology

Highlights: - Compiles relevant SD and LCA studies on steel and presents SWOT Analyses of SD and LCA;

- A model integrating LCA into SD is developed and four simulation runs are performed;

- Uses the European steel industry as a case study, following ISO and ILCD guidelines and standards.

- Integration is feasible and beneficial for both SD and LCA in different levels;

<heading level 1> INTRODUCTION

Steel is the most commonly used alloy of iron and has historically been one of the most essential materials worldwide. It is present in most aspects of everyday life, from infrastructure to transport, from canned food to electronics (World Steel Association, 2012; Beddows, 2014). Steel's cycle through environment and society originates in the ores mined from mountains and underground reserves and most commonly meets its end inside long service life structures or as recyclable scrap (Warrian, 2012; Vaclav, 2016).

Especially during the last decade, steel industries worldwide have expanded their strategic outreach towards environmental goals, improving their supply chain management to encompass both end-of-life and circularity solutions (D'Costa, 1999). Today, steel in Europe is recycled at a 70% rate and most of its byproducts can be reused in other industries (Yellishetty, et al. 2012; World Steel Association, 2017a). In comparison to the 1980s, the average manufacture now uses 50% less energy, helping vehicles become more fuel efficient with stronger and lighter steel alloys, sometimes even being environmentally competitive enough to front plastics and aluminum products (Warrian, 2012; World Steel Association, 2013b; Vaclav, 2016).

As a consequence of the current geopolitical circumstances, the ever-growing presence of Chinese and Indian steelmakers, as well as the decreasing demand from the automotive and energy sectors in Europe and in developed Asian nations, the bold technocentric decision-making behaviors of the post-War period have given way to complex evaluations in capacity, portfolio and environmental impacts of the Technology Critical Elements (TCEs) present in steel (Vaclav, 2016; World Steel Association, 2017b; Nuss and Blengini, 2018).

In order to better support and inform decision-makers regarding their strategies for the future of steel industries, managerial scientists, engineers and academics developed new tools and methods (van Berkel et al., 1997; Baas & Boons, 2004).

Renowned worldwide after the success of the Kalundborg Industrial Park, Industrial Ecology (IE) studies, organizes and models industrial activities and their interactions with the environment by approaching them more organically, in an attempt to benefit from their potential to behave as natural closed-loop systems – in which outputs can become inputs – instead of a traditional open-loop ones – in which outputs end up in sinks (Erkman, 1997; Ehrenfeld, 1997; Ehrenfeld, 2004; Nielsen, 2007; Taddeo, 2016; Prosman et al., 2017).

IE tangibly addresses (a) material and energy flows – known as Industrial Metabolism –, (b) technological change, (c) eco-design, (d) life-cycle planning, (e) dematerialization, (f) decarbonization, (g) corporate responsibility and stewardship, and (h) industrial parks – known as Industrial Symbiosis (Chevalier, 1995; Cohen-Rosenthal, 2004; Gibbs & Deutz, 2007; Despeisse, et al. 2012; Leigh & Li, 2015).

IE professionals nowadays exchange a lot with Circular Economy (CE), which approaches materials from two perspectives: biological nutrients – that should eventually reintegrate the biosphere without causing any harm –, and technical nutrients – which circulate in the economy (Pearce & Turner, 1989; Seager & Theis, 2002; Korhonen, 2004; Ellen McArthur Foundation 2012, 2013, 2014b; Liao et al., 2012; Tukker, 2015; Geissdoerfer et al. 2017).

Aiming to promote the shift from traditional linear production process towards circular ones, CE suggests that all economic activities should be performed focusing on (a) the use of wastes as inputs, (b) the adoption of renewable and clean energy sources,

(c) the accurate biophysical costs of their extraction, transformation, use and reinsertion into either economy or biosphere, and (d) outputs designed from the beginning so as to facilitate collection, recycling, refurbishing, reuse, redistribution, maintenance and sharing throughout their lifespan (Park et al., 2010) (Ellen McArthur Foundation, 2014a, 2015a, 2016, 2017; Haas et al. 2015).

In 2012 the European Union and its members have committed to the application of CE as its economic model, boosting a transition to resource-efficient practices that eventually lead to a regenerative progress toward nature (Zhijun & Nailing, 2007; UNEP, 2011; European Commission, 2012; Su et al., 2013; Kahle & Gurel-Atay, 2014; Ellen McArthur Foundation, 2015b; Gregson et al., 2015).

This article focuses on Life Cycle Assessment (LCA) – one of the tools within IE –, and on System Dynamics (SD) – another methodology that can support CE in achieving such a goal (Lewandowski, 2016; Pomponi & Moncaster, 2017; Winans et al., 2017). We propose that the integration of LCA into SD could provide additional benefits for decision-making on the biophysical aspects of long-term materials sourcing. First, however, it was deemed important to ensure that both LCA and SD would operate properly together, by assessing whether or not such integration could generate results similar to those in existing literature generated independently by LCA and SD.

In the interest of identifying possible barriers or constraints to the integration, available literature was investigated and both LCA and the SD methodology were subjected to SWOT analyses. Next, Business Process Mapping allowed for a clearer understanding of the intricacies within the European steelmaking supply chain in a micro-scale, subsiding the creation of a Causal Loop Diagram (CLD) to conceptualize both problem and system under study. Then, system modelling took place in the Stella

Architect software with the support of LCA's ISO and ILCD standards and guidelines and, once the model of a supply chain representative of the steel industry in Europe was built, four simulation runs were performed, leading to the discussions presented later in this article.

<heading level 2> LCA AND ITS USES IN THE EUROPEAN STEEL INDUSTRY

As a tool, LCA allows for the measurement of environmental impacts and environmental performance of a product throughout a supply chain, enabling detailed analyses and also comparisons with similar goods (Tietenberg, 2004; ISO 2006). LCA has gained ground over the years due to its great quantitative diagnostic application, helping companies identify improvement opportunities in their supply chains (Hunt & Franklin, 1996; Sonnemann et al., 2004).

By individually analyzing the environmental impacts and environmental performance of each stage of a product's life cycle, LCA allows product designers and decision-makers to better visualize the ramifications of inserting a product into the market (Ferreira, 2004). This then allows for the revision and correction of a product's characteristics or of a supply chain's operation in order to reduce potential harm to the environment (Daddi et al., 2017).

The life cycle of steel, summarized in Figure 1, begins with at least one of two main raw materials: iron ore or steel scrap. Iron ore is mined from Hematite (Fe_2O_3, ~ 70% Fe content), Magnetite (Fe_3O_4, ~ 72% Fe content), Limonite ($2Fe_2O_3+3H_2O$, ~ 59% Fe content), Goethite ($Fe_2O_3+H_2O$ ~ 63% Fe content) or Siderite ($FeCO_3$, ~ 48% Fe content) (Stubbles, 2017; Jones, 2017; Kozak & Dzierzawski, 2017).

Steel scrap, on the other hand, often has over 95% Fe content and, once given the appropriate triage and treatment, goes straight into steelmaking after its collection from manufacturing processes, recycling centers, junkyards or even landfills (Warrian, 2012; World Steel Association, 2012; Beddows, 2014; Stahl, 2017).

Figure 1 – Steel's life cycle (adapted from World Steel Association, 2015)

<< insert Figure 1 here >>

Steel can leave the manufacturing stage in many forms with many different chemical and mechanical characteristics, depending on the application to which it was designed (Beddows, 2014; Stahl, 2017). Once it goes into the use stage, it will be stored, reused and remanufactured until losses in quality demand its recycling (World Steel Association, 2012; Vaclav, 2016). Throughout this entire sequence of stages, however, energy is consumed, byproducts are created and environmental impacts are generated, all of which can be measured by a LCA.

By following the guidelines of ISO 14040:2006 and using Simapro as a modelling platform to analyze data from Ecoinvent, Burchart-Korol (2013) developed a LCA of the Polish steel industry. In the study, the functional unit was set to one ton of cast steel produced within Polish cradle-to-gate boundaries, resulting in CO_2eq emissions measurements according to IPCC and CED criteria, as well as in ReCiPe Midpoint indicators for 17 different categories of environmental impacts per main productive process. Not only were the authors capable of identifying the human health and environmental risks posed by the raw materials as well as the energy demand of each productive process, but also to suggest changes in energy sourcing that could allow for the Electric Arc Furnace (EAF) method to be less emission-intensive (Burchart-Korol, 2013).

A similar study was performed in the Turkish steel industry, in which 14 IMPACT2002+ Midpoint indicators were used instead of ReCiPe's 17, focusing on five different steel products: billet, slab, hot rolled wire rod, hot rolled coil (Olmez et al., 2015). The main contributions of this study were (a) identifying hot rolled products as the most environmentally hazardous due to their intensive emission of inorganic particles – thus requiring efficient dust collection methods –, and (b) highlighting the significant Global Warming Potential of this industry as a whole due to its high consumption of fossil fuels (Olmez et al., 2015).

Another similar example of LCA pertinent to the discussion at hand took place in Italy, additionally considering emissions from logistics while focusing on a functional unit of 1 million tons of steel slab (Renzulli et al., 2016). Unlike previous studies, this one suggested the regional reuse of BOF and BF slag for agriculture or infrastructure purposes as a mean to help reduce the overall environmental impact of the production process, while also suggesting a partnership with nearby power plants in order to improve energy efficiency (Renzulli et al., 2016).

Based on literature and practice just as much as on the examples above, Table 1 summarizes the analysis of strengths, weaknesses, opportunities and threats (SWOT) executed by the authors of this article.

Table 1 - SWOT Analysis of Life Cycle Assessment

STRENGTHS	WEAKNESSES
▪ Focus on environmentally friendly product design and its development; ▪ Strong diagnostic and planning approach; ▪ Clear depiction of stocks and flows of a product along a supply chain; ▪ Stakeholder involvement in the supply chain is made visible; ▪ Internationally accepted and indicator-friendly; ▪ Linear, bottom-up approach; ▪ Model structure is objectively representative;	▪ Complex inputs and outputs; ▪ Limited comparability due to high specificity; ▪ High time and effort requirements; ▪ Limited to one product/good at a time; ▪ Limited scenario analyses, often requiring One-Factor-at-a-Time (OFAT) approach; ▪ Lack of a time frame can limit long-term decision-making application; ▪ Disaggregation level can pollute the identification of key issues; ▪ Standard application does not consider market dynamics;
OPPORTUNITIES	THREATS
▪ Allows for ISO certification; ▪ Can spearhead public image efforts regarding a company’s environmental concerns; ▪ Standardization allows for cross-cultural exchanges;	▪ Interpretation of results can be confusing, misleading or complex for general management or communication purposes; ▪ Scarce expertise; ▪ Vulnerable to data availability; ▪ Data inputs regarding future trends or behaviors depend on exogenous sources;

Sources: Hunt & Franklin (1996), Huijbregts (2002), Ferreira (2004), Sonnemann et al. (2004), ISO (2006), Finnveden et al. (2009), Curran (2012), Ahmed (2012), Daddi et al. (2017).

It is from understanding and experiencing some of the limitations above as well as the limited availability of literature on LCA for European steel that the authors of this article considered also exploring how SD can support decision-making in the steel industry.

<heading level 2> SD AND ITS USES IN THE STEEL INDUSTRY

While LCA is capable of giving scholars and decision-makers a very insightful snapshot of a supply chain, SD can, in turn, transform that snapshot into a film. Decision-makers gain, thus, the means to analyze a supply chain as it progresses through the effects of multiple feedbacks and loops of which visibility, relevance or scale could only become evident with the passage of time or with their simultaneous interactions (Forrester, 1962; Booth & Meadows, 1995).

SD is a methodology for studying complex nonlinear behavior within systems, often used for simulating new potential behaviors by adding, removing or changing variables, triggers and delays (Sterman, 2000; Ogata, 2003). To do so, it deconstructs a system into smaller – often binary – interactions and analyzes their behavior not only independently but also as part of the whole, which then generate balancing or reinforcing loops that help determine the system's overall behavior (Ruth & Hannon, 2012).

Instead of pushing data through series of stocks and flows – as LCA commonly does –, SD lets the ensemble of interactions between each correlated pair of variables define the behavior of the system and more easily represents circular behaviors when compared to other methodologies (Ogata, 2003; Ruth & Hannon, 2012). This approach allows for very small-scale problem-solving just as much as it allows for the analysis of large-scale interactions, often encompassing market dynamics and relying on endogenous data to create projections and trends (Sterman, 2000; Ruth & Hannon, 2012).

SD derived from the school of Systems Thinking of the 1950s and 60s, which intended to support and improve productive decision-making (Forrester, 1962; Booth & Meadows 1995), and its application begins on the definition of a clear question. It then proceeds to conceptualize the system where the problem is located, step during which its components, the causal relations and the feedbacks therein are mapped, generating a Causal Loop Diagram (CLD) (Forrester, 1969; Coyle, 1996; Haraldson, 2004; Morgan, 2012; Capra & Luisi, 2014).

Next, the CLD is converted into a Flow Chart (FC), an empirical model which allows for data and variable inputs, usually built in a modelling software such as Stella or Vensim (Morgan, 2012; Ruth & Hannon, 2012). Once a model that precisely represents the reality of the system involved in the question at hand has been built and pertinent data has been added to its components, results and analyses can be derived from the simulation of scenarios (Randers, 1980; Karnopp et al., 1990; Sterman, 2000; Ogata, 2003).

Regarding the steel industry, and especially in Europe, not many studies and publications have yet made use of SD. Below, the authors present examples of SD studies on steel performed by researchers in China, Iran, Sweden and the United Kingdom.

The first study consisted of a macro-level analysis of the sintering process, one of the raw material preparation steps commonly used in the ironmaking stage. Both CLDs and FCs were created, resulting in a SD model capable of replicating the known behavior of sintering operations in the Anshan Iron and Steel Corporation (AISC) (Liu et al., 2015). The model was then used to run a multi-variable simulation comparing the AISC’s operation to the Shouqin Corporation’s operation, pointing to the latter as capable of delivering sinter with better compactedness and higher iron content to the Chinese market (Liu et al., 2015).

The next study focused on reducing the consumption of natural gas and oil in Iranian national steelmaking by simulating the energy requirements through 20 years of subsidies, exports and consumption (Ansari & Seifi, 2012). A macroeconomic SD model was created to test the aforementioned variables simultaneously and in face of price variations, resulting in up to 33% reductions in fossil fuel consumption depending on the mix of subsidy reforms, recycling stimuli and EAF deployment scenarios (Ansari & Seifi, 2012).

Next, researchers studied how SD can support decision-makers in identifying the main obstacles for extending a product's lifespan so as to comprise multiple life cycles (Asif et al., 2015). Global and North American data on steel was used to build a simplified global SD model in which resource scarcity and steel consumption were defined as the main drivers (Asif et al., 2015). As a result, the researchers suggested that enterprises and nations should attempt to keep scarce or non-renewable resources within their supply chains for as long as possible during multiple life cycles in order to accrue the most economic and environmental advantage possible (Asif et al., 2015).

The last study brought to the reader's attention was one of the earliest concerning the steel industry using SD as a methodology. In it, the researchers attempted to create a model capable of reproducing the effects of bottlenecks, breakdowns and other operational constraints in steelmaking supply chains which adopt Minimum Reasonable Inventory (MRI) as a business strategy (Hafeez et al., 1996). After simulating different operational scenarios, the main outcome of the study was a set of strategies to achieve MRI for each individual stock unit according to system-wide operational risks, instead of altogether uniformly, which would tend to require either operational risk insurances or higher levels of working capital binding (Hafeez et al., 1996).

As previously performed for LCA, Table 2 summarizes the SWOT analysis of SD considering the examples above as well as other relevant literature.

Table 2 - SWOT Analysis of System Dynamics

STRENGTHS	WEAKNESSES
▪ Focus on circularity, causality and the effects of variables over time; ▪ Strong for strategic analyses and problem-solving; ▪ Can include subjective or abstract variables; ▪ Allows for the analysis of more than one product/good at a time; ▪ Model structure is easy to adapt and change if necessary; ▪ Non-linear, top-down approach; ▪ Can be used for modelling market dynamics;	▪ Strategic analyses often do not suffice for effective decision-making; ▪ Visualization of stakeholder involvement is highly dependent on how the model is built; ▪ Levels of error and uncertainty are harder to determine; ▪ Aggregation can hide or ignore important variables if not done carefully; ▪ Model structure might not be objectively representative; ▪ Limited support for using indicators;
OPPORTUNITIES	THREATS
▪ Can be of great use for communication purposes; ▪ Can foster the development of multidisciplinary studies; ▪ Can generate endogenous trends and projections;	▪ Scarce expertise; ▪ Analyses can become over-simplistic; ▪ Vulnerable to data reliability;

Sources: Forrester (1962), Booth & Meadows (1995), Coyle (1996), Hafeez et al. (1996), Ogata (2003), Haraldson (2004), Ansari & Seifi (2012), Capra & Luisi (2014), Asif et al. (2015), Liu et al. (2015), Kunc (2017).

After having finished SWOT analyses for both LCA and SD, the authors identified multiple points of divergence but also of convergence. Most importantly, however, is that in situations where one flounders, the other often excels, thus pointing to the potential benefits of a combined approach.

<heading level 1> METHODOLOGY

This section is divided in three parts, namely (a) Research Design – in which the authors introduce question, case-study and the methodological steps –; (b) Model Description – in which the model itself and its development are explained –; and (c) Parameterizing and Operation – where details regarding data inputs, variable control and simulation runs are described.

<heading level 2> RESEARCH DESIGN

Some of the challenges of integrating LCA into SD were identified by their respective SWOT analyses, however, considering that neither was intentionally devised to work with each other, as well as the lack of documented attempts of such an integration until now, the primary concern was to properly envision where, when and how LCA and SD could supplant each other’s weaknesses while maintaining their own strengths. With that in mind, a methodological question took priority over the originally conceived one, resulting in the following:

1. Can the integration of LCA into SD reproduce the results or behaviors previously observed in studies that used LCA or SD independently?

2. What potential benefits derive from this integration toward decision-making on the biophysical aspects of long-term materials sourcing?

Keeping in mind the frameworks and concepts of both IE and CE, the main expected result of the study was achieving a favorable answer to the first question, which would hypothetically indicate that the integration was realized adequately and to the extent of not interfering with either SD's or LCA's correct implementation. The results to be reproduced from previous studies derived from literature already presented thus far, as well as from data input sources to be introduced further in this section.

The criteria for answering the second question, on the other hand, were compiled from the SWOT analyses. It was expected that SD's broader and more flexible modelling approach would contribute to LCA's (a) circularity, (b) long-term perspective, and (c) the macro analysis potential. Simultaneously, it was expected that by keeping LCA and its objective representation of an operation at the core of the integration would allow it to improve SD's (d) stakeholder involvement identification, (e) analysis reliability, and (f) applied/practical usefulness across managerial levels.

The case study used for testing this integration was the European steel industry, chosen by the authors due to its current transition toward more environmentally-concerned decision-making, to its importance for the European economy, to its global contextual concerns regarding the rise of international competitors, and due to its broad operational scope.

As such, the European steel industry posed as an interesting benchmark for the integration attempted in this study, benefits of which could potentially further support both economic and environmental aspects of European policy- and decision-making.

Therefore, as boundary, the study took into account the EU28 zone, represented by the supply chains of the steelmakers members of the Worldsteel Association that operate within it, which account for 84% of the entire European steel industry.

In order to adequately represent this industrial sector, the study followed the methodological steps shown in Figure 2, being the first one a Business Process Mapping (BPM) aimed at identifying all the core processes of steelmaking in Europe, carried out with the support of the BizAgi software. From the start, focus was given to the biophysical transformations that take place throughout the supply chain, keeping in mind European average steel production behavior.

Figure 2 – Methodological steps for model development

<< insert Figure 2 here >>

Once the core processes of European steelmaking were mapped, the next step involved the creation of a Causal Loop Diagram (CLD) capable of representing such a system while also encompassing all the elements necessary to answer the questions previously introduced.

As seen in Figure 3, iron was defined as the driving chemical element of steelmaking, while steel scrap and iron ore were defined as the key raw materials. Nevertheless, connections to all other chemical elements and raw materials involved in steelmaking were included so as to properly enable the subsequent Flow Chart (FC) modelling step.

Two different levels of aggregation were adopted: cradle-to-gate processes were disaggregated down to chemical level, while gate-to-cradle processes were aggregated to product level. This choice was made in order to give decision-making granularity for the steelmakers without overencumbering macro-level analyses that could affect policy-making on end-of-life and circularity services.

Figure 3 – CLD of the system under study, made in OmniGraffle

<< insert Figure 3 here >>

In order to obtain the desired alloy, 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* (i.e. recycling, and repair/refurbishment), so as to enable the system to operate under the definitions of CE and IE.

However useful the CLD was, FCs were identified as the key structural feature of SD that would allow for LCA's integration. Therefore, all of the next steps took place in ISEE Systems' Stella Architect software (ISEE Systems, 2016) and, based on what was learned during the development of the CLD, step 3 was approached modularly in an attempt to make the model as scalable and flexible as possible for use by any stakeholder involved in a European steel supply chain.

<heading level 2> MODEL DESCRIPTION

During Flow Chart (FC) modelling twenty modules were created, one for each chemical element involved in the steel supply chain (e.g. iron, carbon, nickel, chromium, zinc, oxygen), being iron the key driving module as per the CLD. All modules used a functional unit (FU) of 1 ton of steel and were built to be structurally identical, being specific flows and stocks introduced whenever necessary so as to properly represent the typical behaviors of each chemical element throughout the supply chain.

Within each module, the production processes and the stocks of steelmaking were approached modularly and established as individual LCA-based units, capable of being displaced, rearranged or replicated with minimal interference in the overall structure of the model. This allowed for the user interface to be less polluted then traditional SD models and should enable this model to be easily adapted to the reality of different stakeholders in the future.

As exemplified in Figure 4, the 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/Refurbishment – which feeds back into each economic sector according to their share in its demand; and (h) Losses & Landfills – which configures a process-based sink.

Figure 4 – Iron (Fe) Module’s Flow Chart Interface Diagram

<< insert Figure 4 here >>

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 (6) no pricing, costing or speculative variables were considered.

Finally, a control panel was created in order to facilitate the visualization and management of data inputs and variable control, as well as for the easier identification of issues. As exemplified in Figure 5, it allows for the (a) adjustment of variables that affect all 20 modules, (b) monitoring of stocks, flows and outputs of the supply chain, and (c) follow-up on operational losses. Moreover, different levels of granularity were made possible for analysis merely by switching on and off the tracking of individual chemical elements.

Figure 5 – Control Panel, highlighting Iron (Fe)

<< insert Figure 5 here >>

<heading level 2> PARAMETERIZING AND OPERATION

Based on the CLD and on the FC modelling methodological steps, data collection took place next. Table 3 summarizes the data inputs used in the study, all of which encompassed the interval between 2001 and 2014, and were verified for cohesion, coherence and reliability based on the criteria of the ILCD Handbook (European Commission, 2010) and of ISO14044:2006 (ISO, 2006) [1], as well as being compared to their equivalent data points in the Worldsteel Association's Life Cycle Inventory Study for Steel Products (World Steel Association, 2017c).

Table 3 - 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), World Steel Association (2012, 2017b, 2017c), European Union (2011), Madias (2013), Cullen et al. (2012), Yellishetty et al. (2011), EUROFER (2017a)
BFBOF Inputs	Ore, Hot Blast, Scrap, Water, Limestone, Coke, Dolomite	kg/kg of steel	
Typical Chemical Compositions of the Inputs	Scrap, Ore, Coke, Natural Gas, Coal, Dolomite, Limestone, Hot Blast	%	MINDAT (2017) WEBMINERAL (2017)
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 & Prezzi (2011), Adegoloye et al. (2016), EUROSLAG (2017)
Typical Composition Ranges of Emissions to the Atmosphere	EAF Emissions, BF Emissions, BOF Emissions	%	Ferreira & Leite (2015), Ramírez-Santos et al. (2018), Uribe-Soto et al. (2017), Schubert & Gottschling (2011)
Stocks In Use	Automotive,	tons	Pauliuk et al. (2013)

[1] 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.

Participation of Economic Sectors in Steel Demand	Construction, Tools+Machinery, Appliances+Electronics, Heavy Mechanical Equipment, Other Transportation	%	World Steel Association (2017b)
Typical Lifespan of Steel per Economic Sector (as delays)		years	Cooper, et al. (2014)
Recycling/Refurbishment Rate per Economic Sector		%	NFDC (2012), EUROSTAT (2017), Björkman & Samuelsson (2014), BIR (2015), Panasiyk et al. (2016), EUROFER (2017b), Eckelman et al. (2014)
Repair/Reuse Rate per Economic Sector		%	NFDC (2012), EUROSTAT (2017), Dindarian & Gibson (2011), Truttmann & Rechberger (2006), Bovea et al. (2016), Kissling et al. (2013), RREUSE (2012), Eckelman et al. (2014)
Distribution and End-of-Life Losses		%	Pauliuk et al. (2017)
Typical Cooling Water Reuse and Recycling Rates	EAF Cooling Water, BFBOF Cooling Water	%	World Steel Association (2015), WSSTP (2013), Burchart-Korol & Kruczek (2015)

The base run of the model was then parameterized for annual calculations during a period of 200 years, assuming that the demand for steel focused on steel UNS S30400. 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. Keeping in mind that all of the steelmakers considered within the boundaries of the study either import iron ore or ship it from their international branches, a parameter regarding iron ore availability was also set. The parameters used in the base run can be seen in Table 4.

Table 4 - Summary of parameters used to test and run the model

Parameter	**Value**	**Unit**	**Sources**
EAF Tap-to-Tap Time (1)	0,8	hours	Shamsuddin (2016), World Steel Association (2012, 2017b, 2017c), European Union (2011), Madias (2013), Cullen et al. (2012), Yellishetty et al. (2011), EUROFER (2017a)
EAF Furnace Capacity	100.000,00	kg	
BFBOF Cycle Capacity	42.000,00	kg/batch	
BFBOF Productivity (1)	7	batches/h	
Share of EAF Production in the EU28	39,70	%	World Steel Association (2017b)
Share of BFBOF Production in the EU28	60,30	%	
Worldwide Recoverable High-grade Iron Ore	82 billion	tons	Sverdrup & Ragnarsdottir (2014)

(1) As both delay and yield factor.

Finally, and in addition to the base run, the model's behavior was also tested along the lines of the following simulations:

A. Demand of the 6 most produced types of steel (UNS S30400, UNS S31600, UNS S43000, UNS S17400, UNS S32205, UNS S40900), *caeteris paribus*;
B. Linear replacement of BFBOF production for EAF production, *caeteris paribus*;
C. A + B, *caeteris paribus*.

<heading level 1> RESULTS AND DISCUSSION

After performing the simulations, the authors proceeded to verify if the integrated model could reproduce results of studies that used SD and LCA separately. In what regarded SD, the results were favorable and all features of SD remained functional.

Figure 6(a) represents the average biophysical depletion of recoverable high-grade iron ore reserves among all runs. BFBOF production would be forced to begin migrating to inferior grades of iron ores by 2051 and a complete depletion of high-grade iron ore would take place in 2054, 53 years after the initial data point of 2001.

These results very much reproduced those of Sverdrup & Ragnarsdottir (2014), in which such a depletion would occur by the year 2050. Having analyzed and reproduced the means by which their results were achieved, the authors identified that the initial 4-years difference occurred due to two main factors: Sverdrup and Ragnarsdottir (2014) used (a) longer data series and (b) considered the aggregate demand for all steel types.

Figure 6 – High-grade iron ore depletion (a), and presence of iron in the economy (b)

<< insert Figure 6a here >>

<< insert Figure 6b here >>

The inflection points seen after the apices in Figure 6(b) suggest a bottleneck in production capacity, limiting to amount of steel delivered to the market and corroborating the conclusions of Asif et al (2015), in which it was suggested that higher priority should be given to the permanence of resources in a same supply chain as they become scarce, in order to accrue as much environmental and economic benefits from them as possible. To do so for TCEs in the EU28 while keeping in mind CE, however, would require stakeholders within a supply chain to work on improving their operations and their communication, an argument brought up by both Asif et al (2015) and Nuss and Blengini (2018).

Especially considering run C, iron proved not to be an exception to the aforementioned statement: if a transition from BFBOF to EAF production occurs merely linearly until high-grade ore scarcity, steel's presence in the EU28 economy would be forced to go through a decline not only due to other alloying elements, but due to iron itself – argument also previously brought forward by Ansari & Seifi (2012) and Sverdrup & Ragnarsdottir (2014). As mentioned by Asif et al (2015), such pressure can not only increase prices, but also configure a substantial push for substitute materials to gain market share.

Next, regarding LCA, the results were also favorable, but one of its features could not be reproduced. As an example, the average CO_2eq emissions of 837,41kg/FU from EAF production and 2.255,39kg/FU from BFBOF production were aligned with those of Burchart-Korol (2013), however, determining the impacts of these emissions on specific environmental compartments as per ReCiPe indicators, for example, was not feasible. The same outcome occurred for slag generation: while the average results of 459,84kg/FU from the BFBOF and 121,17kg/FU from the EAF aligned with those from Renzulli et al. (2016), determining specific impact indicators was, notwithstanding, unachievable at this point. In the cases of both slag and emissions, nevertheless, the integrated model allowed for easier analysis of individual chemical elements, as exemplified in Table 5.

Table 5 - Summary of observed slag and emission compositions

	Emissions		**Slag**		**Comments**
	BFBOF	**EAF**	**BFBOF**	**EAF**	
CO	39,1%	62,7%	-	-	From partial oxidation in the furnaces.
CO_2	20,8%	3,1%	-	-	From the combustion of fossil fuels.
N	3,4%	30,8%	-	-	Mostly in the form of oxides (NO_x).
H	32,6%	3,3%	-	-	Either as CH_4 or as H_2.
H_2O	4,0%	-	-	-	Byproduct.
Ca	-	-	28,5%	30,6%	As part of CaO and CaS.
O	-	-	36,3%	32,8%	Present in all oxides.
Si	-	-	11,4%	7,3%	As part of SiO_2.
Mg	-	-	4,5%	3,8%	As part of MgO.
Al	-	-	3,9%	2,3%	As part of Al_2O_3.
Cr	*	*	11,8%	1,1%	Free ion or as part of Cr_2O_3.
Mn	*	*	1,5%	3,3%	As part of MnO.
Fe	*	*	0,4%	17,6%	As part of FeO and Fe_2O_3.
P	-	-	0,4%	0,8%	As part of P_2O_5.
S	-	-	1,0%	0,2%	Free ion or as part of CaS.
Zn	*	*	0,3%	0,2%	Free ion or as part of ZnO.
Ti	-	-	*	*	Free ion or as part of TiO2.

* Trace amounts, less than 0,1% altogether.

The results and analyses derived from the integrated model answered favorably the first question, indicating that the integration did not interfere with the results of either LCA or SD. The use of indicators, however, – one of LCA’s features – was rendered impractical. While LCA incorporates indicators from the very beginning of its approach, SD requires them to be modelled individually, point on which more extensive research and development would be necessary.

In order to answer the second question, the authors referred back to the criteria listed in section 2.1, Research Design. Criterion ‘a’ was perceived by the authors as mostly unchanged, with the minor addition of a more detailed understanding of the dynamics of steel in the economy outside of the steelmakers’ gates.

Criterion ‘b’, on the other hand, saw SD give LCA a substantial boost in terms of how many years of steelmaking operation could be simulated or projected using only endogenous data feedback. Whether calculating annualy for a period of 200 years – as performed in this study – or even down to hourly calculations for a certain period of interest, SD’s delay and feedback mechanics allowed LCA to have a better grasp on how the gate-to-craddle dynamics loop back into its mostly cradle-to-gate approach.

The contribution to the improvement of LCA’s macro analysis potential, as per criterion ‘c’, derived mostly from the possibility to track many different elements while concurrently simulating changes in more than one variable at a time throughout the entire supply chain. Moreover, not only did stocks and flows help influence the system’s overall behavior, but so did both feedbacks and delays, features characteristic of SD that broadened LCA’s range of analysis.

With respect to criterion ‘d’, bringing LCA into SD did in fact allow for more precisely and objectively visualizing and accounting the stocks and flows of materials through and within the involved stakeholders, notably after steel leaves the industry and cycles through the economic sectors and through the end-of-life and circularity services. The collection and input of case-specific data following the LCA guidelines of ILCD and ISO improved the reliability and especially the granularity of the SD analyses – criterion ‘e’ –, which were better supported by objective and empirical results such as those exemplified in Table 5.

For these reasons, the practical usefulness of the results across managerial levels – criterion ‘f’ – was also perceived as improved, which could allow for different decision-makers to use the same model for variables that range from chemical composition all the way to ore scarcity and demand planning. In all cases, nevertheless, further improvements to its managerial applicability could be achieved by linking such a model to real-time operational data inputs.

The authors understand that verifying the feasibility and the potential benefits of integrating SD and LCA very much depends on how the integration itself is performed and, considering the methodological steps and the modelling approach used in this study, the integration was deemed not only feasible, but also capable of better supporting stakeholders that would previously only consider SD or LCA, adding to their individual strengths.

With this in mind, it is important to note that LCA seemed to contribute more for the improvement of SD than the other way around. It is to say that, overall, the distinctive diagnostic and process efficiency features of LCA emerged much more tangibly as a result of the integration process than SD’s problem-solving orientation.

For professionals or academics used to LCA applications, the current obstacles for working with indicators might configure enough of a barrier to avoid either a transition or an integration into SD. Future improvements on this integration could potentially solve such issues and favor its adoption. Nevertheless, the aforementioned strategic gains should suffice to attract attention to the discussion and to entice interested agents to further investigate gate-to-cradle dynamics and their feedbacks into production.

For SD scholars, however, the benefits of integrating LCA expertise into SD modelling were substantial. Enhancing the reliability, the granularity and the stakeholder visibility in the results can compensate for many of the weaknesses identified in the SWOT analysis of standard SD applications, notably helping to mitigate the threat of over-simplistic analyses. SD practitioners and policy-makers could take advantage of this approach to better subside their analyses, adding to the levels of objectivity and representativeness of their studies, especially when process efficiency is a key decision factor.

Additionally, particularly from cradle-to-gate, the integrated model was very reminiscent of what IE calls Industrial Metabolism. Certain similarities to Material Flow Analysis (MFA) – another IE tool – became evident as well, especially regarding the visibility of flows and stocks. Also, due to the characteristics of the European steel industry, the model posed as another good example of how CE envisions end-of-life processes as suppliers to the earlier stages of the supply chain. Further studies would need to be done, however, in order to add more renewable energy sources into the operation, as well as to better manage how some chemical elements rejoin the biosphere.

Finally, the authors believe that if data in more disaggregated levels were available, even better results would have been achieved. This could lead to significantly better analyses of individual processes such as sintering, pelletizing, mining, forming, metalworking and recycling, especially regarding emissions and the use of energy directly in the form of heat and electricity.

<heading level 1> CONCLUSIONS AND RECOMMENDATIONS

This study used Business Process Mapping and SWOT Analyses based on relevant SD and LCA studies on steel to subside the creation of a model that integrated LCA into SD. Four simulation runs were performed in ISEE Stella Architect using the European steel industry as a case study and following ISO and ILCD guidelines on data collection. As the main result, the integration was deemed feasible and beneficial for both SD and LCA in different levels.

By allowing the simulation of longer periods of time, the testing of multiple simultaneously changing variables, endogenous feedbacks, and a clear visualization of gate-to-cradle dynamics, SD added some strategic value to LCA, potentially interesting industrial decision-makers who would like to broaden the understanding of their operations. The benefits that LCA brought to SD were more substantial and revolved around increased granularity, reliability and applicability of the results on different managerial levels, factors that could attract policy-makers in need of a deeper understanding of a specific supply chain.

No interferences to the application of SD were identified while reproducing the result of previous studies. The replicability of LCA results from previous studies suffered no interferences either, however, it could not benefit from the use of indicators such as ReCiPe. Further research on how to better integrate LCA indicators into SD is required in order to improve the integration. Moreover, even when integrated into SD, LCA still calls for complex or disaggregated data to be as effective as possible.

Henceforward, the authors recommend further investigation into the integration of LCA and SD. However well aligned it already was to the scopes and frameworks of both IE and CE, more attention to renewable energy sources and to the reintroduction of substances into the biosphere is desirable. Finally, by giving the model pertinent market data and setting other TCEs present in the supply chain as key drivers instead of iron, researchers should also be able to study their scarcity and their effect on demand or prices.

<heading level 1> ACKNOWLEDGMENTS: This article is the first in a series of publications aimed at helping to improve environmentally-oriented policy- and decision-making in the European steel industry, with regard to resource scarcity, supply chain integration and renewable energy sources. It derives from AdaptEconII's project #4, which has received funding from the European Commission's Horizon 2020 Programme through a Marie Skłodowska Curie Fellowship Action in Excellent Research (Grant Agreement no. 675153). The authors would like to thank Mr Gregor Wernet, Executive Director of Ecoinvent, for his methodological insights during the development of this study.

<heading level 1> REFERENCES

ADEGOLOYE, G.; BEAUCOUR, A. L.; ORTOLA, S.; NOUMOWE, A. "Mineralogical composition of EAF slag and stabilised AOD slag aggregates and dimensional stability of slag aggregate concretes." Construction and Building Materials 115, pp 171-178, 2016. https://doi.org/10.1016/j.conbuildmat.2016.04.036

ANSARI, N.; SEIFI, A. "A system dynamics analysis of energy consumption and corrective policies in Iranian iron and steel industry." Energy 43-1, pp 334-343, 2012. https://doi.org/10.1016/j.energy.2012.04.020

ASIF, F. M. A.; RASHID, A.; BIANCHI, C.; NICOLESCU, C. M. "System dynamics models for decision making in product multiple lifecycles." Resources, Conservation and Recycling 101, pp 20-33, 2015. https://doi.org/10.1016/j.resconrec.2015.05.002

BAAS, L. W.; BOONS, F. A. "An industrial ecology project in practice: exploring the boundaries of decision-making levels in regional industrial systems." Journal of Cleaner Production 12-8, pp 1073-1085, 2004. https://doi.org/10.1016/j.jclepro.2004.02.005

BEDDOWS, R. Steel 2050 - How steel transformed the world and now must transform itself. Kingsbridge: Devonian, 2014. ISBN 0993038107

BIR. World Steel Recycling in Figures. Brussels: Bureau of International Recycling, 2015.

BJÖRKMAN, B.; SAMUELSSON, C. "Recycling of Steel." *chapter in* WORRELL, E.; REUTER, M. "Handbook of Recycling", Elsevier, 2014. ISBN 9780123965066

BOOTH, S. L.; MEADOWS, D. The systems thinking playbook. Chelsea Green Publishing, 1995. ISBN 9781603582582

BOVEA, M. D.; IBÁÑEZ-FORÉS, V.; PÉREZ-BELIS, V.; QUEMADES-BELTRÁN, P. "Potential reuse of small household waste electrical and electronic equipment:

Methodology and case study.” Waste Management 53, 2016. DOI: 10.1016/j.wasman.2016.03.038

BRINGAS, J. E.; Handbook of Comparative World Steel Standards. ASTM International, 2004. ISBN 0803133626

BURCHART-KOROL, D.; KRUCZEK, M. “Water Scarcity Assessment of Steel Production.” Metalurgija 54, pp 276-278, 2015.

BURCHART-KOROL, D. “Life Cycle Assessment of Steel Production in Poland: A Case Study.” Journal of Cleaner Production 54, pp 235-243, 2013. https://doi.org/10.1016/j.jclepro.2013.04.031

CAPRA, F.; LUISI, P. L. The systems view of life - a unifying vision. Cambridge: Cambridge University Press, 2014. ISBN 1107011361

CHEVALIER, J. L'économie industrielle des stratégies d'entreprises. Paris: Montchrestien, 1995. ISBN 978-2-7076-1211-3

COHEN-ROSENTHAL, E. “Making sense out of industrial ecology: a framework for analysis and action.” Journal of Cleaner Production 12-8, pp 1111-1123, 2004. https://doi.org/10.1016/j.jclepro.2004.02.009

COOPER, D. R.; SKELTON, A. C. H.; MOYNIHAN, M. C.; ALLWOOD, J. M. “Component level strategies for exploiting the lifespan of steel in products.” Resources, Conservation and Recycling 84; pp 24-34, 2014. https://doi.org/10.1016/j.resconrec.2013.11.014

COYLE, R. G. System Dynamics Modelling: a practical approach. Boston: Chapman & Hall / CRC, 1997. ISBN 978-0412617102

CULLEN, J. M.; ALLWOOD, J. M.; BAMBACH, M; D. “Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods.” Environmental Science and Technology 46, pp 13048–13055, 2012. DOI: 10.1021/es302433p

CURRAN, M. A.; Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products. Beverly: Wiley-Scrivener, 2012. ISBN 978-1-118-09972-8

DADDI, T.; NUCCI, B.; IRALDO, F. “Using Life Cycle Assessment (LCA) to measure the environmental benefits of industrial symbiosis in an industrial cluster of SMEs.” Journal of Cleaner Production 147, pp 157-164, 2017. https://doi.org/10.1016/j.jclepro.2017.01.090

D'COSTA, A. P. The global restructuring of the steel industry - innovations, institutions and industrial change. Oxon: Routledge, 1999. ISBN 0415148278

DESPEISSE, M.; BALL, P. D.; LEVERS, A.; EVANS, S. “Industrial ecology at factory level – a conceptual model.” Journal of Cleaner Production 31, pp 30-39, 2012. https://doi.org/10.1016/j.jclepro.2012.02.027

DINDARIAN, A.; GIBSON A. P. “Reuse of EEE/WEEE in UK: Review on functionality of EEE/WEEE at the point of disposal.” Sustainable Systems and Technology Conference, 2011. DOI: 10.1109/ISSST.2011.5936867

ECKELMAN, M. J.; CIACCI, L.; KAVLAK, G.; NUSS, P.; RECK, B. K.; GRAEDEL, T.E. “Life cycle carbon benefits of aerospace alloy recycling”. Journal of Cleaner Production 80, pp. 38-45, 2014. https://doi.org/10.1016/j.jclepro.2014.05.039

EHRENFELD, J. R. “Industrial ecology: a new field or only a metaphor?” Journal of Cleaner Production 12-8, pp 825-831, 2004. https://doi.org/10.1016/j.jclepro.2004.02.003

EHRENFELD, J. R. “Industrial ecology: A framework for product and process design.” Journal of Cleaner Production 5-1, pp 87-95, 1997. https://doi.org/10.1016/S0959-6526(97)00015-2

ELLEN MCARTHUR FOUNDATION. Towards the circular economy - an economic and business rationale for an accelerated transition. Cowes: Ellen McArthur Foundation, 2012.

ELLEN MCARTHUR FOUNDATION. Towards the circular economy - opportunities for the consumer goods sector. Cowes: Ellen McArthur Foundation, 2013.

ELLEN MCARTHUR FOUNDATION. A new dynamic - effective business in a circular economy. Cowes: Ellen McArthur Foundation, 2014a.

ELLEN MCARTHUR FOUNDATION. Towards the circular economy - accelerating the scale-up across global supply chains. Cowes: Ellen McArthur Foundation, 2014b.

ELLEN MCARTHUR FOUNDATION. Growth within - a circular economy vision for a competitive Europe. Cowes: Ellen McArthur Foundation, 2015a.

ELLEN MCARTHUR FOUNDATION. Delivering the circular economy - a toolkit for policymakers. Cowes: Ellen McArthur Foundation, 2015b.

ELLEN MCARTHUR FOUNDATION. Intelligent assets - unlocking the circular economy potential. Cowes: Ellen McArthur Foundation, 2016.

ELLEN MCARTHUR FOUNDATION. The circular economy - a wealth of flows. Cowes: Ellen McArthur Foundation, 2017.

ERKMAN, S. “Industrial ecology: An historical view.” Journal of Cleaner Production 5-1, pp 1-10, 1997. https://doi.org/10.1016/S0959-6526(97)00003-6

EUROFER. European Steel in Figures. Brussels: EUROFER, 2017a.

EUROFER. Steel, the Backbone of Sustainability in Europe. Brussels: EUROFER, 2017b.

EUROPEAN COMMISSION. ILCD Handbook: General guide for Life Cycle Assessment - Detailed guidance. Luxembourg: Joint Research Centre - Institute for Environment and Sustainability, 2010.

EUROPEAN COMMISSION. Manifesto for a resource-efficient Europe. Brussels: European Commission, 2012.

EUROPEAN UNION. Improved EAF Process Control Using On-Line Offgas Analysis – OFFGAS. Luxembourg: European Union, 2011.

EUROSLAG. European Association of Metallurgical Slag Producers. https://www.euroslag.com (accessed: 05 September 2017).

EUROSTAT. Data reporting on quantity, hazardousness and shipments of waste. http://ec.europa.eu/eurostat/web/waste/data (accessed: 05 September 2017).

FERREIRA, H.; LEITE, M. P. G. “A Life Cycle Assessment study of iron ore mining.” Journal of Cleaner Production 108A, pp 1081-1091, 2015. https://doi.org/10.1016/j.jclepro.2015.05.140

FERREIRA, J. V. Análise do ciclo de vida dos produtos. PhD Thesis. Lisbon: Instituto Politécnico de Viseu, 2004.

FINNVEDEN, G.; HAUSCHILD, M.Z.; EKVALL, T.; GUINÉE, J.; HEIJUNGS, R.; HELLWEG, S.; KOEHLER, A.; PENNINGTON, D.; SUH, S. “Recent developments in Life Cycle Assessment.” Journal of Environmental Management 91-1, pp 1-21, 2009. DOI: 10.1016/j.jenvman.2009.06.018

FORRESTER, J. W. Industrial Dynamics. Boston: MIT Press, 1962. ISBN 1614275335

FORRESTER, J. W. Urban dynamics. Boston: MIT Press, 1969. ISBN 1883823390

GEISSDOERFER, M.; SAVAGET, P.; BOCKEN, N. M. P.; HULTNIK, E. J. “The Circular Economy – A new sustainability paradigm?” Journal of Cleaner Production 143, pp 757-768, 2017. https://doi.org/10.1016/j.jclepro.2016.12.048

GIBBS, D.; DEUTZ, P. “Reflections on implementing industrial ecology through eco-industrial park development.” Journal of Cleaner Production 15-17, pp. 1683-1695, 2007. https://doi.org/10.1016/j.jclepro.2007.02.003

GREGSON, N.; CRANG, N.; FULLER, S.; HOLMES, H. “Interrogating the circular economy: the moral economy of resource recovery in the EU.” Economy and Society 44, pp. 218-243, 2015. https://doi.org/10.1080/03085147.2015.1013353

HAAS, W.; KRAUSMANN, F.; WIEDENHOFER, D.; HEINZ, M. “How Circular is the Global Economy? An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005.” Journal of Industrial Ecology 19-5, pp. 765-777, 2015. https://doi.org/10.1111/jiec.12244

HAFEEZ, K.; GRIFFITHS, M.; GRIFFITHS, C.; NAIM, M. M. “Systems design of a two-echelon steel industry supply chain.” International Journal Production Economics 45-1, pp. 121-130, 1996. https://doi.org/10.1016/0925-5273(96)00052-7

HARALDSON, H. V. Introduction to system thinking and casual loop diagram. Lund: KFS AB, 2004.

HUIJBREGTS, M. “Uncertainty and variability in environmental life-cycle assessment.” The International Journal of Life Cycle Assessment 7, p. 173, 2002. DOI: 10.1007/BF02994052

HUNT, R.; FRANKLIN, E. “How it came about - Personal reflections on the origin and the development of LCA in the USA.” International Journal of Life Cycle Assessment 1-1, pp.4-7, 1996.

ISEE Systems. Stella Architect. https://www.iseesystems.com/store/products/stella-architect.aspx (accessed: 5 May 2017).

ISO. ISO 14044 - Environmental management, life cycle analysis, requirement ans orientations. Geneva: International Standardization Organization, 2006.

JONES, J. A. T. “Electric Arc Furnace Steelmaking.” Steelworks. http://www.steel.org/making-steel/how-its-made/processes/processes-info/electric-arc-furnace-steelmaking.aspx (accessed: 11 February 2017).

JRC - Joint Research Centre - Institute for Environment and Sustainability - European Commission. Product Environmental Footprint (PEF) Guide. Ispra, July 2012. Available at: http://ec.europa.eu/environment/archives/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf

KAHLE, L. R.; GUREL-ATAY, E. Communicating sustainability for the green economy. New york: M.E. Sharpe, 2014. ISBN 0765636816

KARNOPP, D. C.; ROSENBERG, R. C. System dynamics - a unified approach. New York: John Wiley & Sons, 1975. ISBN 0471459402

KISSLING, R.; COUGHLAN, D.; FITZPATRICK, C.; BÖNI, H.; LUEPSCHEN, C.; ANDREW, S.; DICKENSON, J. “Success factors and barriers in re-use of electrical and electronic equipment.” Resources, Conservation and Recycling 80, pp. 21-31, 2013. https://doi.org/10.1016/j.resconrec.2013.07.009

KORHONEN, J. “Industrial ecology in the strategic sustainable development model: strategic applications of industrial ecology.” Journal of Cleaner Production 12-8, pp. 809-823, 2004. https://doi.org/10.1016/j.jclepro.2004.02.026

KOZAK, B.; DZIERZAWSKI, J. “Continuous Casting of Steel: Basic Principles.” Steelworks. http://www.steel.org/making-steel/how-its-made/processes/processes-info/continuous-casting-of-steel---basic-principles.aspx (accessed: 11 February 2017).

KULSUM, A. Getting to Green: A Sourcebook of Pollution Management Policy Tools for Growth and Competitiveness. Washington: World Bank, 2012.

KUNC, M. System Dynamics: Soft and Hard Operational Research. Basingstoke: Palgrave Macmillan, 2017. ISBN 978-1-349-95257-1

LEIGH, M.; XIAOHONG L. “Industrial ecology, industrial symbiosis and supply chain environmental sustainability: a case study of a large UK distributor.” Journal of Cleaner Production 106, pp. 632-643, 2015. https://doi.org/10.1016/j.jclepro.2014.09.022

LEWANDOWSKI, M. “Designing the Business Models for Circular Economy - Towards the Conceptual Framework.” Sustainability 8, pp. 43-51, 2016. DOI:10.3390/su8010043

LIAO, W.; HEIJUNGS, R.; HUPPES, G. “Thermodynamic analysis of human–environment systems: A review focused on industrial ecology.” Ecological Modelling 228, pp. 76-88, 2012. https://doi.org/10.1016/j.ecolmodel.2012.01.004

LIU, C.; XIE, Z.; SUN, F.; CHEN, L. “System dynamics analysis on characteristics of iron-flow in sintering process.” Applied Thermal Engineering 82, pp. 206-211, 2015. https://doi.org/10.1016/j.applthermaleng.2015.02.077

MADIAS, J. “Electric Furnace Steelmaking.” *chapter in* SESHADRI, S. “Treatise on Process Metallurgy”. Elsevier, 2013. ISBN 9780080969879

MINDAT. Mineralogy Database. https://www.mindat.org/ (accessed: 05 September 2017).

MORGAN, M. S. The world in the model. Cambridge: Cambridge University Press, 2012. ISBN 9781107002975

NFDC. The recycling and reuse survey. Herts: UK National Federation of Demolition Contractors, 2012.

NIELSEN, S. N. “What has modern ecosystem theory to offer to cleaner production, industrial ecology and society? The views of an ecologist.” Journal of Cleaner Production 15-17, pp. 1639-1653, 2007. https://doi.org/10.1016/j.jclepro.2006.08.008

NUSS, P.; BLENGINI, G. A. “Towards better monitoring of technology critical elements in Europe: Coupling of natural and anthropogenic cycles”. Science of The Total Environment 613–614, pp. 569-578, 2018. https://doi.org/10.1016/j.scitotenv.2017.09.117

OGATA, K. System dynamics. New York: Prentice Hall, 2003. ISBN 0131424629

OLMEZ, G. M.; DILEK, F. B.; KARANFIL, T.; YETIS, U. “The environmental impacts of iron and steel industry: a life cycle assessment study.” Journal of Cleaner Production 130, pp. 195-201, 2015. https://doi.org/10.1016/j.jclepro.2015.09.139

PANASIYK, D.; LARATTE, B.; REMY, S. “Steel stock analysis in Europe from 1945 to 2013.” Conference on Life Cycle Engineering, Procedia CIRP 48, pp. 348-351, 2016. https://doi.org/10.1016/j.procir.2016.04.084

PARK, J.; SARKIS, J.; WU, Z. “Creating integrated business and environmental value within the context of China’s circular economy and ecological modernization.” Journal of Cleaner Production 18-15, pp. 1494-1501, 2010. https://doi.org/10.1016/j.jclepro.2010.06.001

PAULIUK, S.; WANG, T.; MÜLLER, D. B. “Steel all over the world: Estimating in-use stocks of iron for 200 countries”. Resources, Conservation and Recycling 71, pp. 22-30, 2013. https://doi.org/10.1016/j.resconrec.2012.11.008

PAULIUK, S.; KONDO, Y.; NAKAMURA, S.; NAKAJIMA, K. “Regional distribution and losses of end-of-life steel throughout multiple product life cycles - Insights from the global multiregional MaTrace model”. Resources, Conservation and Recycling 116, pp. 84-93, 2017. https://doi.org/10.1016/j.resconrec.2016.09.029

PEARCE, D. R.; TURNER, K. R. Economics of natural resources and the environment. Baltimore: John Hopkins University Press, 1989. ISBN 9780801839870

POMPONI, F.; MONCASTER, A. “Circular economy for the built environment: A research framework.” Journal of Cleaner Production 143, pp. 710-718, 2017. https://doi.org/10.1016/j.jclepro.2016.12.055

PROSMAN, E. J.; WAEHRENS, B.; LIOTTA, G. “Closing Global Material Loops: Initial Insights into Firm-Level Challenges.” Journal of Industrial Ecology 21-3, pp. 641-650, 2017. https://doi.org/10.1111/jiec.12535

RAMÍREZ-SANTOS, A.; CASTEL, C.; FAVRE, E. “A review of gas separation technologies within emission reduction programs in the iron and steel sector: Current application and development perspectives.” Separation and Purification Technology 194, pp. 425-442, 2018. https://doi.org/10.1016/j.seppur.2017.11.063

RANDERS, J. Elements of the system dynamics method. Massachussets: MIT Press, 1980. ISBN 0915299399

RENZULLI, P. A.; NOTARNICOLA, B.; TASSIELLI, G.; ARCESE, G.; DI CAPUA, R. "Life Cycle Assessment of Steel Produced in an Italian Integrated Steel Mill." Sustainability 8, pp. 719-728, 2016. DOI:10.3390/su8080719

RREUSE. Challenges to boosting reuse rates in Europe. Brussels: RREUSE, 2012.

RUTH, M.; HANNON, B. Modeling Dynamic Economic Systems. New York: SpringerLink, 2012. ISBN 978-1-4614-2209-9

SCHUBERT, E. S.; GOTTSCHLING, R. "Co-generation: A challenge for furnace off-gas cleaning systems." Southern African Pyrometallurgy Institute, 2011.

SEAGER, T. P.; THEIS, T. L. "A uniform definition and quantitative basis for industrial ecology." Journal of Cleaner Production 10-3, pp. 225-235, 2002. https://doi.org/10.1016/S0959-6526(01)00040-3

SHAMSUDDIN, M. Physical Chemistry of Metallurgical Processes. Hoboken: Wiley Kindle Edition, 2016. ISBN 978-1-119-07833-3

SONNEMANN, G.; CASTELLS, F.; TSANG, M.; SCHUMACHER, M. Integrated life-cycle and risk assessment for industrial processes. Madrid: CRC Press, 2004. ISBN 9781566706445

STAHL. “Hot metal and crude steel production.” German Steel Federation. http://en.stahl-online.de/index.php/topics/technology/steelmaking/ (accessed: 11 February 2017).

STERMAN, J. D. Business dynamics - systems thinking and modelling for a complex world. New York: McGraw-Hill, 2000. ISBN 9780072389159

STUBBLES, J. “The Basic Oxygen Steelmaking (BOS) Process.” Steelworks. http://www.steel.org/making-steel/how-its-made/processes/processes-info/the-basic-oxygen-steelmaking-process.aspx (accessed: 11 February 2017).

SU, B.; HESHMATI, A.; GENG, Y.; YU, X. “A review of the circular economy in China: moving from rhetoric to implementation.” Journal of Cleaner Production 42; pp. 215-227, 2013. https://doi.org/10.1016/j.jclepro.2012.11.020

SVERDRUP, H.; RAGNARSDOTTIR, K. V. Geochemical Perspectives: Natural Resources in a Planetary Perspective. Toulouse: European Association of Geochemistry, 2014. DOI 10.7185/geochempersp.3.2

TADDEO, R. “Local industrial systems towards the eco-industrial parks: the model of the ecologically equipped industrial areas.” Journal of Cleaner Production 131, pp. 189-197, 2016. https://doi.org/10.1016/j.jclepro.2016.05.051

TIETENBERG, T. H.; LEWIS, L. Environmental economics and policy. New York: Pearson Addison Wesley, 2004. ISBN 1292026804

TRUTTMANN, N.; RECHBERGER, H. “Contribution to resource conservation by reuse of electrical and electronic household appliances.” Resources, Conservation and Recycling 48-3, pp. 249-262, 2006. https://doi.org/10.1016/j.resconrec.2006.02.003

TUKKER, A. “Product services for a resource-efficient and circular economy - a review.” Journal of Cleaner Production 97, pp. 76-91, 2015. https://doi.org/10.1016/j.jclepro.2013.11.049

UNEP. Towards a green economy - pathways to sustainable development and poverty erradication. Geneva: United Nations' Environmental Programme, 2011.

URIBE-SOTO, W.; PORTHA, J.; COMMENGE, J.; FALK, L. “A review of thermochemical processes and technologies to use steelworks off-gases.” Renewable and Sustainable Energy Reviews 74, pp. 809-823, 2017. https://doi.org/10.1016/j.rser.2017.03.008

VACLAV, S. Still the iron age. Oxford: Butterworth-Heinemann, Elsevier, 2016. ISBN 9780128042359

VAN BERKEL, R.; WILLEMS, E.; LAFLEUR, M. “Development of an industrial ecology toolbox for the introduction of industrial ecology in enterprises.” Journal of

Cleaner Production 5-1, pp. 11-25, 1997. https://doi.org/10.1016/S0959-6526(97)00004-8

WARRIAN, P. A profile of the steel industry - global reinvention for a new economy. New York: Business Expert Press, 2012. ISBN 1631573845

WEBMINERAL. Mineralogy Database. http://webmineral.com/ (accessed: 05 September 2017).

WINANS, K.; KENDALL, A.; DENG, H. “The history and current applications of the circular economy concept.” Renewable and sustainable Energy Reviews 68-1, pp. 825-833, 2017. https://doi.org/10.1016/j.rser.2016.09.123

WORLD STEEL ASSOCIATION. Methodology report Life cycle inventory study for steel products. Brussels: World Steel Association, 2017c.

WORLD STEEL ASSOCIATION. Steel in the circular economy - a life cycle perspective. World Steel Association, 2015.

WORLD STEEL ASSOCIATION. “Steel markets.” World Steel Association (2017a). http://www.worldsteel.org/steel-by-topic/steel-markets/Buildings-and-infrastructure.html (accessed: 30 January 2017).

WORLD STEEL ASSOCIATION. Sustainable steel - policy and indicators 2013. Worldsteel, 2013b.

WORLD STEEL ASSOCIATION. Sustainable steel: at the core of a green economy. World Steel Association, 2012.

WORLD STEEL ASSOCIATION. The white book of steel. Worldsteel, 2012.

WORLD STEEL ASSOCIATION. Water management in the steel industry. World Steel Association, 2015.

WORLD STEEL ASSOCIATION. World Steel in Figures. World Steel Association, 2017b.

WSSTP. Research and Technology Development Needs for Water and Steel. Brussels: Water Supply and Sanitation Technology Platform, 2013.

YELLISHETTY, M.; MUDD, G.; MASON, L.; MOHR, S.; PRIOR, T.; GIURCO, D. Iron resources and production - technology, sustainability and future prospects. Sydney: CSIRO & Monash University, 2012. ISBN 978-1-922173-46-1

YELLISHETTY, M.; MUDD, G.; RANJITH, P. G.; THARUMARAJAH, A. “Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects.” Environmental Science and Technology 14-6, pp. 650-663, 2011. https://doi.org/10.1016/j.envsci.2011.04.008

YILDIRIM, I. Z.; PREZZI, M. “Chemical, Mineralogical, and Morphological Properties of Steel Slag.” Advances in Civil Engineering, 2011. http://dx.doi.org/10.1155/2011/463638

FENG, Z.; NAILING, Y. “Putting a circular economy into practice in China.” Sustainable Sciences 2-1, pp. 95-101, 2007. https://doi.org/10.1007/s11625-006-0018-1