KTH ROYAL INSTITUTE
OF TECHNOLOGY

Doctoral Thesis in Materials Science and Engineering

Recirculation of scrapped resources

The role of material information in enhancing the sustainability of recycling

REINOL JOSEF COMPAÑERO

Stockholm, Sweden 2024

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“Fundamentally, stewardship is about exercising our God-given dominion over His creation, reflecting the image of our creator God in His care, responsibility, maintenance, protection, and beautification of His creation.”

- R.C. Sproul

Abstract

Industries have responded to the climate change problem by positioning their activities as compatible with concepts such as the Circular Economy. Conveying the idea of maximizing and keeping the resources in a manner that aligns with the principles of sustainable development, the endorsements for implementing circularity measures has arguably become a boon for businesses. Firms that have traditionally consumed both primary and anthropogenic resources in the production of materials used in infrastructure, transportation, and other technological requirements are in a special position. On the one hand, their products are needed for societal development. But on the other hand, their activities emit considerable amounts of greenhouse gases.

The steel industry is a classic example where material and energy resource savings are achieved when the End-of-Life (EoL) products are recycled. However, these assumed efficiencies are provisional to scrap being a suitable replacement for ore-based resources. The replacement of primary (i.e. purer) - with secondary (i.e. contaminated) as feedstock for production depends heavily on a recycling system's capability to deal with the complexity of the ferrous scrap streams that society is generating. More specifically, in reference to recovering the material identity through characterization and sorting that lessens or avoids the current practice of either diluting contaminants or compensating for insufficient alloying through addition of primary resources.

This present thesis takes a critical look at the use of scrap with the view that recycling is a technical process that is carried out by enterprises. The impression that recycling consequently replaces the use of primary resources is scrutinized, with consideration of scrap as a characteristically appropriate, but innately challenging feedstock to use. Case studies focusing on the Swedish scrap-based production context revealed that the recycling system actors operate and transact on the basis of scrap's quality, which in turn was interpreted as being multidimensional and dependent on each actor's preferences. The alignment of economic and environmental interests connected with scrap utilization was found to be limited, with companies preferring the use of primary resources when scrap is no longer suitable.

The idea of suitability was then ascribed to compositional information regarding scrap and tested at two levels: having access to partial or full information. The former is what is achieved through the current scrap handling in the reverse loop while the latter is an idealized situation where the exact chemistry of the scrap is known. An optimization program was then used to simulate steel recycling where the scenarios tested were designed to focus on the response of the production model to the scrap chemistry of the input materials. The results obtained showed an overall decrease in production costs and an increase in the proportion of scrap used in production. In most cases, this was attributed to the flexibility to allocate scrap based on its composition to the closest matching target products.

Finally, additional interviews with industry practitioners further clarified established, company-based protocols for dealing with the lack of information and provided insights with regard to opportunities for increasing scrap utilization. An analysis of the responses suggested that there are contextual differences when it comes to practices by each company, and even attitudes, towards anthropogenic resources. Ultimately, the insights from this thesis lend support to the need of enterprises to address the trade-offs related to scrap utilization and lead to enhanced sustainability in steel recycling.

Keywords

Steel recycling, anthropogenic resources, scrap, value of information, Circular Economy, sustainability

Sammanfattning

Industrier bemöter klimatkrisen genom att positionera verksamheten i linje med begrepp såsom cirkulär ekonomi. Genom att förmedla idén om att optimera och cirkulera resurser på ett sätt som överensstämmer med principerna för hållbar utveckling har trycket för att genomföra åtgärder för cirkularitet ökat, samtidigt som det finns tydliga ekonomiska incitament. Företag som traditionellt har förbrukat både primära och antropogena resurser i produktionen av material som används inom infrastruktur, transport och för andra tekniska behov har en särskild ställning. Å ena sidan behövs deras produkter för samhällsutvecklingen. Men å andra sidan ger deras verksamheter upphov till betydande mängder växthusgaser.

Stålindustrin är ett klassiskt exempel där besparingar av material- och energiresurser uppnås när produkterna återvinns i slutet av deras livscykel. De positiva effekterna är dock beroende av att skrot är en lämplig ersättning för malm-baserade resurser. Ersättningen av primära (dvs. renare) resurser med sekundära (dvs. förorenade) som råmaterial för produktionen är starkt beroende av återvinningssystemets förmåga att hantera komplexiteten hos de järn- och stål-skrotströmmar som samhället genererar. Mer specifikt, behöver aktörerna i värdekedjan återställa materialets identitet genom karaktärisering och sortering som minskar eller undviker den nuvarande praxisen att antingen utspäda föroreningar eller kompensera för otillräcklig legering genom tillsats av primära resurser.

Denna avhandling granskar användningen av skrot med uppfattningen att återvinning är en teknisk process som utförs av företag. Intrycket att återvinning följaktligen ersätter användningen av primära resurser granskas, med beaktande av skrot som ett karaktäristiskt lämpligt men samtidigt utmanande råmaterial att använda. Fallstudier som fokuserar på den svenska skrotbaserade produktionskontexten visade att aktörerna inom återvinningssystemet agerar baserat på skrotets kvalitet, vilket i sin tur tolkades som mångdimensionellt och beroende av varje aktörs preferenser. Samstämmigheten mellan ekonomiska och miljömässiga intressen kopplade till skrotanvändning visade sig vara begränsad, med företag som föredrog användningen av primära resurser när skrot inte längre var lämpligt.

Tanken på lämplighet tillskrevs sedan kompositionell information om skrot och testades på två nivåer: att ha tillgång till partiell eller fullständig information. Det förra är vad som uppnås genom den nuvarande hanteringen av skrot i den omvända loopen medan det senare är en idealiserad situation där den exakta kemin hos skrotet är känd. Ett optimeringsprogram användes sedan för att simulera stålåtervinning där de testade scenarierna var utformade för att fokusera på produktionsmodellens respons på skrotets kemiska sammansättning. De erhållna resultaten visade en övergripande minskning av produktionskostnaderna och en ökning av andelen skrot som används i produktionen. I de flesta fall tillskrevs detta flexibiliteten att tilldela skrot baserat på dess sammansättning till de närmast matchande målprodukterna.

Slutligen klargjorde ytterligare intervjuer med branschutövare etablerade och företagsbaserade protokoll för att hantera bristen på information och gav insikter med avseende på möjligheter att öka skrotanvändningen. En analys av svaren antydde att det finns kontextuella skillnader när det gäller praxis från varje företag, och även attityder, gentemot antropogena resurser. Slutligen stöder insikterna från denna avhandling behovet för företag att hantera de kompromisser som är relaterade till skrotanvändning och leder till förbättrad hållbarhet inom stålåtervinning.

Nyckelord:

Stål återvinning, antropogena resurser, skrot, cirkulär ekonomi, hållbarhet

Acknowledgements

Before anything, and above anyone else, all honor to the Creator of this Earth. The motivation to work on this topic of sustainability is because we have so much beauty in this world and have been provided with the resources we need. I am motivated by a desire to do my bit on being a good steward of this planet. There is obviously much to do, but we have the capacity to figure things out.

This thesis is a compilation of four supplements, and my hope is that this written text would give a complete and meaningful representation of my PhD research. Although, the reality is that my whole PhD journey was a continuous accumulation of learnings and experiences, from the workplace and outside of it, across five years (inclusive of a global pandemic). This is my best attempt to express my deepest gratitude to the people, without whom, this journey might have taken longer, or not at all.

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I am grateful to the opponent in my thesis defense, **Dr. Guozhu Ye**, the grading committee, **Dr. Diana Orrling**, **Prof. Jafar Safarian**, and **Assoc. Prof. Ville-Valtteri Visuri**, to **Assoc. Prof. Mikael Ersson** for chairing the defense, and to the substitute at the defense, **Prof. Andreas Archenti**.

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To my parents **Reynaldo** and **Olympia Compañero**, know that this thesis is also proof of your guidance and dedication in raising children who can choose their own paths. And together with my sisters **Karen** and **Katrinna** and her fiancé **Brian**, whose prayers, words of encouragement, and support I have always felt even through a long distance.

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There may be people I missed mentioning or thanking, but I will forever remember this chapter of my life with fondness and gratitude, and by then, surely, I will say thank you again.

Stockholm, February 2024

Reinol Josef Compañero

List of Supplements

Supplement I

Compañero, R.J., Feldmann, A. & Tilliander, A. Circular Steel: How Information and Actor Incentives Impact the Recyclability of Scrap. *J. Sustain. Metall.* 7, 1654–1670 (2021). https://doi.org/10.1007/s40831-021-00436-1

Supplement II

Compañero, R.J., Feldmann, A., Samuelsson, P. *et al.* Appraising the value of compositional information and its implications to scrap-based production of steel. *Miner Econ* (2023). https://doi.org/10.1007/s13563-022-00361-z

Supplement III

Compañero, R.J., Feldmann, A., Samuelsson, P., Jönsson, P.G. A value of information approach to recycling. *First round of revisions in Resources, Conservation and Recycling*

Supplement IV

Compañero, R.J., Feldmann, A., Samuelsson, P., Jönsson, P.G. A review of scrap handling practices and prospects for increasing scrap consumption in recycling. *Under review in Steel Recycling International*

Contribution statement

Supplement	Order of authors	**Contributions**(adopted from Allen 2019)
I	**Compañero, Reinol Josef**; Feldmann, Andreas; Tilliander, Anders	Conceptualization, Investigation, Writing – Original Draft, Writing - Review & Editing, Visualization, Project Administration, Funding Acquisition *Conceptualized the basic idea then performed the interviews and site visits, analysis of the interview data with co-authors, and major part of the writing. Also wrote part of the funding application.*
II	**Compañero, Reinol Josef**; Feldmann, Andreas; Samuelsson, Peter; Tilliander, Anders; Jönsson, Pär Göran; Gyllenram, Rutger	Conceptualization, Methodology, Formal analysis, Investigation, Validation, Writing – Original Draft, Writing - Review & Editing *Conceptualized part of the model then performed all the simulations, part of the data analyses, and major part of the writing.*
III	**Compañero, Reinol Josef**; Feldmann, Andreas; Samuelsson, Peter; Jönsson, Pär Göran	Conceptualization, Methodology, Formal analysis, Investigation, Validation, Writing – Original Draft, Writing - Review & Editing *Conceptualized most of the model expansion then performed all the simulations, most of the data analyses, and all of the writing.*
IV	**Compañero, Reinol Josef**; Feldmann, Andreas; Samuelsson, Peter; Jönsson, Pär Göran	Conceptualization, Methodology, Formal analysis, Investigation, Validation, Writing – Original Draft, Review & Editing *Conceptualized the topic then performed part of the interviews, analyses of the interview data, and all of the writing.*

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List of abbreviations

CE	Circular Economy
EAF	Electric Arc Furnace
EoL	End-of-Life
EVPI	Expected Value of Perfect Information
RMM	RAWMATMIX®

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Chapter 1: Introduction

Crutzen (2002) referred to the period of increasing human impact on the Earth, signified by the rising levels of CO_2 in the atmosphere, as the 'Anthropocene', and stated that *"a daunting task lies ahead for scientists and engineers to guide society towards environmentally sustainable management."* The risk of a future impacted negatively by climate change brings a sense of urgency because, *"no city, region, or country alone could insulate* itself *from its effects"* (Jones, 2017). With the changing global environment, one approach is to take the initiative and *"…take the human pressure off of the Earth System by vastly improved technology and management, wise use of Earths' resources…"* (Steffen et al., 2007).

The idea that society is operating beyond the limits of the Earth's capacity is a stimulus for behaving sustainably (McMichael et al., 2003; Raven, 2002). Sustainability, or sustainable development as it is defined in the report of the Brundtland Commission (Brundtland, 1987; Holdgate, 1987), is based on an agreement to fulfill the threefold mission according to Huber (2000): to facilitate economic development while ensuring that ecological limits are respected in securing social equity. The philosophy of firms transformed, from profit at all costs to paying attention to the environment (Sarkis and Zhu, 2018). Sustainable development to an extent signifies continued production and consumption so that developing regions could have the opportunity to catch-up and achieve a high level of well-being maintained in developed regions. After all, the aim of sustainability, as McMichael et al, (2003) put it, is to achieve *"desired human experiential outcomes."*

Industrial production involving the use of resources and energy, has garnered much attention (Jasti et al., 2022; Reijnders, 1996) because the use of (natural) resources are necessary to fulfill *"functions that enable meeting the physical needs of humans, but also are part of the natural environment and hence can also play a role in ecosystems functioning,"* (Dewulf et al., 2015). For a time now, heavy industries that are responsible for producing the raw materials needed in infrastructure, mobility, housing, and packaging have maximized the production capacity to fulfill the demands of a growing population, led to pollution, waste, loss of biodiversity, and major stress on natural resources (OECD, 2021). These enterprises are central to the growth and functioning of societies, especially minerals and metals, but in addition to the non-renewable characteristic of these resources, the problem is that their production activities are also some of the most environmentally damaging (van der Voet et al., 2013).

It has been pointed out that unsustainable resource use exacerbates problems such as climate change and scarcity of resources needed to maintain equitable living conditions globally, while a significant portion of the world population remains in poverty (UNEP, 2024). One prominent idea put forward in mitigating the effects of society's predominant linear (i.e. take-make-waste) model of production and consumption is to shift to a Circular Economy (CE). The definition offered by Korhonen et al., (2018) for example, gives a notion of resources being used in a cyclical manner through the active participation of those who produce and consume them. Within this paradigm, waste is considered a resource (Reuter et al., 2019). Other definitions of this concept that are heavily linked with sustainability or having sustainable development as its goal (Kirchherr et al., 2017) have been suggested, making it attractive for policy makers and businesses (Chizaryfard et al., 2021). The transition towards a circular economy is now incorporated in governmental strategies acknowledging the efficient use of materials as essential in accomplishing the global climate goals. Furthermore, similar to the evolution of corporate responsibility in the 1980s (Jones, 2017), CE has provided an avenue for businesses to further bolster the idea that commercial activity and sustainability can go hand-in-hand, especially in sectors where there is already a notion of resources circling back at some point along their value chains.

While CE and its definition "*will likely be in a state of perpetual evolution,*" (Kirchherr et al., 2023), it does promote the idea that resources need to be managed that allows for multiple circulations, in a manner where losses are minimized, and imparting a somewhat semi-renewable aspect to finite resources such as metals. This also takes advantage of the technological capability to reuse these at the end of one cycle of use as production input, and then in the next cycle, and the following cycle after that.

1.1 Research background

Gutowski et al., (2017) posits that materials consumption generally increase as it is tied to providing our basic needs, enabling development, and can even represent one's social standing. Because societies are now accustomed to receiving high levels of utility from materials and products, maintaining this level of welfare that is also inclusive requires that extraction of resources be abated by actions that 'use and nurture materials efficiently' (Allwood et al., 2011; Worrell et al., 2016). Acting on opportunities during a material's life cycle to be efficient results in savings on energy, and reductions on both Green House Gas (GHG) emissions and waste (Cooper et al., 2016; ISRI, 2020; Worrell et al., 1995).

A way to manage the stocks of finite materials is through finding pathways to enable their recirculation. Moreover, in the backdrop of climate change, recycling can provide products at reduced energy requirements, perhaps for some materials the least energy and emissions levels (Allwood, 2014). While the nature of the activity of recycling inextricably links it to the CE concept, this work refrains from comparing recycling against other CE actions and its standing in a hierarchy (e.g. 9R circular strategies listed by Potting et al., 2017). Instead, it concentrates on the fundamental idea that through recycling, there is an opportunity to preserve the value of the resource after a use phase. With this in mind, an analysis of a recycling system for the purpose of enhancing its economic and environmental efficiencies is both timely and relevant.

Products and materials after their service lives *"will have to be recycled at some point,"* said Worrell et al. (2024). But to utilize these products and materials when *scrapped* --- discarded and removed from service with the purpose of converting or using it as raw material for recycling, is not as straightforward (Harvey, 2021; Worrell et al., 2024). One issue with production based on scrap stems from the very nature of anthropogenic resources, which are considerably more complex than primary resources (Ciacci et al., 2016; van der Voet et al., 2013). Allwood (2014) described it well: *"Almost all recycling processes operate by breaking down a solid waste stream into a liquid, which is then purified by some means. With today's technologies, some wastes cannot be broken down and some liquids cannot be purified…the energy required to achieve this may be very much greater than that required to liberate an equivalent stream of atoms from other sources (e.g., ores or even mining tailings), and the process of doing so may lead to other environmentally harmful consequences such as the release of toxins or greenhouse gases."* It could be assumed that a situation described as such practically leads to sustainability trade-offs that manifest in decisions of the actors within a recycling system on how to conduct their business.

The attention of investors and financiers on Environmental, Social, and Governance (ESG) metrics has led to new projects focused on recycling, which at times is equated to *greening* the metals industry (Campbell et al., 2022). High economic values and potential for reuse, coupled with continuous demand, make metals arguably the most attractive material type to recirculate. Steel exemplifies this as the most used metal (Bracquené and Duflou, 2019) and it is also widely recycled, where the advantages of using scrap for production has long been established. But there is still room for improving efficiencies if one considers for example, the practice of *sweetening* (i.e., *"...the addition of primary material to dilute the contamination levels of the melt..."*) (Ciacci et al., 2016; Pauliuk et al., 2013) that addresses production target requirements but is untenable from a sustainability context, losses associated with open loops (Nakamura et al., 2012), and downcycling (Helbig et al., 2022).

The aspect of steel recycling that is the main interest in this research is engaged with the characterization and sorting infrastructure of scrap. More specifically, how information on scrap composition, depending on the level that it is recovered, transmitted, and utilized, influences how much of the value of the steel's constituents will be retained for future cycles. This is relevant to facilitate "*identifying and segregating at the point of discard*", that Chen and Graedel (2012) discussed as a means to keep alloys (by extension the components in them) in use as originally designed.

1.2 Research questions and objectives

Birat et al., (2002) working on sustainability of recycling, said that *"Such a detailed approach would probably not have been necessary if the objective had been to enforce a "once-around-only" recycling practice. This target has already been reached. Indefinite recycling on the other hand is a challenge worthy of steel, because sustainability requires that the most recycled material goes beyond the present state of full recyclability and because the steel industry needs scrap as a raw material in high volumes and high quality."* This present work, even though unconnected to the now 20-year-old study, maintains the idealization of what recycling systems need to accomplish with regards to scrap use. The main focus is on scrap as a feedstock for the production of new steel.

As a consequence of a reverse flow infrastructure (Bell et al., 2006) that is unable to prevent intermixing between discarded metal streams, contaminants are introduced and accumulate in this production system. Contaminants are recognized as being problematic for achieving successful steel production and consequently diminish the quality level of scrap. The direct effect in terms of scrap use would be to rely on primary, ore-based inputs instead (Lüngen, 1998). The issue of contamination brought about by the insufficiency of sorting and characterization is conceptualized as symptomatic of an inadequate knowledge about the compositional information of scrap during its recycling phase.

Steel is the most recycled metal on the planet and at EoL, steel scrap could provide the needed iron and alloying units for producing new steel. One could also identify a functioning system of actors who supply and buy scrap, enabling its use as a resource. But with the increasing complexity of material and product compositions made of and using steel, *why is there an apparent inadequacy in the recycling system infrastructure to recover the steel's identity at a sufficient level that lessens or avoids the use of primary resources during its recycling?*

The following queries arose from this overarching research question (RQ) as the work progressed. First (RQ1), *what is the current praxis of handling scrap for use in production in a recycling system?* The question reflects a need for establishing not only a literature description of recycling, but adds a more practical, organizational view of the actors involved in the process. It would also reveal how these actors rate scrap in terms of their own operations' dependence on this resource; what they obtain as their input and what they put back in the system as their products. The research objective (RO1) at this stage was an exploration of the system, to reinforce the understanding on the issues that remain in the recirculation of scrap as a raw material for steel production, using technical and organizational standpoints in the analysis, and formulating it as a quality issue related to information.

Next (RQ2), *what is the value of more accurate compositional information about the scrap and how does having access to it change production outcomes?* Generally, literature conveys that recycling systems operate under a level of uncertainty requiring operational decisions that manifest as sustainability trade-offs. Tackling this question aims at achieving a comparison that in turn could be useful for motivating the industry to consider implementing upgrades on their process and/or infrastructure. A research objective (RO2) of value attribution, to develop the idea of value of (compositional) information in this context, why it matters, and problematize how the lack of it contributes to an overall loss of value of materials, was conceived.

Finally (RQ3), *how do actors work with the current level of information they have now and what do they see as opportunities for increasing scrap consumption?* If improvements towards a more sustainable use of scrap entail enhanced information flows, then actors could corroborate from their own experiences. This query led to a final research objective (RO3) of validation, to discuss the practicalities around the opportunities for improved scrap management that entails enhanced information flows with the intent of retaining material value for future cycles.

Throughout the thesis, discussing the results uses a CE-lens as a framework. Recycling of course requires engineering knowledge (Stahel, 2016), but it also occurs through enterprises. Analyzing the findings using the CE framework could highlight trade-offs that the actors face and their typical course of action. Moreover, CE imposes an ideal that resources stay in an interminable loop, so recycling systems need continuous improvement.

1.3 The Supplements and the structure of the thesis

An overview of the Supplements that comprise this thesis is provided in **Table 1**. The research questions in the previous section were adapted as objectives in each Supplement. Qualitative and quantitative approaches were incorporated to fulfill the objectives.

This thesis is then structured as follows: *Chapter 2* positions the study within the literature and establishes the themes in this present work, thereafter *Chapter 3* presents the chosen approaches and parameters investigated, *Chapter 4* summarizes and discusses the results of the Supplements comprising the thesis with particular focus on the research questions, *Chapter 5* contains the concluding remarks, and finally, suggestions for future work are listed in *Chapter 6*. Copies of the four Supplements follow subsequently.

Table 1. An overview of the appended Supplements.

Supplement	Topic	Objective	Approach	Parameters
I	Circular Steel: How information and actor incentives impact the recyclability of scrap.	• Investigate and describe a recycling system. • Identify issues in using scrap as a raw material for steelmaking.	Literature review and interviews with industry practitioners representing the actors in the recycling system.	• Data from extant literature. • Semi-structured interviews with steel recycling industry actors.
II	Appraising the value of compositional information and its implications to scrap-based production of steel.	• Develop the idea of the value of (compositional) information. • Apply a simulation model to quantify the value of information.	Simulation of scrap-based production via an optimization software. The production scenarios involved one scrap type and one stainless steel grade.	• Scrap chemistry generated using a spreadsheet program based on scrap specifications. • Target product composition based on product specification.
III	A value of information approach to recycling.	• Improve the practical application of the simulation model from Supplement II by introducing additional constraints.	An extension of the work performed in Supplement II. The production scenarios involved two scrap types and four stainless steel grades.	• Scrap chemistry generated using a spreadsheet program based on scrap specifications. • Target product composition based on product specification.
IV	A review of scrap handling practices and prospects for increasing scrap consumption in recycling.	• Determine how companies deal with the lack of information. • Discuss the opportunities for increasing scrap consumption.	In-depth interviews with industry practitioners involved and/or have had experience in scrap handling.	• Semi-structured interviews with steel recycling industry actors.

Chapter 2: Literature Review

2.1 Recycling in a Circular Economy

While this present thesis does not aim to debate, much less offer another definition of CE, it is useful at this stage to refer to the concepts that frame the thesis itself. It is difficult to navigate the CE literature, and thus position recycling in this context, because there are more than 200 different definitions that are not necessarily in agreement with one another (Kirchherr et al., 2023). Several strategies have become generally known in the CE literature which are then placed in a hierarchy. In such a ranking, avoidance of material use becomes the highest priority while recycling ranks low, just above (energy) recovery from waste material (Rli, 2015), and 'true' circularity is the prevention of waste from happening at the source (Ellen MacArthur Foundation, 2021). Still, some view recycling with its resource-saving perception, as an integral part of CE (e.g. Khajuria et al., 2022; Milios, 2018).

This thesis takes a more pragmatic view that a CE is about maximizing *"…value at each point in a product's life"* (Stahel, 2016), and a way of *"…keeping the resources within the economy when products no longer serve their function"* (Di Maio et al., 2017). One can then recognize the strength of recycling in taking the European Parliament and the Council of the European Union's (2008) definition in the Waste Framework Directive, that recycling is, *"any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes.*" Recycling fills a supply need or gap relating to the need for more resources in a growth scenario (Legarth, 1996). With recycling, there is the perceived, overall reduction of a product chain's consumption of resources and the related environmental effects while stretching out the reserves or stocks of the same resources (Potting et al., 2017; Sovacool et al., 2020).

It must be noted though that concurrent to seeing recycling as a necessary aspect of a CE, is the view that performing recycling does not instantly displace primary production as discussed by Geyer et al., (2016). According to them, *"…one to one displacement is an assumption, not a fact. Displacement is a consequential effect; a change in secondary production causes a change in primary production. The causality is market mediated. There is no engineering relationship or law of physics that requires primary production to decrease as recycling increases."* The resource conservation that can be attributed to recycling is to the extent that is technically and economically feasible (Merz, 2016). This interplay of technical and economic factors is crucial and is incorporated in the analysis of results obtained in this work. Having a view that it is an activity that operates as an organized system of institutional and physical infrastructures (Hotta, 2013) helps in elaborating on issues such as contamination that could hinder future cycles (Daehn et al., 2017).

This section on positioning recycling within a CE context ends with an excerpt from a report (UNIDO, 2019): *"Recycling can act as a fundamental lynchpin of the circular economy in that it plays a transformative role in turning post-consumer materials into valuable substances or products, feeding used materials back into the value chain and correspondingly achieving the "waste-to-resource" paradigm. It thus presents numerous economic, environmental and social opportunities. Despite this, its potential has yet to be fully realized due to a number of legal, policy, infrastructural and market barriers."*

2.2 A functioning recycling system – the case of steel

The amount of steel produced worldwide exceeds all the other metals by a factor of ten (Ashby, 2016). Steel is also versatile, and can be used in various applications, produced at relatively low cost, and the wide availability of its primary raw material is supported by a secondary scrap-based production (Oda et al., 2013). With the supposed scale of production and a *"well-oiled recycling infrastructure"* (Atasu et al., 2021), it is comprehensible that society will continue to have stocks for future cycles. Some studies are estimating that an increasing scrap supply may even lead to secondary production of steel accounting for around 50% by 2050 (Xylia et al., 2016).

Hence the view that recycling facilitates material use endlessly (Worldsteel, 2020) is understandable considering that recycling has been performed for a long time, especially for steel, and dealers of ferrous scrap have the *"…luxury of long history…with that, of comparatively well-established markets for his products."* (Wulff, 1985). Generally, once steel is discarded, a recycling system is able to take it back.

Steel recycling occurs within a system that is technologically established, where several enterprises find that their activities are not just profitable, but are also seen as highly desired in the sustainability agenda (McMillan et al., 2012). However, because a big part of the system is comprised of such enterprises, this means that recycling, or the use of secondary resources, will be subject to a typical firm behavior of aiming for profit optimization (Eccles et al., 2014; Schlosser et al., 2021). Recycling costs could make the scrap less desirable than other iron inputs that may be in abundant supply and more suitable for production (Tonini et al., 2022). The latter characteristic is usually associated with tramp elements and is "decisive" for obtaining a good product quality (Grosso et al., 2017).

2.3 The internal and external recirculation of secondary materials

2.3.1 Scrap as a resource and suitable feedstock

Greer et al., (2021) talked about the Waste-Resource Paradox (WRP) where a material is possibly a waste and a resource, *"…depending on the perspective of the handlers, the practicality of its use at the end of life, the cultural and geographical context surrounding it, and the legal backdrop on which is it evaluated."* Steel scrap is widely considered as a resource, where its recycling has already been viewed as a *circle* that starts when scrap is discarded and completed when scrap returns as new steel as a product for consumer use (Wulff, 1985). However, as indicated in the WRP, there is a dependency, a context, where steel scrap is a resource. There are limits to its recycling, primarily thermodynamic in nature that is driven by the quality of the scrap, that affect its economic viability (Reuter, 2011).

Unlike its primary counterpart (i.e. derived from ores) that is static and concentrated in a locality, the nature of scrap as a type of anthropogenic resource is more dynamic (Müller et al., 2006). Steel is used as a material, component, or product and found in EoL waste streams fused and fastened onto other materials. Scrap gets transported and stockpiled, mixed, and sorted (Brooks and Gaustad, 2019; Clausen et al., 2018). The ownership of the resource changes has changed several times before it reaches the scrapyard of a steelmaker as a function of how the reverse loop is set up (Giannetti et al., 2013; Johnson, 1998). By then, uncertainty regarding its quality has become its characteristic and inhibits its use (Nicolli et al., 2012).

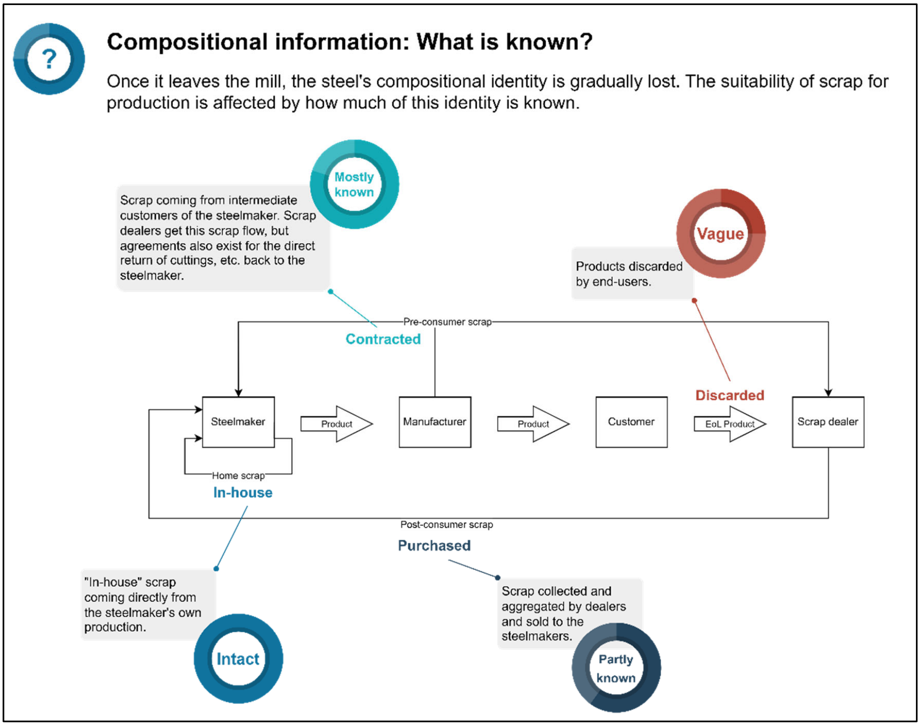

Figure 1. Scrap generation in the production and consumption of steel.

What is shown in **Figure 1** is a simplified and generalized representation of when and where scrap is generated (Brodrick, 1978; Graedel and Reck, 2019), with the exclusion of dissipative flows and those that end-up in landfills. Steel is produced via two main routes, through the Blast Furnace – Basic Oxygen Furnace (BF-BOF) and EAF, where the former is generally known to utilize primary Ore Based Metallics (OBMs) and some scrap, while the latter is mostly associated with scrap as input. (Arens et al., 2017; Blunt et al., 1993; Brodrick, 1978). Then, it goes to intermediate manufacturers who in turn use the steel into products that will be used in society. At each stage in the product chain, scrap is generated, and can then be ideally rerouted back into production where it supplements metal production (see **Figure 2,** where RIR is the Recycling Input Rate).

Going back to **Figure 1**, an approximate estimation of the scrap quality based on known compositional information about the scrap at each stage is indicated. It is then the post-consumer type of scrap that is most uncertain in terms of quality because it is *"collected in different quality grades, sorted depending on the size and origin, which have different content of tramp elements and mineral materials"* (Grosso et al., 2017). The degree of information about the scrap chemistry are only estimates based on descriptions of scrap types in literature (Fenton, 2004; Graedel and Reck, 2019), but they provide insight on how attractive of a resource scrap becomes. It relates to how much effort the steel mill (producer) needs to employ to make new steel out of the scrap in terms of matching the composition between their input and the output. Scrap generated in-house and in special arrangements with their direct customers have compositions that are highly known compared to post-consumer (user) variety (Vercammen et al., 2017; Yuzov and Sedykh, 2003). Overall, looking at the contribution of scrap can be considered a *"...measure of independence from geological resources"* (Tercero Espinoza et al., 2020).

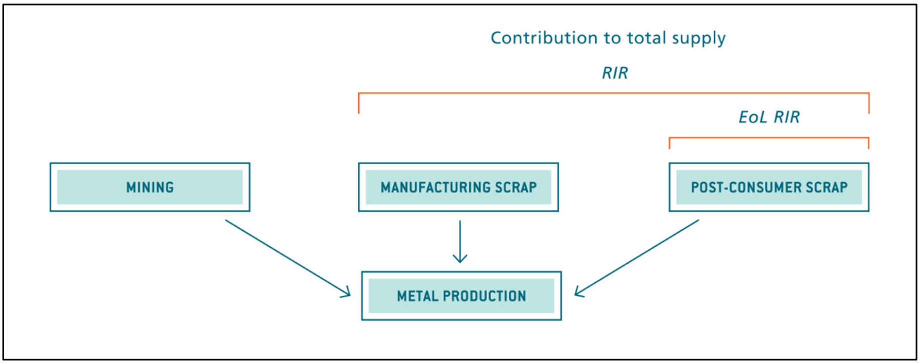

Figure 2. The contribution of scrap to replacing primary raw materials in metals production[1].

In this system, scrap dealers perform an important role because it is the primary point where an infrastructure of characterization and sorting is installed. By fulfilling specifications, they can deliver generally sorted and categorized scrap that are sellable as production input for mills (Muchová and Eder, 2010). Scrap's identity is first re-established in the scrapyard, which is critical, in order to prevent downcycling that represents a loss of material value (Helbig et al., 2022; Raabe, 2023) and in the bigger picture, constrains what type of steel production is realistic under a carbon budget (Watari et al., 2023).

Oftentimes analyses of recycling flows point to its limitations as to why rates remain low (Graedel et al., 2011). Materials do leak out of the system because of thermodynamic limits, mishandling, and dissipative use (Solow, 2009). But another departure point is considered in this thesis. That is, the possibility of a situation where the scrap that becomes available might be too difficult for steel mills to use as input, with the worst-case scenario where they eventually end up stockpiled or landfilled, instead of complementing primary production. Hence there is a need to consider the role and value of information that accompany these reverse flows. The economics complement the analysis because all actions, including acquisition of this information, come at a cost (Conrad, 1999).

2.3.2 Recovering material identity through scrap management.

Correct handling of scrap is critical because as recyclable byproducts, their compositional information gets lost, deliberately or by design (i.e. patents, trademarks, etc.), and usually does not accompany the material flows (Khor et al., 2016). This becomes even more challenging due to alloy specificities (Graedel et al., 2022). The circular qualitative valuations in **Figure 1** are indicative of what remains of this information and it becomes apparent that the material of concern in this context is obsolete or postconsumer scrap that represents the highest portion of material having either an unknown

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[1] Image reused with written permission from Luis Tercero Espinoza.

composition (Taszner et al., 2007) or variations (Vicente et al., 2020) fed in the furnace that will require interventions.

Technical and systemic contamination (Baxter et al., 2017) in recycling is a problem that manifests at the point of loading the furnace at the melt shop. Rong and Lahdelma (2008) describes a scrap optimization problem; there is an overall lack of information, or uncertainty, whether the elements that comprise the scrap will lead to a successful heat, where the melt composition falls within the specified limits of the final product. Szaniawski (1967) said that information *"provides a basis for better solutions of decision problems"* and relating to this research context, the value of information is the *"highest price in (in utility) to be paid for the information, compatible with the condition that the best use made of perfect information is at least as good as any action previously available."* All scrap generated from activities that either produces, transforms, or uses the steel have their specific chemical identity, that under the assumption of proper management, will end up as viable input materials for production of the same or similar steel products.

The scrap management that occurs in the reverse loop to an extent, recovers in increasing detail, the identity of the material. The steps within consist of a series of activities from when the scrap is generated up to the point it is once again made available as an input material for production. Four main actions under this broad interpretation are summarized in **Table 2**. An additional activity, preparation, was included to categorize activities that support or contribute the main ones.

Table 2. Information recovery during scrap handling.

Activity	Description	Reference
Collection	Gathering and reinserting anthropogenic stocks at the end of their use phase to the reverse loop. It involves physical transport from the point of the scrapped product's generation to a point where subsequent scrap handling activities may take place.	(Gauffin and Pistorius, 2018; Valdes, 1991)
Sampling	Obtaining a portion from the bulk of the collected material for the purpose of analysis. There is a prerequisite that this sample should be a representative of the whole pile.	(Dulski, 1996; Gauffin, 2015)
Characterization	Recovering and documenting of material information via material analysis techniques that establishes a high level of confidence of what the material was originally.	(Brooks and Gaustad, 2019; Gurell et al., 2012; Noll et al., 2015; Pierre et al., 2020; Stachowiak, 2016; Terrell, 2019; Wieczorek and Pilarczyk, 2008)
Sorting	Segmenting the bulk into agreed (i.e. by industry standards or production requirements) classes that facilitates either transfer to another entity or ready use in production of a corresponding metal product.	(Dalmijn and De Jong, 2007)
Preparation	Homogenizing the physical condition, shape, and form of the material that facilitates handling and other activities described herein. This activity can be considered as auxiliary or contingent to specific needs (e.g. crushing, shredding, cutting to size, classifying according to size, etc.)	(Bonifazi and Serranti, 2019)

In relation to **Table 2**, information on scrap composition is recovered sequentially in the reverse loop as illustrated in **Figure 3**.

Some societies have good practices that begin at the household (Bergquist et al., 2023; Nakamura and Kondo, 2002) that contribute to directing the metal to the correct recycling facility. The flow also depicts that steelmakers are aware about what they have in the post-consumer scrap they purchase (Compañero et al., 2023). Recycling systems by design, facilitate information recovery through sorting and characterization (Tu and Hertwich, 2021). The concern is if the information recovered is enough to maximize the value of the scrap in the production.

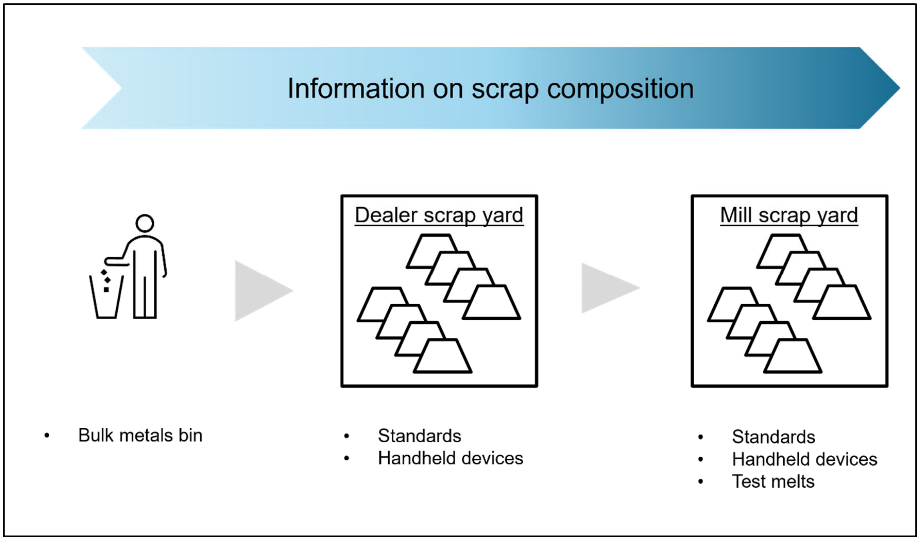

Figure 3. Generalized flow of compositional information recovery.

In terms of technologies (i.e. general methods of analysis) and practices used to characterize the scrap, it is almost the same industry wide. There are advantages and disadvantages associated to whatever equipment or procedure is selected (see **Table 3**, adopted from Taszner et al., 2007). Assuming proper disposal, collection, and management, the information on scrap's identity is regained through protocols and equipment. Standards have also been established. The examples are those of the American Society for Testing and Materials (ASTM) standards relating to identifying mixed lots of metals and municipal ferrous scrap, while the European Commission's Joint Research Center has published a report that include material management of scrap (Remus et al., 2013). Overall, this area is continuously developing that could be an indication that there is a growing interest and need for finding suitable scrap types. There are reports of technologies ranging from general scrap preparation techniques, targeted contamination removal, image analysis of scrap, and automated sorting at various levels of "readiness" (Manning, 2023) or development(e.g. Brown et al., 1986; Daehn et al., 2019; Dalmijn and De Jong, 2007; Gurell et al., 2012; Javaid and Essadiqi, 2003; Kashiwakura and Wagatsuma, 2015; Kutila et al., 2005; Mannanal et al., 2013; Mesina et al., 2007, 2005; Riley et al., 1983; Scharun et al., 2013; Whiteside et al., 2006; Wieczorek and Pilarczyk, 2008).

On the application of these techniques, Riley (1983), observed that it depended on the added value generated by "increased degrees of separation" and that sampling, or what his study mentioned as presorting, is required to gain an initial idea of what is to be analyzed because calibration of the equipment is also necessary. In the case of handheld equipment for example, the speed by which these portable X-Ray Fluorescence (XRF) or Laser-Induced Breakdown Spectroscopy (LIBS) techniques can generate the chemical composition was somehow subdued by exhibiting inaccurate and imprecise results in some tests (Brooks and Gaustad, 2019). It would be interesting to dissect this further to current developments when moving material streams are involved (Jin and Mishra, 2020).

Table 3. Advantages and disadvantages of some characterization options.

	Melting tests	**Mobile analytical devices**	**Statistical evaluation**
Advantages	Melt is homogenous	Acceptable costs, arbitrary selection of sampling points	Lower costs, easily carried out, accuracy depends on how wide the data sets are
Disadvantages	Expensive	Critical sensitivity of the spectrometer, possibility of false sampling	Different databases will give different conclusions

A model constructed by (Li et al., 2011) attempted to understand recycling decisions on working out material mixes to produce finished goods and asks "*how much sorting is enough*?" Contextualizing that action in steel recycling, it is actually two main actors (Compañero et al., 2021) who tackle this question. Both have economic-driven objectives. A scrap dealer may ask, *"how much sorting do I need to perform that allows a delivery to be accepted?"* while the scrap-based producer will ask *"how much additional sorting do I need to do that ensures that I get the most value out of this scrap?"*

Janke et al. noted that as steelmaking becomes more efficient, less home and prompt scrap will be generated (Janke et al., 2006), in line with material efficiency strategies such as reductions in scrap generation in production (Cullen et al., 2012). A consequence of this happening is that companies would rely more on the scrap market to fulfill their input volumes.

2.4 The Expected Value of Perfect Information

An underlying reason for recovering the material identity in the reverse flow of anthropogenic resources is not limited to enabling its recirculation, but to also find an application where it can provide a maximum of the value (Compañero et al., 2023; Sasikumar and Kannan, 2008). In steelmaking, the failure to account for the uncertainty in scrap can result in failed production heats (Rong and Lahdelma, 2008). Having the information gap between what is stated in the scrap specifications (e.g. Baillet, 1995; JBF AB, 2020) and the actual composition of the delivery is usually dealt with in a refining unit with Ore Based Metallics (Holappa, 2014). It could be said that steelmakers have managed dealing with partial information, but again, questions will be asked about how resource efficient scrap-based production actually is and the degree of environmental relief that recycling unburdens from primary resource extraction (Huysman et al., 2015; McMillan et al., 2012).

The previous section explains how scrap management recovers information, but getting even more information in order to increase the efficiency of recycling requires some form of decision regarding whether this is worth doing. This is because additional information comes at a cost, as Koenig

(Koenig, 1998) frames making this decision as *"...a methodology for calculating the tradeoff between making a decision with partial information versus expending resources to obtain more information and thereby making a decision based on more complete information."*

Szaniawski, (1967), commonly credited with conceptualizing the Expected Value of Perfect Information (EVPI), described the aforementioned transaction where *"...of any two such informations* [sic] *one will, in general, make it possible to obtain a higher utility by a suitable choice of action than the other,"* that a decision maker has to face. EVPI is also referred to as the resulting benefit of decision analysis applied to *"...multiple (and usually conflicting) objectives and uncertainty,"* (Parnell, 2009) or regarded as the increase in profitability (Avriel and Williams, 1970). Since scrap-based steelmaking also deals with uncertainty, EVPI can be used as a concept to frame efforts to evaluate and resolve the information gap to improve scrap usage.

Examples of fields where EVPI has found its utility are healthcare, adoption of innovation, and also in the earth and environmental sciences (Eidsvik et al., 2015; Keisler et al., 2014; Marchese et al., 2018; Ødegård et al., 2019; Oostenbrink et al., 2008; Zabeo et al., 2019). There are studies that can be found in terms of scrap mix optimization, such as the use of mathematical tools to support managers (Aggarwal and Gupta, 2014) and predictive models to define scrap combinations (Gyllenram and Westerberg, 2016; Miletic et al., 2008; Mombelli et al., 2021; Sakallı and Baykoç, 2011). However, these studies generally focus more on minimizing costs and are less concerned with knowing the content in the scrap that may reduce the loss of value of the elements due to downcycling.

2.5 Sustainability trade-offs in recycling

The path to achieving the sustainable development goals in the resources sector is filled with 'wicked problems' (Pryshlakivsky and Searcy, 2013). There is a big-picture aspect of scrap use, with Brooks and Gaustad (2019), in reference to the study by Gaustad et al., (2011), saying that the *"...build-up of impurities necessitates that batch planning, homogenization of metals to form new metal naturally assume a high error --- capping scrap utilization rates and requiring increasing volumes of primary metal for dilution."* The statement can be an encapsulation of the issue at hand. Recycling is almost synonymous with scrap utilization, and consequently equated to or expected to alleviate demand for primary resources. But if the scrap is not of a suitable quality, then the steelmaker may resort to using Ore Based Metallics (Tonini et al., 2022).

Van der Voet et al., (2019) said this about iron: *"Significantly reducing emissions is therefore not possible without a completely novel low-carbon production process, or without significantly increasing the share of secondary production."* To an extent, it implies increasing the share of post-consumer recycled content (see again **Figure 2**) in steelmaking, because this type of scrap constitutes a bigger share of what is available (Raabe et al., 2022). Using more scrap, more specifically achieving a good substitutability, has also been shown to have a stabilizing effect on a volatile market because it compensates for primary supply shortages (Fleming et al., 2011).

Overall, increasing the use of scrap seem so obvious as far as solutions to sustainable metals consumption and production go, but the trend is that products are becoming less recyclable (Dahmus and Gutowski, 2007), and with all the problems this situation leads to, the recycling firms are often limited in making investments that are related to increasing suitability of scrap for their own process. Raabe et al., (2022) suggested an alternative scenario, *"...it would surely be desirable in the future to reduce the number of alloy variants on the market, and even to develop certain standards to govern which alloys should be used for certain parts so as to avoid the often-observed wide variation in alloy types used in the same product, which makes subsequent scrap separation a challenge."* But considering the current situation, companies ought to evolve; in this case, strive to use more scrap if the target is, genuinely, circularity or sustainability (Pieroni et al., 2019).

Chapter 3: Methodology

The nature of the research topic and the research questions brought about the topic called for an interdisciplinary approach. Its implementation in this thesis was accomplished through a combination of qualitative and quantitative methods, where each Supplement contributed towards answering the research questions in Chapter 1. This chapter covers the process of selecting the empirical context, procedures for data collection, building a simulation model, and data analysis.

3.1 Overall research design

The whole thesis could be thought of, or split into, distinct "phases" that build upon each other. A succeeding phase was guided and shaped as the research objectives of the current one was fulfilled (see **Figure 4**). In a sense, the progression occurred in a linear manner. The first phase, *system exploration,* provided an understanding of the system under study, and what makes it distinct or similar from other systems and the roles of the different actors within it. Then, *value attribution* was the undertaking to quantify the value of information. Making use of the concept of the Expected Value of Perfect Information (EVPI), the approach was to take the difference between select metrics from simulated, scrap-based production, as a function of the level of accessible information about the scrap chemistry. Finally, *validity review* checked to what extent the insights obtained from the simulations were reflecting the practicalities of steel recycling through the experiences of practitioners. Additionally, to also get a forward-looking view regarding the use of scrap as a resource.

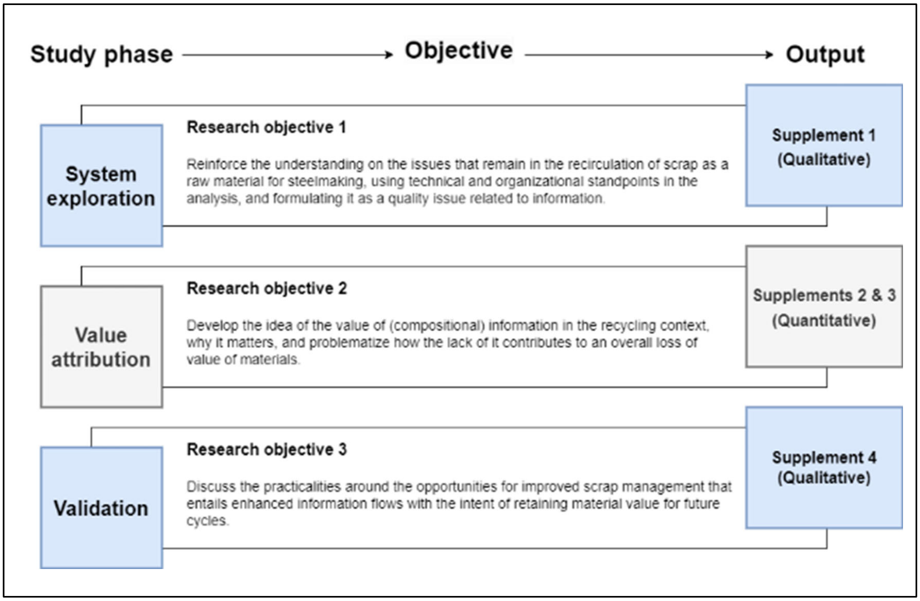

Figure 4. The research objectives as thesis phases and its link to the Supplements.

The research design incorporated methods that were effective in achieving the goals coherent with the various phases of the research. This is to say, the decision to implement mixed methods was taken because it *"allows for extend findings beyond those observable using a single method,"* (Grafton et al., 2011). Mixed methodologies are becoming popular as a *third major research approach* after qualitative and quantitative (Johnson and Onwuegbuzie, 2007), but rarely practiced in engineering. The theme of sustainability is inculcated in this current thesis, and it has been pointed out that the *"…quantification of sustainability can be done through a combination of skills drawn from business fields and the sciences working together"* (Krehbiel et al., 1999). While it is mostly in the fields of education, sociology, psychology and health sciences where mixed methods are used and developed (Molina-Azorín and López-Gamero, 2016), it is beneficial to link different stakeholders towards a more holistic analysis (Sahamie et al., 2013). In the context of the thesis, recycling of materials is at its core a technical activity, performed by enterprising actors.

Therefore, in view of the interdisciplinary nature of the topic, Supplements 1 and 4 were performed qualitatively, aimed at fulfilling the first objective. Building knowledge about the recycling system as well as updating this knowledge according to the relevant findings called for qualitative methods. On the other hand, attributing value to information meant arriving at some form of metric to support the hypothesis that obtaining this information was beneficial. The quantitative method through the optimization model implemented in Supplements 2 & 3 mainly contributed to this aim.

3.2 Data collection and analysis for the descriptive phases 1 and 3

A fundamental review of material recirculation was first obtained from literature, with the subsequent selection of steel recycling as the appropriate system to be studied. The Swedish steel recycling system was then chosen for a case study because its characteristics make it interesting from the standpoint of the nature of scrap that enters the recycling system. Firstly, the steel industry in Sweden can be considered as compact, with eleven scrap-based production sites accounting for one third of the total crude steel production. The actors who agreed to be interviewed already represented more than 50% of the volume in the system as mentioned in Supplement 1. They do not compete in sales to the local market since the steelmakers' production is mostly niche-oriented, where the majority of products are special steels that are exported. Moreover, the actors are mostly supplied by local availability, with a distribution channel that runs through one major broker called the *JBF (AB Järnbruksförnödensheter)*, that is also co-owned by the major steel producers. What becomes available as the supply of scrap, the local, standard grade requirements, are fulfilled by imports. This situation adds ambiguity to the compositional identity once the steel gets scrapped.

In Supplement 1, the Swedish system of scrap-based, steelmaking was a single-case study with embedded cases (Yin, 2009). Such single-case studies allowed for thorough investigations useful for building theory or obtaining understanding of complex issues (Eisenhardt and Graebner, 2007; Eisenhardt, 1989). It also facilitated widening of the scope of the thesis and bringing in an alternate context for comparison, performed in Supplement 4. On the one hand, in Supplement 1 the Swedish steel recycling system was a representative case of a developed, higher-income context (HIC), national system, complete with identifiable actors involved in scrap collection and production of specialized steel grades using scrap.

On the other hand, Supplement 4 added to the list of interviewees a consultant from what was designated as a lower-income context (LIC). The Philippine steelmaker that was exemplified sources its scrap supply independently from smaller, scrapyard-equivalent *junkshops* who also take in scrap collected through scavenging that is typical for developing economies (Chohaney et al., 2016; Medina, 2013). This type and scale of scrap collection is *"…not only a source of income for many people facing precarious economic conditions, but it also generates a positive environ- mental externality on natural resource use and on landfill lifespan"* (Moreno-Sánchez and Maldonado, 2006). It is an example of *Necessity-Driven Circular Economy*, as Korsunova et al., (2022) formulated, that in this circumstance generates pure enough steel scrap for the local production where the recycled content in production is maximized. The responses of the consultant led to a reflection on practices in a lower income context and were included for a basic comparison with that of the Swedish steel recycling system.

Semi-structured interviews targeting recycling actors were performed as data collection for Supplement 1. These interviews were arranged as physical meetings in either the main office or in a production site of the respondents and were performed together with another doctoral student. A general profile of the actors who were interviewed can be found in **Figure 5**, with more details available in Supplement 1. The information received from the respondents was validated by comparing interview notes with another doctoral student. Whenever possible and allowed, a tour of the respective scrap yards followed right after the discussions.

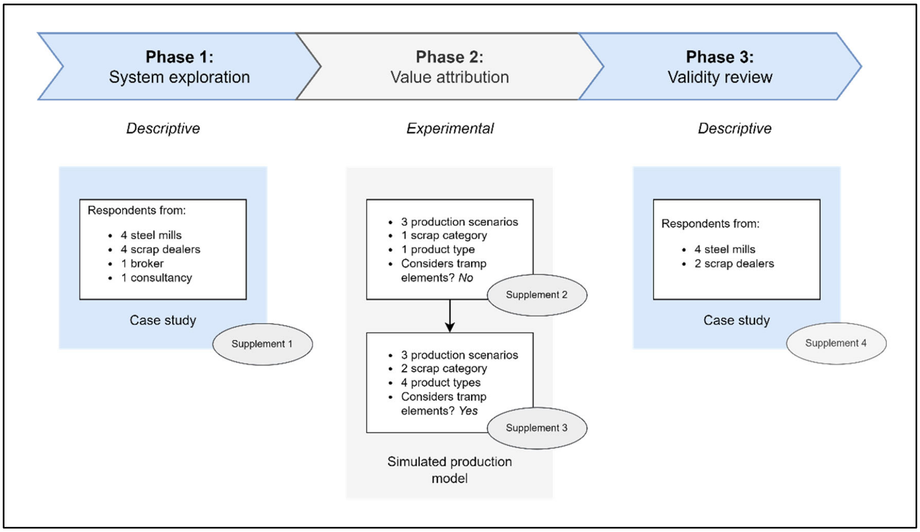

Figure 5. A summary of the respondents and simulation model cases.

The interviewees' responses together with the observations made from the tour were complemented with reviews of publicly available documents of the companies. Then, the data analysis focused on extracting themes related to scrap handling and management in the actors' respective scrapyards. Details on scrap quality and how the different actors worked based on their definition and expectations of *quality* were regarded as critical to answering the research question.

For the final phase, that is, Supplement 4, the execution of the study was performed in a similar manner to the first, employing semi-structured interviews complemented by information provided in company documents. The investigation was centered on checking with the industry how the prevalent lack of information is being addressed at present, and to also pinpoint their view on overall opportunities to increase scrap consumption in recycling systems. There were new industry practitioners interviewed, although the list of respondents included some who were already interviewed for the first Supplement. Additional details are provided in Supplement 4. These particular interviews, where a respondent was interviewed several times, can be considered *serial interviewing,* and were found to yield valuable understanding on the complex topic of recycling. Read (2018), described the method as *"...appropriate when studying complex or ill-defined issues, when interviews are subject to time constraints, when exploring change or variation over time, when participants are reluctant to share valid information, and when working with critical informants. A further benefit is the opportunity it provides for verifying and cross-checking information,"* all of which were recognizable in both the system under study and the actors who were contacted. The selection criteria for the interviewees remained the same: that they, as part of their role and/or experience, were directly involved in the management of scrap. These included roles such as raw materials manager, purchaser, process development, scrapyard manager, site manager, and operator.

Outside of the arranged interviews, other sources of information were discussions with other academics and industry practitioners through avenues such as doctoral courses, forums, and conferences, some of which also included technical visits to scrapyards. These were particularly useful in corroborating information, clarifying points, and keeping in touch with the trends in this field of study.

3.3 Data collection and analysis for Phase 2

For the quantitative phase of the research, a method to measure the value of information was developed. From the analysis of scrap dealer-steelmaker transactions in Supplement 1, the examined aspect in Supplement 2 shifted to the preparation of the feedstock with scrap and pure alloys for production. This was accomplished using the specified chemistries found in a scrap standard as the baseline level of compositional information. In Sweden, the standard is called the scrap book, "*skrotboken*", which is published by the JBF. The required chemistries were indicated within tolerance limits for specific scrap type within this standard. It can then be assumed that the actors have *partial* knowledge of what any delivery might contain. This was compared to an idealized state where the actors have the exact analysis or perfect information. The concept of EVPI was found to be a fitting framework for the analysis.

3.3.1 Selection of scrap categories and product grades

Generally, for both quantitative Supplements 2 and 3, the basis of selecting the input-output pairings that were simulated in the production was that the scrap category has a matching steel product for it in terms of the corresponding chemical compositions. For example, in **Table 4** one can look at the required analysis of scrap category *951*, then compare it to the target composition of either AISI 304 or 305 in **Table 5** taken from a product standard(Euro Inox, 2007). Moreover, just based on the scrap chemistries, the product can be produced entirely scrap-based without the need for adding pure alloys or Ore Based Metallics, since all the necessary alloying elements (e.g. Cr, Ni, and Mo) are already present in the scrap. The selected scrap categories and steel grades were alloyed. This was intentional, so that the increased sensitivity of the optimization model to fulfill both *(1)* the targeted final composition of the product and *(2)* the least cost of production, to the respective prices of raw materials could be emphasized.

Note that in **Table 4** and **Table 5**, Cu was designated as an impurity element in the simulations. The limit for Cu in the product was a practical limit, meaning, the indicated value (e.g. ≤ 0.25) does not appear in the product standard referenced, but was based on one practitioner's background in the industry.

Table 4. Specifications of the input or feed materials used in the simulations.

Scrap categories	**Used in**	**Price (in €/kg)**	**Elements of interest (in wt-%)**				
			Fe	Cr	Ni	Cu*	Mo
951 *styckeskrot*	Supplements 2 & 3	2.18	balance	16 to 20	8 to 13	≤ 0.5	≤ 0.5
962 *styckeskrot*	Supplement 3 only	3.12	balance	15 to 20	10 to 13	≤ 0.5	2 to 2.5
Alloying elements	**Label**		**Content (in wt-%)**				
Fe	Pure Fe	0.45	100				
Cr	Pure Cr	3.51		100			
Ni	Pure Ni	21.15			100		
Mo (in MoO3)	Pure Mo	37.07					56

Table 5. Specifications of the target products used in the simulations.

Stainless steel grades	**Used in**	**Elements of interest (in wt-%)**				
		Fe	Cr	Ni	Cu*	Mo
AISI 304 (EN 1.4301)	Supplements 2 & 3	balance	17.5 to 19.5	8 to 10.5	≤ 0.25	-
AISI 305 (EN 1.4303)	Supplement 3 only	balance	17 to 19	11 to 13	≤ 0.25	-
AISI 316 (EN 1.4401)	Supplement 3 only	balance	16.5 to 18.5	10 to 13	≤ 0.25	2 to 2.5
AISI 316 (EN 1.4436)	Supplement 3 only	balance	16.5 to 18.5	10.5 to 13	≤ 0.25	2.5 to 3

3.3.2 Input and output target compositions

The composition data or the chemistries for the scrap was created using a spreadsheet program, using a function that generated random numbers from a normal distribution within a specified range (i.e. the lower and upper limits of each element according to the standard). An example of the chemistries of the deliveries designated as individual deliveries of scrap category 951 and were used in simulations in Supplement 2 are shown in **Table 6**. It is followed by **Table 7** for the two scrap categories that were used in Supplement 3. In the latter, a set of deliveries were generated where the assumed statistical distribution of the scrap chemistries was skewed *to the right* with respect to the alloying elements Cr, Ni, and Mo, and skewed *to the left* for the tramp element. This was deemed to be a more realistic view of deliveries in actual scrapyards, where suppliers would aggregate collected scrap containing the minimum level of alloys while ensuring that any contamination is just under the maximum limit. The industry practitioners were consulted to ascertain that the generated data was reasonable. All the compositional details of the deliveries were uploaded in RAWMATMIX® (RMM) and the quantity of each delivery was set at 100 tons[2].

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[2] Throughout this document, ton refers to the metric ton (=1000 kg).

Table 6. The set of generated scrap chemistries for Supplement 2.

Alloying element		**wt-% Cr**	**wt-% Ni**
Product specification	Max	19.5	10.5
	Min	17.5	8
Scrap specification	Max	20	13
	Min	16	8
Delivery 1		16.9	12.7
Delivery 2		18.6	10.8
Delivery 3		18.6	10.0
Delivery 4		16.4	8.6
Delivery 5		16.8	11.8
Delivery 6		20.0	11.4
Delivery 7		19.1	10.1
Delivery 8		18.8	12.5
Delivery 9		17.6	11.7
Delivery 10		19.2	10.8

The elements of particular interest that the scrap contained were the alloys (e.g. Cr, Ni, and Mo), and were critical in the analysis because the relatively high costs of these elements as pure alloys could highlight the effect of using more scrap in the feed. Especially in the case of Ni in Supplement 2 and Ni and Mo in Supplement 3. In the simulations, the minimum amount or the lower limit of these elements were set as the product targets with the assumption that steelmakers will tend to minimize alloying element additions.

Table 7. Compositions of scrap deliveries used in Supplement 3.

	951 styckeskrot				962 styckeskrot				951 styckeskrot				962 styckeskrot			
Distribution:	*Normal*				*Normal*				*Skewed*				*Skewed*			
Alloy	Cr	Ni	Cu	Mo	Cr	Ni	Cu	Mo	Cr	Ni	Cu	Mo	Cr	Ni	Cu	Mo
Delivery 1	17.0	10.7	0.19	0.21	16.1	11.6	0.27	2.14	16.8	8.0	0.50	0.24	16.8	11.1	0.37	2.11
Delivery 2	17.3	8.8	0.48	0.37	17.9	11.1	0.33	2.40	16.0	9.8	0.47	0.16	15.5	10.6	0.29	2.03
Delivery 3	17.6	10.1	0.41	0.22	19.6	10.0	0.39	2.39	16.8	8.5	0.34	0.21	15.0	10.0	0.45	2.00
Delivery 4	18.1	9.2	0.37	0.38	18.8	12.4	0.24	2.22	16.4	8.5	0.47	0.08	16.1	10.9	0.37	2.05
Delivery 5	16.8	9.0	0.20	0.10	18.5	11.5	0.22	2.04	16.4	8.3	0.50	0.13	15.3	10.8	0.47	2.03
Delivery 6	18.8	10.4	0.43	0.04	15.4	11.0	0.19	2.17	16.6	8.0	0.42	0.03	15.0	10.2	0.47	2.08
Delivery 7	16.9	8.2	0.09	0.24	16.4	11.1	0.37	2.16	17.1	9.3	0.50	0.00	16.1	11.7	0.29	2.03
Delivery 8	17.7	11.9	0.07	0.00	17.9	12.3	0.22	2.26	17.5	8.5	0.47	0.13	16.1	10.0	0.45	2.05
Delivery 9	19.1	10.9	0.34	0.19	19.9	12.0	0.29	2.23	16.2	8.5	0.42	0.34	16.8	10.0	0.32	2.11
Delivery 10	18.5	11.1	0.17	0.41	19.6	12.2	0.11	2.21	16.6	8.3	0.50	0.08	15.5	10.2	0.45	2.18
Delivery 11	17.2	11.9	0.10	0.24	19.7	11.2	0.02	2.12	16.8	9.1	0.47	0.16	16.6	10.8	0.47	2.05
Delivery 12	19.1	8.7	0.44	0.24	19.1	12.1	0.44	2.32	16.0	8.0	0.42	0.08	15.3	10.2	0.37	2.16
Delivery 13	17.1	9.9	0.47	0.32	18.7	10.8	0.26	2.38	16.2	9.8	0.34	0.03	15.3	11.1	0.50	2.29
Delivery 14	17.2	10.1	0.42	0.18	19.2	12.6	0.12	2.14	16.0	9.6	0.50	0.16	15.3	10.8	0.37	2.05
Delivery 15	17.7	9.1	0.24	0.25	17.8	12.2	0.28	2.16	17.9	8.8	0.47	0.26	15.3	11.9	0.47	2.13
Delivery 16	19.4	10.4	0.09	0.37	16.8	11.7	0.12	2.09	17.3	8.3	0.47	0.03	15.8	10.2	0.37	2.08
Delivery 17	19.0	12.1	0.09	0.11	17.3	11.7	0.16	2.02	16.0	8.0	0.29	0.05	17.4	10.3	0.45	2.05
Delivery 18	16.2	9.4	0.18	0.19	15.3	12.9	0.20	2.38	16.2	8.0	0.45	0.00	16.1	12.4	0.45	2.00
Delivery 19	16.1	12.5	0.28	0.36	18.2	12.6	0.25	2.10	17.1	8.0	0.50	0.05	15.0	10.8	0.42	2.03
Delivery 20	16.4	11.7	0.47	0.25	19.0	10.3	0.08	2.01	17.7	8.0	0.50	0.05	15.8	10.8	0.45	2.13

3.3.3 Simulating scrap-based production

A model that simulated the production of the selected stainless-steel grades from comparable scrap categories, was set up in the optimization tool RMM[3]. This software was developed by the KTH spin-off company Kobolde and Partners AB and has been used in similar calculations related to scrap use in steelmaking (Gyllenram et al., 2021; Gyllenram and Westerberg, 2016). It was a suitable module to use since the RMM's optimization algorithm can be subjected to constraints such as scrap chemistry, quantity, and raw material price. Using simulations as a proxy for actual production was sufficient for the purpose of obtaining 'proof-of-concept'-type of results in Supplement 2, then building on this further by adding constraints in Supplement 3.

A production schedule in each of these supplements consisted of 100-ton heats, where the total number of heats (10, 20, or 40) was related to the case or scenario being investigated (see **Figure 5** again). For example, in Supplement 2, there were 3 cases investigated. In each case, the production schedule consisted of 10 heats. Then in Supplement 3, the cases investigated incorporated more constraints, therefore included 20 to 40 heats. An equivalent amount of scrap, distributed across 100-ton deliveries, was always available for use depending on the case.

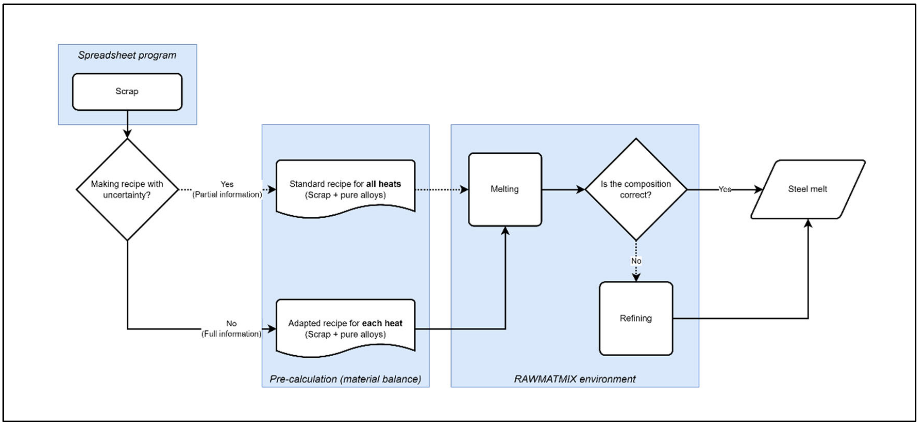

Figure 6. Visualization of the simulation model.

Once the production schedule was set corresponding to the case being investigated, the EVPI was then operationalized by contrasting the blending of input materials in scrap-based production that depended either on partial or perfect information as illustrated in **Figure 6.** The generated data from the spreadsheet program uploaded in the database of RMM was used as the basis to compare several cases influenced by having access to different degrees of information. With only partial information as the basis, a standard recipe consisting of precalculated quantities of scrap and pure alloys was used for all production heats of the same product. The calculation was based on a material balance that considered how much of the steel melt's required composition can be fulfilled through the scrap and

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[3] More information about its other products and services can be found in https://www.kobolde.com/.

how much more, if necessary, needed to be added as pure alloys. An overview of this process, along with a worked example is provided in **Figure 7.**

It is straightforward for the situation where having access to full information was simulated. The recipes were specialized in the sense that the software was set up to utilize the scrap deliveries freely and combine these in a single heat. The model was optimized to minimize production costs and constrained to fulfill the product's compositional requirements.

Within the RMM environment, steelmaking was simplified in this study as a melting process through a melting unit with an auxiliary refining step. The latter, depicted as a *refining unit*, was used only in cases where there was a need for adjusting or correcting the composition. A melt with the correct composition resulting from the recipe would be considered complete and the simulated production finishes. Otherwise, the melt was put through a refining step to correct the composition. Again, this latter situation was expectedly more expensive owing to additional raw material input and subsequently increased energy usage due to the utilization of the refining unit.

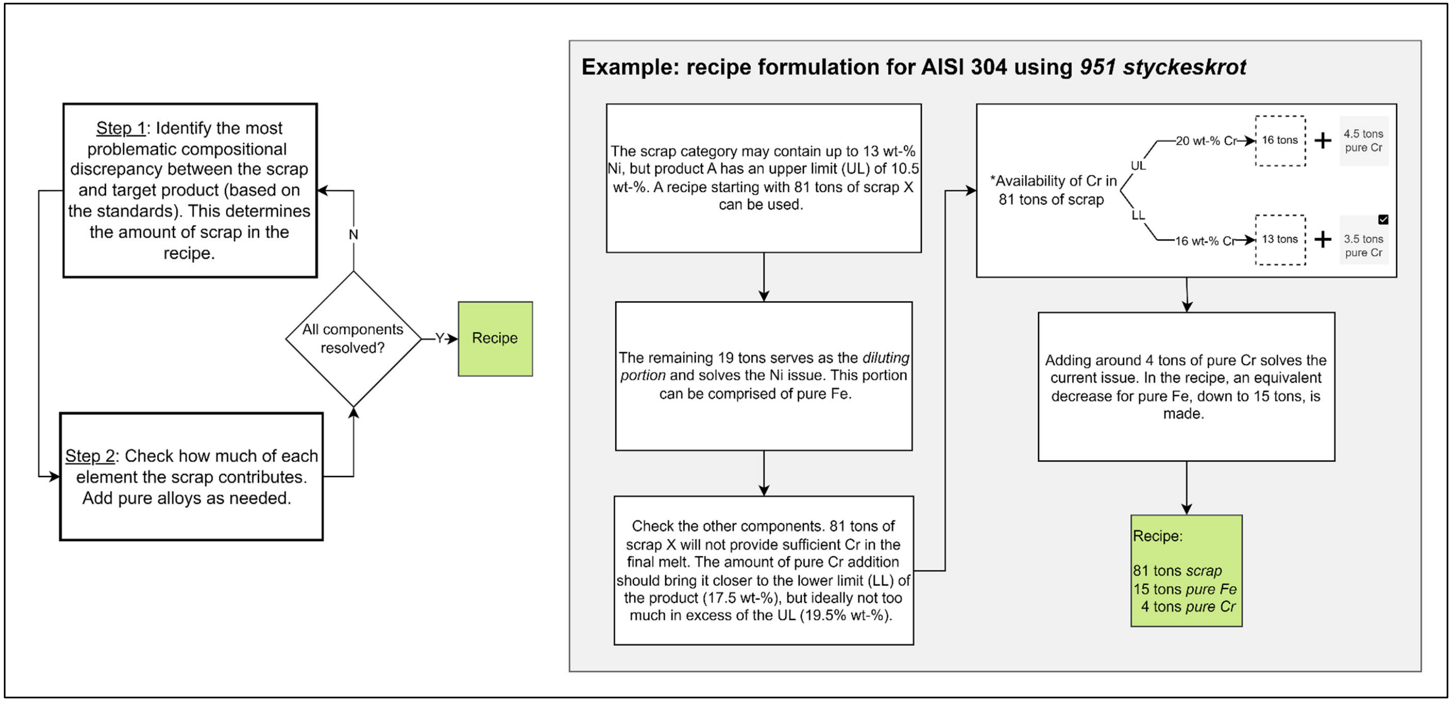
3.3.4 The cases investigated in Supplements 2 and 3

The general premise in designing the scenarios or cases for investigation in both Supplements 2 and 3 was to increase the realism of the cases progressively. This was accomplished through the implementation of additional constraints to the model such as increasing the number of scrap categories, product grades, and total number of heats, changing the price of the pure alloys, and changing the statistical distribution of the scrap chemistries.

Supplement 2 was geared towards establishing the functionality of the model and started with a first scenario wherein the constraint was mainly to achieve the target composition. The production schedule consisted of 10 heats and 10 scrap deliveries were also available. The standard recipe assumed that since the deliveries were of the category 951, that is essentially AISI 304 scrap, the melting unit in each heat would fully use the scrap. It was specified that RMM was to use the same delivery for each heat, for instance Heat 1 used all 100 tons of delivery 1. Correspondingly, any addition of pure alloys can only be done in the refining unit.

In the next scenario, a limit of 5 tons was set on the total amount of pure alloys that can be added in the refining unit. This was a practical constraint since steelmakers would rarely add too much material simply to adjust the composition of the melt. Finally, the third scenario in Supplement 2 added a constraint on scrap availability, where the quantity drawn from one delivery and used in one heat becomes unavailable for other heats. Here, the program was allowed to combine different deliveries.

Figure 8 was illustrated to give a concise summary of the cases in the 3rd Supplement. Box 1 shows the scrap-product pairings. The 1st case (labelled 1a) involved adding a second target product to be produced from the 951-category scrap. Hence 20 deliveries were generated (see again **Table 7**), divided between 10 heats of AISI 304 and 10 heats of AISI 305. This additional steel grade, again from the basis of its required composition, can also be made fully from the scrap category used, but requires more Ni (see again **Table 5**). The hypothesis to test was that with access to full information, scrap deliveries with higher Ni content will be utilized in AISI 305 production heats.



Step 1: Identify the most problematic compositional discrepancy between the scrap and target product (based on the standards). This determines the amount of scrap in the recipe.

Step 2: Check how much of each element the scrap contributes. Add pure alloys as needed.

Example: recipe formulation for AISI 304 using *951 styckeskrot*

The scrap category may contain up to 13 wt-% Ni, but product A has an upper limit (UL) of 10.5 wt-%. A recipe starting with 81 tons of scrap X can be used.

The remaining 19 tons serves as the *diluting portion* and solves the Ni issue. This portion can be comprised of pure Fe.

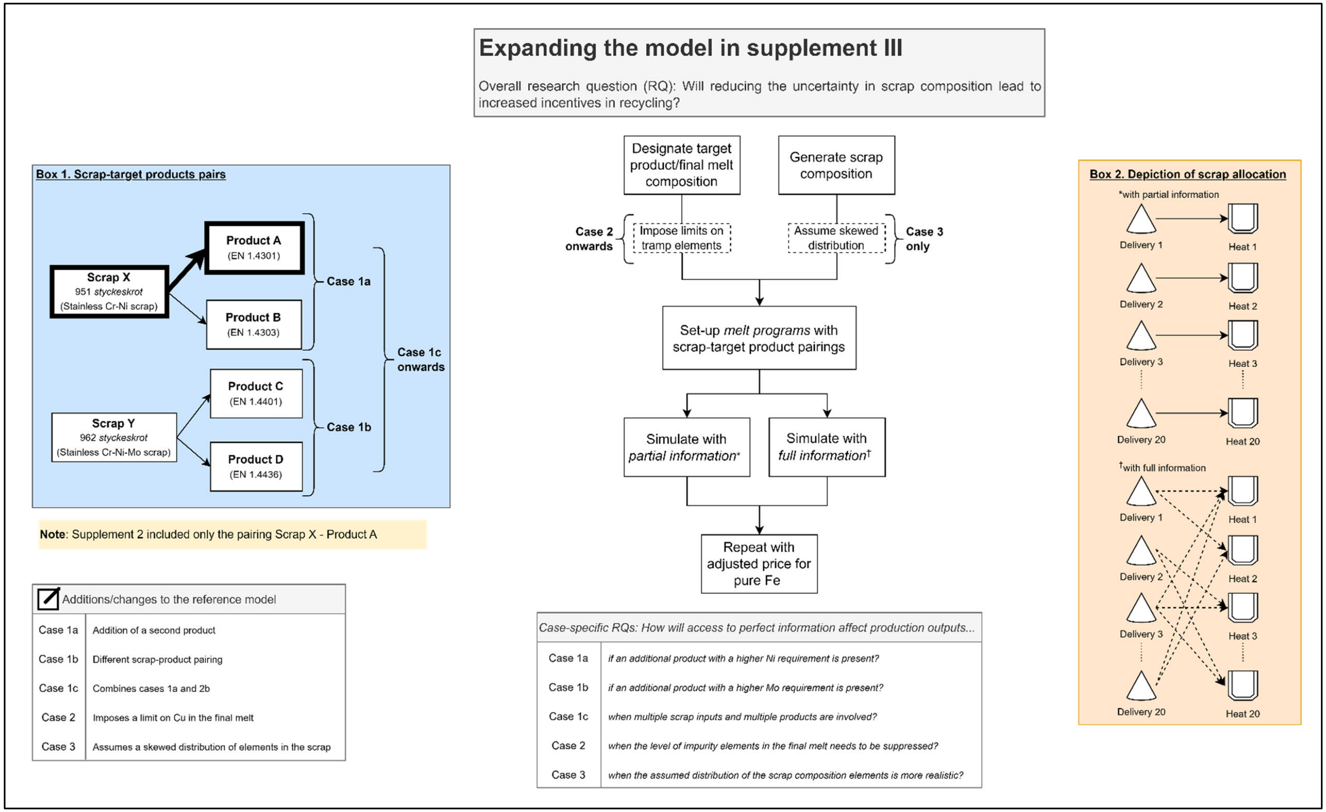
Check the other components. 81 tons of scrap X will not provide sufficient Cr in the final melt. The amount of pure Cr addition should bring it closer to the lower limit (LL) of the product (17.5 wt-%), but ideally not too much in excess of the UL (19.5% wt-%).

Adding around 4 tons of pure Cr solves the current issue. In the recipe, an equivalent decrease for pure Fe, down to 15 tons, is made.

Recipe:

81 tons *scrap*
15 tons *pure Fe*
4 tons *pure Cr*

Figure 7. The recipe formulation scheme in Supplements 2 and 3.



☑	Additions/changes to the reference model
Case 1a	Addition of a second product
Case 1b	Different scrap-product pairing
Case 1c	Combines cases 1a and 2b
Case 2	Imposes a limit on Cu in the final melt
Case 3	Assumes a skewed distribution of elements in the scrap

Case-specific RQs: How will access to perfect information affect production outputs...	
Case 1a	*if an additional product with a higher Ni requirement is present?*
Case 1b	*if an additional product with a higher Mo requirement is present?*
Case 1c	*when multiple scrap inputs and multiple products are involved?*
Case 2	*when the level of impurity elements in the final melt needs to be suppressed?*
Case 3	*when the assumed distribution of the scrap composition elements is more realistic?*

Figure 8. An infographic on adding realism in the Supplement 3 cases.

The same conditions were followed in building the next case (1b), but with another scrap category, 962 *styckeskrot*, the scrap that matches to the Mo-containing AISI 316 stainless steel grade. Two different AISI 316 grades were “paired” with the second scrap, where one required a higher content of Mo. Case 1c then combines both cases 1a and 1b, with the purpose of testing how the scrap allocation will proceed since scrap 951 may also contain some Mo.

Case 2 in Supplement 3 introduced a tramp element into the simulations. It affected the formulation of the recipes, especially in simulations where the information available was only partial because the content of the tramp element must be accounted for. Based on the specifications, the selected scrap categories may contain Cu, up to an amount of 0.05 wt-%, which was taken to be the tramp element in the study. The recipe should then be diluted to at least half this value, a practicable level according to personal communication with a practitioner.

As a final case, the scrap deliveries having chemistries generated from a skewed distribution were used in the simulations. All the cases were performed following the sequence in **Figure 8**. A representation of how scrap allocation occurs in the simulations is provided in Box 2.

3.3.5 Post-processing of the simulation results

The essential outputs from RMM were transferred to a spreadsheet program for post-processing in order to compare each production heat and to report the aggregated (i.e. average) results for a whole production schedule.

Another metric was also calculated, namely the *excess cost*. It ‘penalized’ a melt having an alloying element content above the minimum required of the product. The results of the simulations to this extent answered the question of what having access to perfect information possibly brings to production.

Chapter 4: Results and discussion

It is straightforward to study recycling from a technical standpoint because it involves EoL materials going through a process to obtain a product of, ideally, the same or higher quality. Achieving this clearly requires knowledge of the materials sciences, although what is often overlooked from this viewpoint is that recycling occurs through firms incentivized to carry it out. Recycling is both a technical and a commercial activity. Employing this interdisciplinary view meant examining scrap and how it is utilized as a resource through the enterprises in a system. To recirculate materials is to utilize scrap. This scrap customarily flows through a system consisting of actors whose protocols and decisions affect its fate; between being assimilated into a new product, the landfill, or transformed into energy. Based on this reasoning, the research work in fact would benefit from the inclusion of technical and organizational perspectives.

With CE as the context, recycling, among the other circular strategies in the context of production, became the focal point of this work because it is the only relevant circularity strategy directed at the material level. Thus, scrap became the material of interest. Recovery is also at this level but entails 'destroying' the material in exchange for energy. All other strategies are at the product level.

4.1 Steel recycling and the connection between scrap quality and information

The advantage of starting with a qualitative exploration and having a description of the selected system was that distinct themes for further studies were identified. That is, the subsequent work built on the findings of this first one; then, the following supplements took the insights of the preceding ones. It facilitated the describing the nature of a 'functioning' recycling system. The unit of analysis was directed towards the firms as actors within this system because the flow of scrap follows the transactions between them. The underexplored subject of the system's lack of information on scrap chemistry was inferred from a deeper understanding that resulted from the work carried out during this phase. Operationally, the system cannot provide high quality scrap consistently, and worse, compositional uncertainty is already embedded with the scrap. Thus, the next step was finding a means to attribute value to increasing the level of this type of information.

The study of recirculating materials in industrial processes was undertaken from the point of view of anthropogenic resources. Specifically, the author's previous experience on working with reprocessing of industrial waste from mineral processing. In that work, the goal was to extract values from stockpiled mine tailings (e.g. Cu from artisanal Au-mining and W from an old mining site). This view that an efficient recovery of the values cannot be designed unless there was sufficient characterization of the tailings carried over as an expectation of how other industries that utilize this type of resource would behave.

An interest developed and eventually was directed towards the steel recycling in Sweden and the manner in which scrap is utilized in this context. An understanding of how this system functions was needed because the recirculation of materials is subject to technical complexities at the process level and the involvement of different actors at the organizational level.

The literature on this topic drew attention to concerns on 'contamination' and 'intermixing' of scrap streams (Stephenson, 1983) that put in question the notion of steel as 'infinitely recyclable' (World

Steel Association, 2019a). The identity loss of the steel, its composition, becomes more obscure as it moves through the value chain. The steel industry recognizes this as an issue to address but has settled on “sweetening" or the utilization of purer, ore-based feedstock (Ciacci et al., 2016; Pauliuk et al., 2013; Raabe et al., 2022; Zhu and Cooper, 2019) as the solution. Some studies (e.g. Igarashi et al., 2007; Yamada et al., 2006) predict that continuing operations as usual could lead to difficulties in utilizing these lower quality, ‘dirty’ scrap. One view from the quality aspect is that conveys that there is a comparable, ‘higher’ quality type of scrap that would be preferred, and it depended on who is utilizing the scrap. Cu for example is generally characterized as a contaminant (Daehn et al., 2019, 2017) but is utilized in a controlled manner in some steel grades (Pardo et al., 2006). Alloying elements are intentionally added to impart properties to the steel in the first place. Then, in the reverse flow, if these elements end-up in the correct melt, their values are retained. This ‘functional recycling’ occurs when a material is used to produce the same in the next use (Diener and Tillman, 2015).

A feature of the industry was that the system can be considered highly functioning, where the commercial activities of its actors facilitate the flow of scrap for the country’s scrap-based production. Sweden, at the time of writing, has ten active steelmaking plants, six major scrap dealers, and a broker co-owned by some of the steel producers. The meso-level study of the industry revealed that the quality of scrap is defined or rated differently by different actors, whose perspectives are summarized through four quality dimensions in **Table 8**. Except for the physical condition of the scrap where both group of actors agreed, the other three dimensions with respect to the desired content, shape and size, and homogeneity, all reflect the suitability aspect of the scrap to their respective operations.

Table 8. Dimensions of scrap quality as described by the identified actors.

Quality dimension	**Description**	
	Steel mills	Scrap dealers
Desired content	Preference of buying scrap with the lowest levels of contamination and/or a high content of element needed in their products.	Finding the cheapest supply of scrap with minimum preparation required that meets the requirements of the mill to which they deliver.
Physical condition	Related to the safety of operations by preventing scrap that pose radioactive, health, and explosive hazards from entering the scrapyard or the steel plant.	
Shape and size	Steel mills prefer denser scrap to load EAF better. This is a function of the shape and size of the scrap.	Related to scrap preparation with the observed increase in value for scrap of higher density.
Homogeneity	The expectation that the category of scrap supplied to them is free from abrupt deviations in and across delivery batches.	Establishing trusting relationships with customers with the consistency of their deliveries.

The system actors were found to require quality levels that are specific to their needs. The meaning of high quality for one steel mill is not necessarily the same as for another, and this affects how suppliers act. The demands that the business side of recycling puts on scrapyard operations of the dealers, whose actions greatly influence the quality of scrap supplied to the steelmakers, are challenging. It is one thing to say sorting must be done so that the intrinsic value of the elements is captured, such as ensuring that carbon steel is separated from stainless steel as demonstrated by Nakamura et al., (2017). However, when pieces that are in-between categories arrive and minimum delivery volumes need to be aggregated to fulfill the supply order, coupled with the motive to maximize the profits on each delivery, then it makes business sense to bundle together into the category that will lead to the highest payoff.

Operational behaviors impact scrap quality and information—and ultimately, circularity. Dealers want high-quality scrap because it is easy to sell, and mills want it because it is easy to use. But the reality is that scrap needs to be delivered, and steel needs to be produced, under complicated conditions. Actors make trade-offs that always prioritize economic considerations rather than material resource efficiencies.

Thus, recycling does not happen automatically. Rather, it occurs through the deliberate actions of actors who found incentives for recycling, from collection up to the actual use of scrapped material to produce new material. Furthermore, it is in the reverse flow, where the scrap needs to end up in the right production, that quality becomes conditional on the amount of information that is available and/or recovered. The scrap dealers and the steelmakers act on what they know. As more information is available or recovered, a higher quality level can be achieved, that ideally leads to elements ending up in the correct steel product with their intrinsic value preserved. However, the actors' efforts to ensure this outcome depend on the value they get in return for their efforts.

4.2 The Expected Value of Perfect Information in steel recycling

One of the main contributions of Supplement 2 was operationalizing having access to partial and full information in the simulations.

There were attempts to obtain actual data, specifically the chemical composition of delivery batches, from the system actors. However, this type of data proved to be inaccessible for the following reasons: either the companies consider it as 'business confidential' or that it was data that they do not record.

The model simulated the production of the stainless steel grade AISI 304 from its analogous scrap category, *951 styckeskrot,* through the optimization software RMM. It was a suitable module to use since RMM's optimization algorithm can be subjected to constraints such as the scrap chemistry, quantity, and raw material price. Using simulations as a proxy for actual production was sufficient for the purpose of obtaining 'proof-of-concept'-type of results. The contents of the scrap deliveries were only of the elements of interest (e.g. Cr and Ni), with the reasoning that the high cost of these elements as pure alloys would already highlight the effect of using more scrap in the feed for example. For Supplement 2, the production schedule consisted of ten, 100-ton heats, where an equivalent amount of scrap was available for use. The Cr and Ni requirements for the product were taken from a product standard(Euro Inox, 2007) for AISI 304 and in the simulations, the minimum amounts were targeted (17.5 wt-% and 8 wt-%, respectively).

Once the link between scrap quality and compositional information was established, the next step was to measure what additional information can bring to scrap-based steelmaking. Variations are inherent in obsolete scrap even if they are sorted into same category. Uncertainty affects scrap usage and inhibits the presumed economic and environmental advantages for the scrap-based steelmaker. It is widely accepted that reducing the uncertainty in scrap as a feedstock would be beneficial to recycling (Haupt et al., 2017; Rigamonti et al., 2018). Having a means to measure this 'expected value' may lead to a further consideration of what access to more information can give. If a steelmaker knows the identity of the scrap better, to a more accurate level than the lower and upper limits that scrap standards specify, what then? The actors respond to incentives, so getting quantitative results would be a meaningful way to exemplify the value of information.

With the scrap chemistries of actual deliveries being inaccessible, the procedure implemented for the feedstock or recipe formulation based on the available scrap standards and product specifications was found to be ideal. By basing it from these standards that are used in the transactions between recycling actors, it gives a perspective of the scrapyard operation when it is time to utilize the scrap. Considering the number of active steel grades that are scrapped (EUROFER, 2015), then to receive scrap sorted into only a handful of categories means operating under a level of uncertainty.

The third scenario was the most realistic simulation in Supplement 2 because of the combination of constraints. For the production schedule consisting of ten heats, each one must meet the target composition, with an imposed practical limit on the amount of pure alloy addition in the refining unit and the availability of scrap deliveries are finite (e.g. using 50 tons of delivery 1 in the first heat leaves 50 tons available to use for the remaining 9 heats, and so on). The average of the results between having access to partial or full information across ten heats are summarized in **Table 9**. Here, the total excess cost accounts for both Cr and Ni in excess of the minimum required in the melt.

Table 9. The difference in the production metrics in Supplement 2.

	Partial information	**Full information**	**Δ%**
Raw melt unit cost, (€/ton)	2 021	1 867	-8%
Alloyed melt unit cost, (€/ton)	2 042	1 867	-9%
Total excess cost, (€/ton)	211	0	-100%
Excess melt, (tons)	2	0	-100%
Scrap usage per heat, (tons)	81	69	-15%

The recipe that was used in the partial information case, 81:16:3 proportions of scrap-pure Fe-pure Cr, is enough for the range of Cr- and Ni-content in the deliveries. Pure Ni was not needed simply because the generated scrap chemistry was based on a normal distribution, putting the average content of the deliveries at 10 wt-% Ni which is already above the 8 wt-% minimum requirement for the steel grade. The main disadvantage of this input blend is that even if the scrap delivery is of the right composition, it always uses 19 tons worth of pure alloys. Further to that, even worse is if the Cr added might not even be in the mix as an alloy but just to lower the Ni content.

In comparison, with access to full information, the average scrap usage of 69 tons maximizes the alloy content in the scrap. Clearly pure alloys are still needed to reach the required Cr and Ni levels in the product, but without leading to excess costs. While the 15% reduction in recycled content may seem a disbenefit, it applies only to this production schedule, and it would be different when a product that requires a higher Ni content, for example, is included. This is one of the model developments that was implemented in Supplement 3. Additionally, production heats in this context can do away with the refining step because the recipe at the melting step is already satisfactory which is the reason why the raw melt unit cost is the same as the alloyed melt unit cost.

The EVPI based on the simulated cases could be associated to the reduced downcycling of Cr and/or Ni (also discussed in the second Supplement), or being able to regulate the addition of pure alloys which is beneficial for steelmakers considering that raw material inputs constitute up to 70% of the EAF production costs (Medarac et al., 2020). In the succeeding set of simulations made for Supplement 3, having access to full information increased scrap utilization, allowing for the mixing of different deliveries to achieve as-close-as-possible final composition for each melt. EVPI is a frame of reference to present what possibilities can be generated by having additional information and extends its application to the materials industry. As the reliance of society on anthropogenic stocks increases, ensuring that material identity is intact and traceable in the reverse loop is vital. Thus, showing the value, particularly the economic potential of this type of information, is one approach to motivate actions such as upgrading the characterization and sorting infrastructure.

4.3 Adding realism to the EVPI-model

The solution space that was explored in Supplement 2 was reasonably constrained but still provided relevant insights that could influence decision-making in different business units of a firm other than production. For example, in the purchasing department and raw material handling. The simulations in Supplement 3 continued to develop the argument that if the incentives brought about by having access to perfect information on the recycling feed can be shown, then it can support the decision-making of steelmakers regarding their scrap usage. Utilizing more scrap is economically and environmentally advantageous for them and assists with figuring out how to deal with sustainability trade-offs. With the share of old scrap supply projected to continually increase (Raabe et al., 2022; Xylia et al., 2018), the problem of uncertainty in scrap composition, of “unusable” scrap and accumulation of problematic, tramp elements will only limit recycling systems.

Three scenarios were simulated in Supplement 2, with increasing complexities with respect to the production schedule described earlier in this section. First, exemplifying an operation that loads the furnace with 100% scrap because the chemistry of the input and output are matching. Next, using a recipe that was formulated using the logic as described in **Figure 7.** Finally, the optimized scenario where the simulation was allowed to ‘pick’ and combine different deliveries. The direct outputs from RMM related to production costs and quantity of scrap consumed were analyzed.

The next step was to address some of the simplifications in Supplement 2 and increase the realism of the cases. Supplement 2 was designed to be a more conceptual, initial step that established a method to calculate the value of information. Supplement 3 aimed at developing the model by seeing how it responds to a more complex production schedule. Hence the addition of another scrap category and multiple target products, together with the inclusion of tramp elements in the analysis. *962 styckeskrot* was introduced as the other scrap category. Added on the product side were AISI 305 (EN 1.4303) and two types of AISI 316 (1.4401 and 1.4436) stainless steel grades to AISI 304 (EN 1.4301). The details of the cases simulated in Supplement 3 can be seen again in **Figure 8**. The procedure for generating scrap composition data was repeated prior to the simulations as well.

Even with a more complex production schedule, or rather, more so when dealing with multiple scrap inputs and products, having access to full information improved production in terms of (1) a general increase in scrap quantity used in the heats, (2) a decrease in production costs, and (3) an increased flexibility in feedstock allocation to regulate the excess costs. The results of the simulations are summarized in **Table 10**. The sub-labels *i* to *iv* correspond to the following: i: partial information at the original pure Fe price, ii: full information at the original pure Fe price, iii: partial information with the modified pure Fe price, and iv: full information with the modified pure Fe price; except in Case 1c where only full information simulations were performed. It must be noted that only the alloyed melt unit cost changes in the partial information case with a higher (modified) pure Fe price (i.e. *-i* in contrast to the *-iii* results).

Sections A through C relate to the results for the three sub-cases of Case 1 and sections D and E relate to cases 2 and 3, respectively. The table also shows that simulations were replicated with a modified price for pure Fe where it becomes marginally more expensive (+0.1 €/kg) than the respective scrap. Since the optimization is sensitive to the price of raw materials, this basically favors the use of more scrap. This was consistently observed in the results and is more in line with the recycling reality. What this means is that anything that stimulates the supply of suitable scrap in the market is a way to keep economic and environmental incentives aligned.

Table 10. Summary of results for all Supplement 3 simulations.

Note: Reported numbers are average values	SECTION A				SECTION B				SECTION C		SECTION D				SECTION E			
Simulations results:	*1a-i*	*1a-ii*	*1a-iii*	*1a-iv*	*1b-i*	*1b-ii*	*1b-iii*	*1b-iv*	*1c-i*	*1c-ii*	*2-i*	*2-ii*	*2-iii*	*2-iv*	*3-i*	*3-ii*	*3-iii*	*3-iv*
Scrap quantity used for the whole production	88	90		100	92.5	87		100	89	100	50	89		97	50	61		62
%Δ in scrap quantity used with access to full information for the whole production		**+2%**		**+14%**		**-6%**		**+8%**	**-1%**	**+11%**		**+78%**		**+94%**		**+22%**		**+24%**
Alloyed melt unit cost for the whole production (€/ton)	2 315	2 130	2 474	2 258	3 439	3 084	3 606	3 263	2 607	2 761	3 399	2 608	4 343	2 773	3 413	3 177	4 365	3 905
%Δ in production cost with access to full information for the whole production		**-8%**		**-9%**		**-10%**		**-10%**	**-9%**	**-10%**		**-25%**		**-36%**		**-7%**		**-11%**
Excess costs (€/ton)	201	76		274	368	0		305	38	322	255	39		245	79	17		15
%Δ in excess cost with access to full information for the whole production		**-62%**		**+36%**		**-100%**		**-17%**	**-87%**	**+13%**		**-84%**		**-4%**		**-78%**		**-81%**

To further illustrate the benefits of having access to perfect information, Sankey diagrams of input material allocation are provided in **Figure 9**. These diagrams show from the left, the available scrap types, and pure alloys, then their utilization in the middle, and finally the Total Material Consumed (TMC) to the right. The diagrams at the top show the difference between having access to partial information (a), and full information (b). The bottom diagram (c) shows complete utilization of all the deliveries when pure Fe is more expensive than scrap.

In *a*, as already observed in Supplement 2, even a carefully formulated recipe that is based on partial information would require the use of pure alloys. Product B requires a higher Ni content than product A. Thus, the best allocation would be to use scrap deliveries with higher Ni contents in product B heats, but it becomes a matter of luck whether the delivery picked contains a high Ni content. Therefore, 10 tons of pure Ni was needed. Pure alloys additions were also needed in case *b*, but to a lesser degree when having access to full information; even more important is that it leads to maximizing the use of Ni that is already present in the deliveries. The impact is more noticeable in a situation where the scrap is cheaper than pure Fe, as shown in *c*. It must be noted that there was an increase in excess costs when using only scrap that can be linked to the absence of pure Fe in the production heats that limits the ability to dilute other alloying elements that the scrap might have that report to the melt, to an extent more than the minimum required. Mo in this case, which is even more expensive than Ni (37.07 €/kg and 21.15 €/kg, respectively), can be present in the scrap according to the scrap specifications.

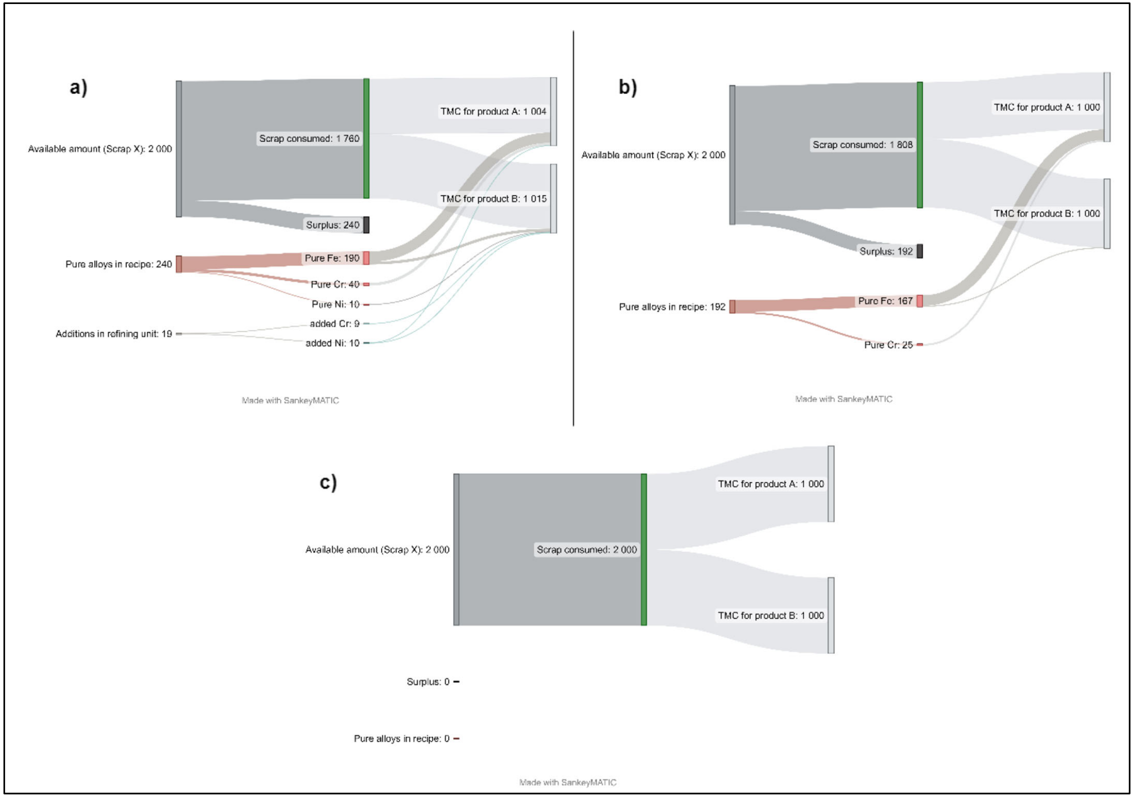


Figure 9. Sankey diagrams showing the raw material utilization in Case 1a.

At the time of running the simulations, the price of Mo was more expensive than Ni as previously mentioned, and it was observed that a portion of scrap A was used in the production of product C as seen in *b* and *c* in **Figure 10**. More specifically, *a* and *b* refer to Case 1c, while *c* refers to Case 2-iv of Supplement 3. In (a), the price of pure Fe is the original price at 0.45 €/kg, while it is the modified price in (b) (i.e. 2.19 €/kg for 951 and 3.13 €/kg for 962, respectively). A key observation here is the atypical allocation, although in relatively limited amounts, of the scrap categories. In 5b, scrap X was used for product C and scrap Y in products A and B; and again, in 5c where scrap X was used in product C.

This is yet another demonstration of what access to full information brings; where even at a rudimentary level, Stahel's (2016) remark that the goal of recycling specific atoms, can be accomplished.

With the functional recycling aspect of having access to full information demonstrated, the conditions of the production also made to incorporate the presence of tramp elements then finally, a more realistic prospect regarding the content of elements in the scrap (refer to sections D and E in **Table 10**). The latter meant that new scrap chemistries were generated, which were still within the range of possible values according to the scrapbook but using a statistical distribution that resulted in the alloying elements Cr, Ni, and Mo contents to be closer to the lower limit while the Cu content was almost at its maximum value.

The EVPI in either situation can be linked to higher recycled content in the production heats that led to lower production costs and excess costs. The increased complexity of the production schedule can be thought of as the reality of scrap-based steelmakers having to deal with the changing composition profiles of scrap that is available to them. Again, the suitability of scrap can be improved through reestablishing its identity. Scrap dealers can supply products with increasing specificity and steel mills can control what gets in the melt. This would possibly slow down the accumulation of tramp elements.

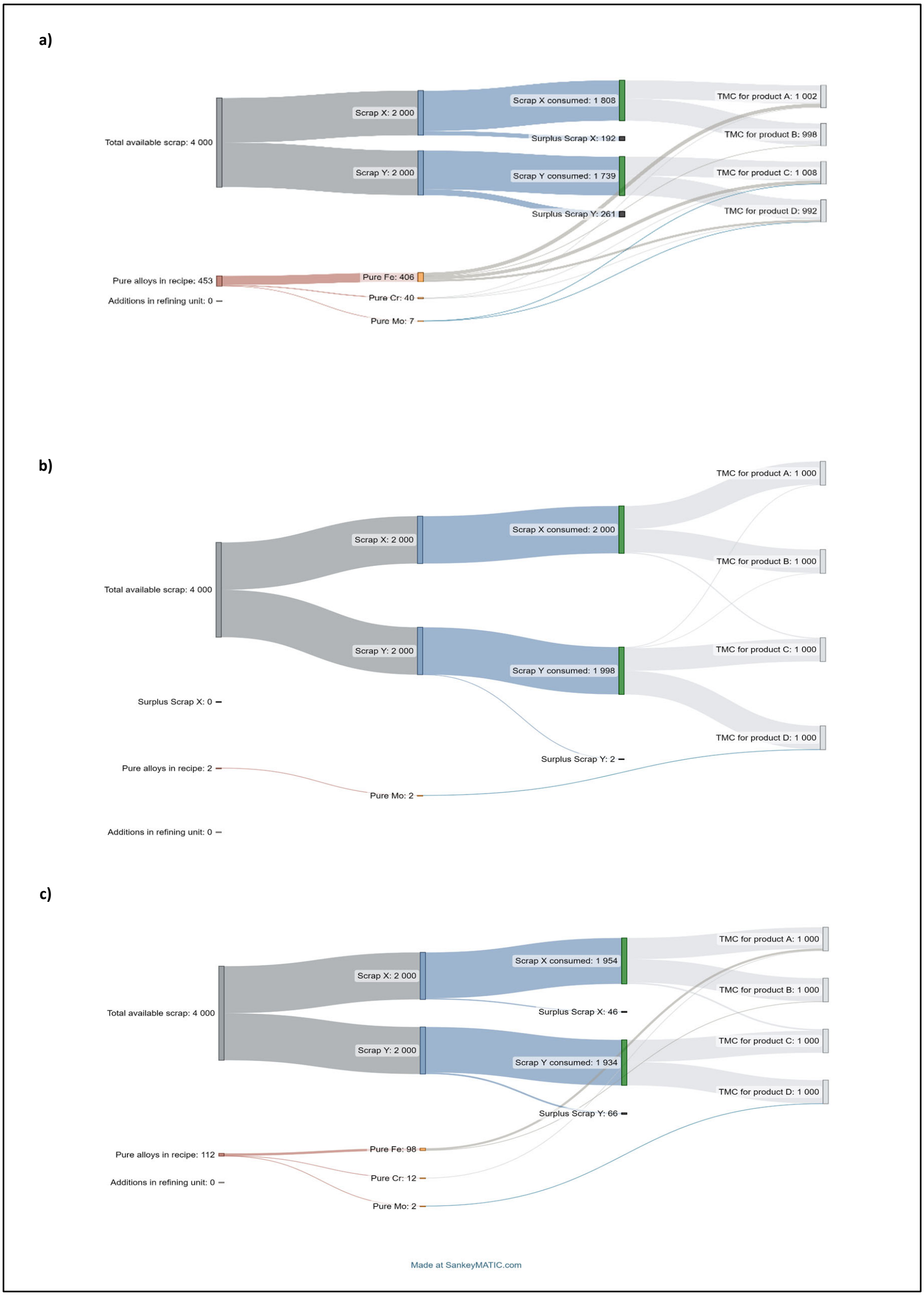


Figure 10. Sankey diagrams showing the raw material utilization in select cases.

4.4 Dealing with lack of information and opportunities for increasing scrap consumption

The interviews that were performed in this final phase targeted respondents in terms of their extensive career experiences related to scrap handling or management. The value of information in recycling was shown through simulations in the previous phase, but how actors deal with the compositional uncertainty in practice and what they see as opportunities to increase scrap consumption should be considered. Utilizing more scrap is economically and environmentally advantageous, but what essentially happens in recycling is decided by the actors.

Going through the responses of the actors, a recognizable degree of context-dependency in respective scrap management practices (see **Table 11**) was revealed, spurred by the discussion with a consultant for a steel mill from a 'lower-income context', where the steelmaker was currently utilizing 100% scrap in production heats. The main reason that was given was the attitude of the small-scale 'junk shops' where they meticulously pick and sort out different metals as each represent different profit streams. In this case, the steelmaker has observed that they can use the scrap delivered to them directly, although Ore Based Metallics are also in-stock and available as needed.

Table 11. Scrap handling protocols by industry actors in different contexts.

Recycling actor	Lower-income context (LIC)	Higher-income context (HIC)
Scrap dealer/supplier	• Complete reliance on manual labor to sort and separate collected metallic scrap. • In the case of joined components, basic equipment is used to carry out the separation.	• Portable analytical equipment is used, which allows for a more defined characterization. • Semi-automated sorting and classification between metallic streams.
Steelmaker	• Scrap specifications are used for transactions. • Visual inspection of scrap deliveries is performed.	• Scrap specifications are used for transactions. • Visual inspection of scrap deliveries is performed via visual and handheld analytical equipment. • Test melts are performed.

The protocols that steelmakers have implemented have been tailored to address their production contexts. It supports the findings of the 1st Supplement that they try to reach the highest possible incentives that are not all the time the most environmental (e.g. use of Ore Based Metallics vs. scrap). These finer points of recycling can be distinct in different economic contexts (lower-income or higher-income) and remain an underexplored theme in research focused on recycling.

Figure 11 shows a generalized strategy that one respondent described as being practiced in their production. The example given was that for a standard grade, they will have multiple sub-types of this grade that are subject to their customers' requirements. This way, they adjust their production based on the eventual chemical composition of the steel melt.

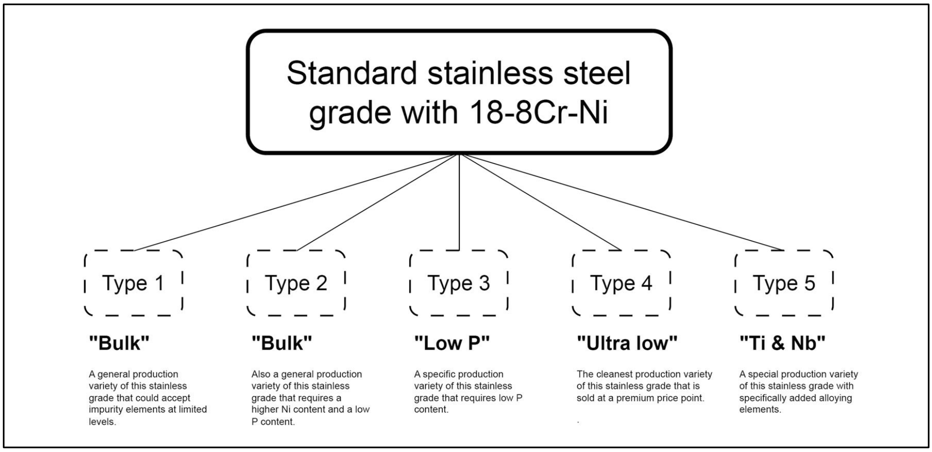


Figure 11. A description of steelmaking adapting to the variation in scrap chemistry.

When asked about what they think of obtaining more information with respect to the chemical composition *before* the respondents seemed to agree that more information can lead to increased consumption. Their responses listed in **Table 12** point to opportunities they can imagine implementing in-house and those that require interacting or collaborating with other actors in the system.

Table 12. Opportunities for increasing scrap consumption.

Internal	External
• Characterize inbound scrap deliveries and practice good record-keeping. • Improve sorting of internal scrap and ensure there is no mixing between piles. • Product development of 'scrap-tolerant' steel grades. • Refrain from putting more and more alloying elements into products.	• Stimulate the scrap market (i.e. scrap suppliers and aggregators) to provide higher quality scrap with a willingness to pay more. • Work with product manufacturers to gain an understanding of how the product was designed for disassembly and/or recycling. • Regulations need to be intelligent and timely, because the actors act in accordance with the logic of these rules. • Consider reselling scrap to other recyclers if current customers (i.e. active production recipes) do not need what is in the scrap. • Update scrap standards and ensure that these reflect the recent steel grades in the market.

With respect to the methodology, the number of interviews is on the low side. However, considering the cumulative experience of the respondents, as well as the companies they work in/worked for, may already offer enough depth, relative to the size and nature of the respective steel industries of the countries included. Moreover, the methodology was heavily influenced by being introduced to *interpretative phenomenological analysis* as a research method from a conference presentation where it was used to study the experiences of a small but select number of designers regarding their experiences in circular building design.

Ultimately, the actors in steel industry will continue to use scrap primarily because of the economic incentives that it brings to their operations. The findings in Supplement 4 once again emphasized the value of recovering scrap chemistry information because the current protocols of these actors reflect that they basically work with uncertainties.

Chapter 5: Concluding remarks

The Supplements included in this thesis, after working through the respective research questions, contributed to the fulfillment of the research objectives. The main results from each study are summarized in **Table 13** and further elaborated in section 5.1.

In the current backdrop of 'greening' the steel industry, recycling continues to be a direct and proven pathway for decarbonization. The impacts of the EAF, which is the technology customarily associated with scrap-based production, are well-known. Contrarily, the decarbonization technologies being developed that radically change the way steel is produced, like shifting to hydrogen as a reducing agent instead of carbon and carbon capture and storage (CCS), are still in development but have increasingly garnered attention since businesses now also operate focusing on the additional "currency" named GHG emissions. While waiting for these new technologies to reach industrial implementations, and aside from lowering steel consumption, intensifying scrap usage will continue to lessen CO_2 emissions.

Using more scrap in this thesis meant increasing the recycled content in production, if possible, more than at the current levels. The ISO (ISO 14021-2016) defines recycled content as *"the proportion, by mass, of recycled material in a product. Only pre-consumer and post-consumer material shall be considered as recycled content."* Understandably, there are other aspects that must be included in the discussion on reaching increasing recycled contents, such as the careful consideration of regulatory frameworks establishing recycled content targets (AISC, 2017; IRP, 2020), so the production industries can realistically contribute with positive changes in their production behaviors, where sustainability goals can be reached. And there might be evidence from the plastics sector that incremental steps are possible. In Japan, a study concluded that *"To further encourage the use of recycled plastic materials, policy interventions should directly incentivize producers to increase the use of recycled plastics"* (Kumamaru and Takeuchi, 2023). Recycling, after all, is both a technical endeavor and a profit-motivated activity.

All things considered within the scope of this thesis, it is again emphasized that, when a comparable anthropogenic stock is available for material production, recycling ought to lessen or prevent the need for new material from being drawn from the primary resources stock. This replacement is a clear feature of recycling that can lower steelmaking's carbon emissions.

Table 13. A summary of the insights obtained from each Supplement in the thesis.

Supplement	Topic	Objective	Main results
I	Circular Steel: How information and actor incentives impact the recyclability of scrap	• Investigate and describe a recycling system. • Identify issues in using scrap as a raw material for steelmaking.	• The meaning of scrap quality differs between actors in a recycling system. • Compositional information is an integral aspect of scrap quality because it is a determinant of suitability. • As a commercial activity, recycling is susceptible to favoring economic incentives.
II	Appraising the value of compositional information and its implications to scrap-based production of steel	• Develop the idea of the value of (compositional) information. • Apply a simulation model to quantify the value of information.	• Access to perfect information lowers production costs. • Alloying elements dissipation needs to be measured through metrics such as excess costs. • EVPI can be a useful tool to check the feasibility of upgrades in characterization and sorting infrastructure. • Having perfect information may lead to higher recycled content.
III	A value of information approach to recycling	• Improve the practical application of the simulation model from Supplement II by introducing additional constraints.	• Difficulties related to uncertainty of input are addressed with more information. • With the right compositional information, steelmaking can be fully scrap-based. • With access to perfect information on scrap chemistry, scrap utilization increases. • More scrap in a production heat saves valuable alloys.
IV	A review of scrap handling practices and prospects for increasing scrap consumption in recycling	• Determine how companies deal with the lack of information. • Discuss the opportunities for increasing scrap consumption.	• Uncertainty in scrap composition is an issue that is worsening. • Steelmakers have protocols adapted to their own production. • There are key areas articulated by the practitioners that can lead to increased scrap consumption.

The position held throughout this work is that scrap, like any other anthropogenic resource, is challenging to use. But even with these difficulties, this work contends that there is space for intensifying scrap-based production. Even for steel — whose being recycled precedes the conception of CE, with a recycling rate that is already remarkably high compared to other materials (Daehn et al., 2017; World Steel Association, 2019b), and its known production routes can accommodate scrap by now.

Based on the report by Blasenbauer (2020), Winterstetter (2021) categorized into three main aspects the challenges that must be overcome for secondary or anthropogenic resources to be used effectively in a CE context. According to them, for these types of resources, there are aspects of (1) resource potential, connected to the quantity and quality of the resource as a function of use and disposal patterns, (2) recovery potential related to the considerations depending on the type of 'anthropogenic mine', and (3) utilization potential that pertains to the resource's barriers to re-entry to the material or product life cycle.

These aspects and the associated challenges of each are interrelated, and this thesis was only able to address a few, at varying depths within the scope and boundaries of this work. The findings in this thesis should be read in consideration of some limitations. First and foremost is the lack of primary data on scrap chemistries. While the method developed for illustrating the lack of information as having access to partial or full information in Supplements 2 and 3, the bearing of the results will remain indicative. The resulting numbers will not lead to the restructuring of established infrastructures of scrap management of a company to invest in new characterization equipment or to include an extra sorting step within the process flow.

Similarly, the quantitative results from Supplements 2 and 3 were based on fixed material costs. Recalculations are necessary if an outlook on the current state of the recycling industry is desired. This is in consideration of the fact that the prices of commodities such as the alloying elements Cr, Ni, and Mo, and even stainless steel scrap used in the calculations can change over time.

Another limitation is that scrap-based production was found to be highly context-based. For example, the Swedish steel industry has this feature where high-performance steels produced locally are exported while importing the standard grades according to *Jernkontoret,* which is the Swedish iron and steel producers' association. This situation gives a different profile to the local scrap supply in relation to the production. In contrast, the Philippines which was featured as the low-income context in Supplement 4 has not reached a highly industrialized state so the scrap types that are available is a closer match with the local production.

5.1 Fulfillment of the objectives

The anthropogenic resource of interest, and the focus of the thesis, was on steel scrap and its usage as feedstock for production from a context that brought together technical and business aspects. Hence, performing the study at the level of activities in the scrapyards of dealers and steelmakers was a fitting point of departure.

5.1.1 On the 1st phase: *system exploration*

Research Objective 1: Reinforce the understanding on the issues that remain in the recirculation of scrap as a raw material for steel production, using technical and organizational standpoints in the analysis, and formulating it as a quality issue related to information.

In Chapter 1, the associated research question (RQ1) to this objective was, *"what is the current praxis of handling scrap for use in production in a recycling system?"* This question was addressed in the 1st Supplement by:

- *Formulating a link between how scrap quality is described in the literature and how it is reflected in the transactions between key actors in the reverse flow of end-of-service steel.*
- *Expanding the definition of quality to include the importance of obtaining compositional information.*

The recurring idea in literature relating to scrap management was that contamination issue would be addressed if the characterization and sorting infrastructure at the reverse flows of materials were efficient. The portrayal of scrap was that it was either of a low-quality — contaminated with unwanted elements, or of a high-quality — pure and easy to use. *Supplement 1* was an investigation at the operational level that concluded that the meaning of scrap quality differs between recycling actors. Suitability for their own commercial activities basically dictates if a piece of steel scrap will eventually be remelted to make new steel. The transactions between scrap dealers and steelmakers reflect this, where the prevailing scrap standards provide the basic language of the contracts, but specific business-to-business (B2B) arrangements are common. Moreover, quality is multidimensional and may also differ between actors.

These actors benefit from having a high level of certainty regarding scrap chemistry. In this Supplement it was attributed to their desired content. Simply put, scrap that conform closely to the compositional requirements of the eventual scrap-based production are rated highly. Steelmakers work hard to procure scrap supply that will be suitable for their product portfolio.

5.1.2 On the 2nd phase: *value attribution*

<u>Research Objective 2: Develop the idea of value of (compositional) information in this context, why it matters, and problematize how the lack of it contributes to an overall loss of value of materials.</u>

The direction of the work then went in the direction of answering RQ2, "*what is the value of more accurate compositional information about the scrap and how does having access to it change production outcomes?"* Supplement 2 laid the groundwork for quantifying the value of compositional information and dealt with the question:

- *What possible value does perfect compositional information bring to scrap-based steel production?*

The approach that was featured in Supplement 2 showed how fully knowing what is contained in the input scrap compositionally speaking can lead to lower production costs, mainly associated to lower raw material input. What makes scrap so valuable is that it already contains what is essentially found in steel products. Ideally, there are no tramp elements if only the scrap is properly characterized, sorted into the right pile, and ends up in the scrapyard of a steelmaker producing the matching goods.

Supplement 3 then worked on addressing some of the simplifications made in Supplement 2, most notably the inclusion of Cu as a tramp element which may be present in the scrap but needed to be controlled up to a certain limit in the products. There were several insights obtained from the 3rd Supplement's objective:

- *To further demonstrate how access to perfect information can lead to improved recycling incentives.*

The flexibility in allocating different scrap deliveries into different production batches, through specialized input blends or recipes, led to maximizing the recycled content. This consequently extends to being able to fine-tune other aspects of a production heat known to be affected by the scrap chemistry such as energy consumption, slag recipes, and production planning. Moreover, the access to perfect information allows for keeping the alloyed content at the minimum level required in a product. This is particularly important in consideration of the cost of these pure alloys (e.g. Cr, Ni, and Mo). Having them in excess amounts without resulting in any contribution to the performance or property of the steel, plus the 'waiting' period before it becomes available as future scrap, is simply wasteful.

Based on the simulated cases, having access to perfect information can help to align the economic and environmental incentives for the recycler. In a situation where the supply of scrap with known analysis comes at a fair price and consistent supply, all the incentives point towards using more scrap and less pure alloys, perhaps even reaching 100% recycled content in some situations.

Practically speaking, the EVPI approach can be a useful tool to justify the feasibility of upgrades in characterization and sorting infrastructure. It makes it possible to compare the capital outlay on state-of-the-art equipment against the savings that can be made.

5.1.3 On the 3rd phase: *validation*

Research Objective 3: Discuss the practicalities around the opportunities for improved scrap management that entails enhanced information flows with the intent of retaining material value for future cycles.

Finally, with RQ3, *"how do actors work with the current level of information they have and what do they see as opportunities for increasing scrap consumption?"* Supplement 4 was concerned with the following:

1. *To describe in more detail the current practices in the recycling system that deal with the lack of information.*
2. *To understand what opportunities there are to increase the consumption of post-consumer scrap in consideration of different operating contexts.*

The issue of uncertainty in scrap composition will remain a significant feature of recycling systems and will become even harder to deal with if the characterization and sorting infrastructure continue to lag in terms of development compared to the number of new steel grades and products being manufactured. Steelmakers have adapted and optimized their operations to address the prevailing contamination or lack of high-quality scraps, most often by relying on Ore Based Metallics through the practice of 'sweetening'. But this really opens recycling to critique if no displacement of primary resources takes place.

There are concerns about the lack of high-quality scraps and this will be the operating background. It must be recognized that even the composition of company production scraps that are traditionally recognized as having well-identified chemistries can be subject to intermixing and becoming difficult to utilize internally. In an effort to address this, some steelmakers have implemented internal scrap categories which are much more defined (i.e. having sub-categories for scrap they purchase in the market). The attitude is also changing in terms of the willingness to pay more for scrap that is particularly aggregated and prepared for them through scrap dealers.

Formulating new steel grades or high-entropy alloys (HEAs) that can accommodate lower-quality scrap (i.e. contaminated), provided there will be demand for these, is a promising solution. Perhaps the way to go is to look through practices in different contexts and adapt the solution at the company/organizational level. For example, the highly manual sorting practices normally associated with low-income regions that lead to 'cleaner' streams of scrap supply. What is often overlooked is the expertise of the personnel in the scrapyards who have accumulated years of experience in their line of work. Ensuring that this type of expertise is retained, transferred, and rewarded could prove to be beneficial for maintaining successful scrapyard operations.

5.2 Final remarks

This research was a critical and systematic investigation of how scrap is utilized in steelmaking, by offering an alternative perspective where access to more information (i.e. reduced uncertainty) leads to the favorable circumstance where economic and environmental incentives align.

Recycling should be framed and thought of as a continuous activity, performed over multiple cycles. Such a view places the onus on the steelmakers to consider that the products they release to market could eventually make their way back in their scrapyards as their raw material for future production. Take-back arrangements with downstream customers will likely expand, for the same reason scrap dealers are being bought up by steelmakers: to secure both the quality and quantity of supply.

The quality of supply of the latter conceivably affects the former. There have been calls to classify scrap as a critical or strategic raw material (EUROFER, 2023). But as it has been pointed out, the problem is not in terms of quantity per se, but that the amount of suitable scrap that the industry desires is in decline (EuRIC, 2023). This aligns with the findings in this research that recovering the identity of the scrap in the reverse loop in order to "generate additional directly usable scrap quantities" for the industry to utilize.

Chapter 6: Future work

This thesis offered an interpretation of how a reduction in the uncertainty of the scrap composition can increase steel scrap utilization. The value of information, resulting from an infrastructure that recovers the material identity of scrap, can keep economic and environmental incentives aligned for a recycling actor. However, there are many aspects that need consideration if such an approach is to progress further into a decision support tool for the recycling industry. The following are suggested:

1. The approach developed in this research can be applied to critically evaluate and compare with the recirculation of other anthropogenic stocks. By showing that material information is valuable, it stimulates discussions on how different actors, from practitioners to researchers to stakeholders, with respect to recycling as an activity.
2. Other factors need to be incorporated in the model used in Supplements 2 & 3 such as the real distribution factors of the elements between the melt, slag, and furnace atmosphere.
3. A sensitivity analysis may be performed to model the stepwise increase in value as more accurate information becomes available or is obtained.
4. Further collaborate with other disciplines because sustainability trade-offs include the social aspect. The roles of policy and legislation also affect recycling systems.
5. Supplement 4 may be considered a groundwork for an expanded study with respect to different contexts of recirculating materials for purposes of documenting state-of-the-art technologies and adopting best practices.

References

Aggarwal, S., Gupta, N., 2014. Applications of Mathematical Programming Models for Product Mix Optimization in World Steel Industry: Challenges and Directions, in: Springer Proceedings in Business and Economics. Springer India, New Delhi, pp. 133–142. https://doi.org/10.1007/978-81-322-1979-8_10

AISC, 2017. More than Recycled Content: The Sustainable Characteristics of Structural Steel. Am. Inst. Steel Constr. 1–16.

Allen, L., O'Connell, A., Kiermer, V., 2019. How can we ensure visibility and diversity in research contributions? How the Contributor Role Taxonomy (CRediT) is helping the shift from authorship to contributorship. Learn. Publ. 32, 71–74.

Allwood, J.M., 2014. Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies, in: Handbook of Recycling: State-of-the-Art for Practitioners, Analysts, and Scientists. pp. 445–477. https://doi.org/10.1016/B978-0-12-396459-5.00030-1

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Material efficiency: A white paper. Resour. Conserv. Recycl. 55, 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002

Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi, A., Zhang, Q., 2017. Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. J. Clean. Prod. 163, 84–98. https://doi.org/10.1016/j.jclepro.2015.12.097

Ashby, M.F., 2016. Materials and sustainable development. Amsterdam : Butterworth-Heinemann Publishing.

Atasu, A., Dumas, C., Van Wassenhove, L.N., 2021. The Circular Business Model: Pick a strategy that fits your resources and capabilities [WWW Document]. Harv. Bus. Rev. URL https://hbr.org/2021/07/the-circular-business-model (accessed 11.1.23).

Avriel, M., Williams, A.C., 1970. The Value of Information and Stochastic Programming. Oper. Res. 18, 947–954.

Baillet, G., 1995. Pourquoi un nouveau référentiel ferrailles ?*. Rev. Met. Paris 92, 1187–1194.

Baxter, W., Aurisicchio, M., Childs, P., 2017. Contaminated Interaction: Another Barrier to Circular Material Flows. J. Ind. Ecol. 21, 507–516. https://doi.org/10.1111/JIEC.12612

Bell, S., Davis, B., Javaid, A., Essadiqi, E., 2006. Final Report on Effect of Impurities in Steel. https://doi.org/10.13140/RG.2.2.33946.85440

Bergquist, A.K., Lindmark, M., Petrusenko, N., 2023. Creating Value out of Waste: The Transformation of the Swedish Waste and Recycling Sector, 1970s-2010s. Bus. Hist. Rev. 97, 3–31. https://doi.org/10.1017/S0007680522000745

Birat, J.-P., Aboussouan, L., Lavaud, A., 2002. Design with steel for an easy and cost-effective recycling. Rev. Métallurgie 99, 991–1000. https://doi.org/10.1051/metal:2002111

Blasenbauer, D., Bogush, A., Carvalho, T., Cleall, P., Cormio, C., Guglietta, D., Fellner, J., Fernández-Alonso, M., Heuss-Aßbichler, S., Huber, F., Kral, U., Kriipsalu, M., Krook, J., Laner, D., Lederer, J., Lemière, B., Liu, G., Mao, R., Mueller, S., Quina, M., Sinnett, D., Stegemann, J., Šyc, M., Szabó, K., Werner, T.T., Wille, E., Winterstetter, A., Žibret, G., 2020. Knowledge base to facilitate Anthropogenic Resource Assessment. https://doi.org/10.5281/ZENODO.3739164

Blunt, S.M., Chapman, A.C., Gallagher, E.M., Johnson, B., Ward, N.J., Williams, K.P., 1993. Steel Industry Raw Materials And Wastes, in: Richards, I.G., Palmer, J.P., Barratt, P.A. (Eds.), The Reclamation of Former Coal Mines and Steelworks. Elsevier, pp. 253–279. https://doi.org/10.1016/s0166-1116(08)70746-5

Bonifazi, G., Serranti, S., 2019. Recycling Technologies, in: Themelis, N.J., Bourtsalas, A.C. (Thanos) (Eds.), Recovery of Materials and Energy from Urban Wastes. Springer New York, New York, NY, pp. 63–118. https://doi.org/10.1007/978-1-4939-7850-2_116

Bracquené, E., Duflou, J.R., 2019. Waste stream characterisation for industrial symbiosis matchmaking: A case study for ferro metals, in: AIP Conference Proceedings. AIP Publishing LLC AIP Publishing, p. 060009. https://doi.org/10.1063/1.5112604

Brodrick, J., 1978. Energy conservation in the U. S. economy from increased recycle of obsolete steel scrap. Argonne, IL (United States). https://doi.org/10.2172/6263322

Brooks, L., Gaustad, G., 2019. Positive Material Identification (PMI) Capabilities in the Metals Secondary Industry: An Analysis of XRF and LIBS Handheld Analyzers, in: Minerals, Metals and Materials Series. Springer International Publishing, pp. 1375–1380. https://doi.org/10.1007/978-3-030-05864-7_170

Brown, R.D., Riley, W.D., Soboroff, D.M., 1986. Sorting techniques for mixed metal scrap. Conserv. Recycl. 9, 73–86. https://doi.org/10.1016/0361-3658(86)90136-0

Brundtland, G.H., 1987. Our Common Future—Call for Action. Environ. Conserv. 14, 291–294.

Campbell, R., Bond, D.E., Connellan, C., Mohen, P., Foo, J., 2022. From trash to treasure: Green metals from recycling | White & Case LLP [WWW Document]. URL https://www.whitecase.com/insight-our-thinking/trash-treasure-green-metals-recycling (accessed 9.1.22).

Chen, W.-Q., Graedel, T.E., 2012. Anthropogenic Cycles of the Elements: A Critical Review. Environ. Sci. Technol. 46, 8574–8586. https://doi.org/10.1021/es3010333

Chizaryfard, A., Trucco, P., Nuur, C., 2021. The transformation to a circular economy: framing an evolutionary view. J. Evol. Econ. 31, 475–504. https://doi.org/10.1007/s00191-020-00709-0

Chohaney, M.L., Yeager, C.D., Gatrell, J.D., Nemeth, D.J., 2016. Poverty, Sustainability, & Metal Recycling: Geovisualizing the Case of Scrapping as a Sustainable Urban Industry in Detroit, in: Urban Sustainability: Policy and Praxis. Springer International Publishing, Cham, pp. 99–133. https://doi.org/10.1007/978-3-319-26218-5_8

Ciacci, L., Harper, E.M., Nassar, N.T., Reck, B.K., Graedel, T.E., 2016. Metal Dissipation and Inefficient Recycling Intensify Climate Forcing. Environ. Sci. Technol. 50, 11394–11402. https://doi.org/10.1021/acs.est.6b02714

Clausen, A., Althaus, M., Pretz, T., 2018. Commingled waste collection as chance for technical separation: Alternative collection systems. Handb. Environ. Chem. 63, 105–118. https://doi.org/10.1007/698_2017_29/FIGURES/7

Compañero, R.J., Feldmann, A., Samuelsson, P., Tilliander, A., Jönsson, P.G., Gyllenram, R., 2023. Appraising the value of compositional information and its implications to scrap-based production of steel. Miner. Econ. 1, 1–18. https://doi.org/10.1007/s13563-022-00361-z

Compañero, R.J., Feldmann, A., Tilliander, A., 2021. Circular Steel: How Information and Actor Incentives Impact the Recyclability of Scrap. J. Sustain. Metall. 7, 1654–1670. https://doi.org/10.1007/s40831-021-00436-1

Conrad, K., 1999. Resource and waste taxation in the theory of the firm with recycling activities. Environ. Resour. Econ. 14, 217–242. https://doi.org/10.1023/A:1008301626219

Cooper, S., Skelton, A.C.H., Owen, A., Densley-Tingley, D., Allwood, J.M., 2016. A multi-method approach for analysing the potential employment impacts of material efficiency. Resour. Conserv. Recycl. 109, 54–66. https://doi.org/10.1016/j.resconrec.2015.11.014

Crutzen, P.J., 2002. Geology of mankind - Crutzen - Nature. Nature 415, 2002.

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

Daehn, K.E., Cabrera Serrenho, A., Allwood, J.M., 2017. How Will Copper Contamination Constrain Future Global Steel Recycling? Environ. Sci. Technol. 51, 6599–6606. https://doi.org/10.1021/acs.est.7b00997

Daehn, K.E., Serrenho, A.C., Allwood, J., 2019. Finding the Most Efficient Way to Remove Residual Copper from Steel Scrap. Metall. Mater. Trans. B Process Metall. Mater. Process. Sci. 50, 1225–1240. https://doi.org/10.1007/s11663-019-01537-9

Dahmus, J.B., Gutowski, T.G., 2007. What Gets Recycled: An Information Theory Based Model for Product Recycling. Environ. Sci. Technol. 41, 7543–7550. https://doi.org/10.1021/es062254b

Dalmijn, W.L., De Jong, T.P.R., 2007. The development of vehicle recycling in Europe: Sorting, shredding, and separation. JOM 59, 52–56. https://doi.org/10.1007/s11837-007-0141-1

Dewulf, J., Mancini, L., Blengini, G.A., Sala, S., Latunussa, C., Pennington, D., 2015. Toward an Overall Analytical Framework for the Integrated Sustainability Assessment of the Production and Supply of Raw Materials and Primary Energy Carriers. J. Ind. Ecol. 19, 963–977. https://doi.org/10.1111/jiec.12289

Di Maio, F., Rem, P.C., Baldé, K., Polder, M., 2017. Measuring resource efficiency and circular economy: A market value approach. Resour. Conserv. Recycl. 122, 163–171. https://doi.org/10.1016/J.RESCONREC.2017.02.009

Diener, D.L., Tillman, A.M., 2015. Component end-of-life management: Exploring opportunities and related benefits of remanufacturing and functional recycling. Resour. Conserv. Recycl. 102, 80–93. https://doi.org/10.1016/j.resconrec.2015.06.006

Dulski, T.R., 1996. A Manual for the Chemical Analysis of Metals. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959.

Eccles, R.G., Ioannou, I., Serafeim, G., 2014. The Impact of Corporate Sustainability on Organizational Processes and Performance. Manage. Sci. 60, 2835–2857. https://doi.org/10.1287/mnsc.2014.1984

Eidsvik, J., Mukerji, T., Bhattacharjya, D., 2015. Value of Information in the Earth Sciences. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781139628785

Eisenhardt, K., Graebner, M., 2007. Theory building from cases: Opportunities and challenges. Acad. Manag. J. 50, 25–37. https://doi.org/10.2307/20159839

Eisenhardt, K.M., 1989. Building Theories from Case Study Research. Acad. Manag. Rev. 14, 532. https://doi.org/10.2307/258557

Ellen MacArthur Foundation, 2021. Recycling and the circular economy: what’s the difference? [WWW Document]. URL https://www.ellenmacarthurfoundation.org/articles/recycling-and-the-circular-economy-whats-the-difference (accessed 10.30.23).

EuRIC, 2023. Recycled steel scrap is not a strategic nor a critical raw material [WWW Document].

Euro Inox, 2007. Stainless Steel: Tables of Technical Properties, 2nd ed. Euro Inox, Luxembourg.

EUROFER, 2023. Ensuring access to critical materials for steel and wind sectors essential for EU clean-tech economy [WWW Document]. Press Release.

EUROFER, 2015. Steel and the Circular Economy.

European Parliament and the Council of the European Union, 2008. Directive 2008/98/EC of the

European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance) [WWW Document]. Off. J. Eur. Union. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098#d1e608-3-1 (accessed 2.9.24).

Fenton, M.D., 2004. Iron and Steel Recycling in the United States in 1998, Flow Studies for Recycling Metal Commodities in the United States. U.S. Geological Survey.

Fleming, N., Alonso, E., Field, F., Kirchain, R., Roth, R., 2011. Recycling and Material Price: An Exploration of the Effects of Secondary Substitutability on Price Stability, in: Monteiro, S., Verhulst, D., Anyalebechi, P., Pomykala, J. (Eds.), EPD Congress 2011 - Proceedings Symposia. TMS (The Minerals, Metals & Materials Society), San Diego.

Gauffin, A., 2015. Improved mapping of steel recycling from an industrial perspective. KTH Royal Institute of Technology.

Gauffin, A., Pistorius, P., 2018. The Scrap Collection per Industry Sector and the Circulation Times of Steel in the U.S. between 1900 and 2016, Calculated Based on the Volume Correlation Model. Metals (Basel). 8, 338. https://doi.org/10.3390/met8050338

Gaustad, G., Olivetti, E., Kirchain, R., 2011. Improving aluminum recycling: A survey of sorting and impurity removal technologies. Resour. Conserv. Recycl. 58, 79–87. https://doi.org/10.1016/j.resconrec.2011.10.010

Geyer, R., Kuczenski, B., Zink, T., Henderson, A., 2016. Common Misconceptions about Recycling. J. Ind. Ecol. https://doi.org/10.1111/jiec.12355

Giannetti, B.F., Bonilla, S.H., Almeida, C.M.V.B., 2013. An emergy-based evaluation of a reverse logistics network for steel recycling. J. Clean. Prod. 46, 48–57. https://doi.org/10.1016/j.jclepro.2012.05.024

Graedel, T.E., Allwood, J., Birat, J.P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011. What do we know about metal recycling rates? J. Ind. Ecol. 15, 355–366. https://doi.org/10.1111/j.1530-9290.2011.00342.x

Graedel, T.E., Reck, B.K., 2019. Defining the Criticality of Materials. pp. 103–115. https://doi.org/10.1142/9789813271050_0006

Graedel, T.E., Reck, B.K., Miatto, A., 2022. Alloy information helps prioritize material criticality lists. Nat. Commun. 13, 1–8. https://doi.org/10.1038/s41467-021-27829-w

Grafton, J., Lillis, A.M., Mahama, H., 2011. Mixed methods research in accounting. Qual. Res. Account. Manag. 8, 5–21. https://doi.org/10.1108/11766091111124676

Greer, R., von Wirth, T., Loorbach, D., 2021. The Waste-Resource Paradox: Practical dilemmas and societal implications in the transition to a circular economy. J. Clean. Prod. 303, 126831. https://doi.org/10.1016/j.jclepro.2021.126831

Grosso, M., Niero, M., Rigamonti, L., 2017. Circular economy, permanent materials and limitations to recycling: Where do we stand and what is the way forward? Waste Manag. Res. 35, 793–794. https://doi.org/10.1177/0734242X17724652

Gurell, J., Bengtson, A., Falkenström, M., Hansson, B.A.M., 2012. Laser induced breakdown spectroscopy for fast elemental analysis and sorting of metallic scrap pieces using certified reference materials. Spectrochim. Acta Part B At. Spectrosc. 74–75, 46–50. https://doi.org/10.1016/j.sab.2012.06.013

Gutowski, T., Cooper, D., Sahni, S., 2017. Why we use more materials. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. https://doi.org/10.1098/rsta.2016.0368

Gyllenram, R., Arzpeyma, N., Wei, W., Jönsson, P.G., 2021. Driving investments in ore beneficiation and scrap upgrading to meet an increased demand from the direct reduction-EAF route. Miner. Econ. https://doi.org/10.1007/s13563-021-00267-2

Gyllenram, R., Westerberg, O., 2016. The impact of scrap upgrading on EAF production cost and environmental performance. Stahl und eisen 31–36.

Harvey, L.D.D., 2021. Iron and steel recycling: Review, conceptual model, irreducible mining requirements, and energy implications. Renew. Sustain. Energy Rev. 138, 110553. https://doi.org/10.1016/j.rser.2020.110553

Haupt, M., Vadenbo, C., Zeltner, C., Hellweg, S., 2017. Influence of Input-Scrap Quality on the Environmental Impact of Secondary Steel Production. J. Ind. Ecol. 21, 391–401. https://doi.org/10.1111/jiec.12439

Helbig, C., Huether, J., Joachimsthaler, C., Lehmann, C., Raatz, S., Thorenz, A., Faulstich, M., Tuma, A., 2022. A terminology for downcycling. J. Ind. Ecol. 26, 1164–1174. https://doi.org/10.1111/jiec.13289

Holappa, L., 2014. Iron and Steel Technology, 1st ed, Treatise on Process Metallurgy. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-096988-6.00001-8

Holdgate, M.W., 1987. Our Common Future: The Report of the World Commission on Environment and Development. Oxford University Press, Oxford & New York: xv + 347 + 35 pp., 20.25 × 13.25 × 1.75 cm, Oxford Paperback, £5.95 net in UK, 1987. Environ. Conserv. 14, 282–282. https://doi.org/10.1017/S0376892900016702

Hotta, Y., 2013. Recycling Policy: The Sound Material Cycle Society and 3R Concepts from Japan to Developing Asia, in: Waste as a Resource. The Royal Society of Chemistry, pp. 162–186. https://doi.org/10.1039/9781849737883-00162

Huber, J., 2000. Towards industrial ecology: sustainable development as a concept of ecological modernization. J. Environ. Policy Plan. 2, 269–285. https://doi.org/10.1002/1522-7200(200010/12)2:4<269::AID-JEPP58>3.0.CO;2-U

Huysman, S., Sala, S., Mancini, L., Ardente, F., Alvarenga, R.A.F., De Meester, S., Mathieux, F., Dewulf, J., 2015. Toward a systematized framework for resource efficiency indicators. Resour. Conserv. Recycl. 95, 68–76. https://doi.org/10.1016/j.resconrec.2014.10.014

Igarashi, Y., Daigo, I., Matsuno, Y., Adachi, Y., 2007. Estimation of the Change in Quality of Domestic Steel Production Affected by Steel Scrap Exports. ISIJ Int. 47, 753–757.

IRP, 2020. RESOURCE EFFICIENCY AND CLIMATE CHANGE: Material Efficiency Strategies for a Low-Carbon Future. https://doi.org/10.5281/zenodo.3542680

ISRI, 2020. Recycling Industry Yearbook 2019.

Janke, D., Savov, L., Vogel, M.E., 2006. Secondary Materials in Steel Production and Recycling, in: von Gleich, A., Ayres, R.U., Gößling-Reisemann, S. (Eds.), Sustainable Metals Management: Securing Our Future - Steps Towards a Closed Loop Economy. Springer Netherlands, Dordrecht, pp. 313–334. https://doi.org/10.1007/1-4020-4539-5_11

Jasti, N.V.K., Jha, N.K., Chaganti, P.K., Kota, S., 2022. Sustainable production system: literature review and trends. Manag. Environ. Qual. An Int. J. 33, 692–717. https://doi.org/10.1108/MEQ-11-2020-0246

Javaid, A., Essadiqi, E., 2003. Final Report on Scrap Management, Sorting and Classification of Steel. https://doi.org/10.13140/RG.2.2.30171.98089

JBF AB, 2020. SKROTBOKEN 2020.

Jin, H., Mishra, B., 2020. Minimization of Copper Contamination in Steel Scrap, in: Minerals, Metals and Materials Series. Springer, Cham, pp. 357–364. https://doi.org/10.1007/978-3-030-36830-2_34

Johnson, P.F., 1998. Managing value in reverse logistics systems. Transp. Res. Part E Logist. Transp. Rev. 34, 217–227. https://doi.org/10.1016/S1366-5545(98)00016-7

Johnson, R.B., Onwuegbuzie, A.J., 2007. Toward a Definition of Mixed Methods Research. J. Mix. Methods Res. 1, 112–133. https://doi.org/10.1177/1558689806298224

Jones, G., 2017. Making Money by Saving the World 1. https://doi.org/10.1093/OSO/9780198706977.003.0006

Kashiwakura, S., Wagatsuma, K., 2015. Rapid sorting of stainless steels by open-air laser-induced breakdown spectroscopy with detecting chromium, nickel, and molybdenum. ISIJ Int. 55, 2391–2396. https://doi.org/10.2355/isijinternational.ISIJINT-2015-316

Keisler, J.M., Collier, Z.A., Chu, E., Sinatra, N., Linkov, I., 2014. Value of information analysis: the state of application. Environ. Syst. Decis. 34, 3–23. https://doi.org/10.1007/s10669-013-9439-4

Khajuria, A., Atienza, V.A., Chavanich, S., Henning, W., Islam, I., Kral, U., Liu, M., Liu, X., Murthy, I.K., Oyedotun, T.D.T., Verma, P., Xu, G., Zeng, X., Li, J., 2022. Accelerating circular economy solutions to achieve the 2030 agenda for sustainable development goals. Circ. Econ. 1, 100001. https://doi.org/10.1016/j.cec.2022.100001

Khor, K.S., Udin, Z.M., Ramayah, T., Hazen, B.T., 2016. Reverse logistics in Malaysia: The Contingent role of institutional pressure. Int. J. Prod. Econ. 175, 96–108. https://doi.org/10.1016/j.ijpe.2016.01.020

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kirchherr, J., Yang, N.H.N., Schulze-Spüntrup, F., Heerink, M.J., Hartley, K., 2023. Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. Resour. Conserv. Recycl. 194, 107001. https://doi.org/10.1016/J.RESCONREC.2023.107001

Koenig, M.E.D., 1998. DECISION ANALYSIS & EVPI, VALUE of PERFECT INFORMATION, in: Information Driven Management Concepts and Themes: A Toolkit for Librarians. K. G. Saur, München, pp. 65–69. https://doi.org/10.1515/9783110949155.65

Korhonen, J., Nuur, C., Feldmann, A., Birkie, S.E., 2018. Circular economy as an essentially contested concept. J. Clean. Prod. 175, 544–552. https://doi.org/10.1016/j.jclepro.2017.12.111

Korsunova, A., Halme, M., Kourula, A., Levänen, J., Lima-Toivanen, M., 2022. Necessity-driven circular economy in low-income contexts: How informal sector practices retain value for circularity. Glob. Environ. Chang. 76, 102573. https://doi.org/10.1016/j.gloenvcha.2022.102573

Krehbiel, T.C., Gorman, R.F., Erekson, O.H., Loucks, O.L., Johnson, P.C., 1999. Advancing ecology and economics through a business–science synthesis. Ecol. Econ. 28, 183–196. https://doi.org/10.1016/S0921-8009(98)00036-6

Kumamaru, H., Takeuchi, K., 2023. The recycled content of plastic products: estimating the impact of a recycling law on the input mix. Environ. Econ. Policy Stud. 25, 355–376. https://doi.org/10.1007/s10018-023-00360-6

Kutila, M., Viitanen, J., Vattulainen, A., 2005. Scrap Metal Sorting with Colour Vision and Inductive Sensor Array, in: International Conference on Computational Intelligence for Modelling, Control and Automation and International Conference on Intelligent Agents, Web Technologies and Internet Commerce (CIMCA-IAWTIC'06). IEEE, pp. 725–729. https://doi.org/10.1109/CIMCA.2005.1631554

Legarth, J.B., 1996. Sustainable metal resource management—the need for industrial development: efficiency improvement demands on metal resource management to enable a (sustainable) supply until 2050. J. Clean. Prod. 4, 97–104. https://doi.org/10.1016/S0959-6526(96)00030-3

Li, P., Dahmus, J., Guldberg, S., Riddervold, H.O., Kirchain, R., 2011. How much sorting is enough: Identifying economic and scrap-reuse benefits of sorting technologies. J. Ind. Ecol. 15, 743–759. https://doi.org/10.1111/j.1530-9290.2011.00365.x

Lüngen, H.B., 1998. TECHNOLOGICAL INNOVATIONS IN IRON AND STEELMAKING AND THEIR EFFECTS ON COAL, COKE AND IRON ORES, in: Ranieri, R., Aylen, J. (Eds.), Steel Industry in the New Millennium, 1: Technology and the Market. CRC Press LLC, pp. 39–60.

Mannanal, S.J., Dehnhardt, S., Eickmeyer, T., Fußholz, K., Gesser, A., Tiedke, S., Boston, A., McGrath, J., Nolan, P., Monfort, G., Desneux, P., Sved, J., Menduev, N., Koehrmann, F., Russo, P., Husson-Tissier, B., 2013. On-line bulk composition analysis of steel scrap using PGNAA (Scrap Probe). Luxembourg.

Manning, C.G., 2023. Technology Readiness Levels [WWW Document].

Marchese, D.C., Bates, M.E., Keisler, J.M., Alcaraz, M.L., Linkov, I., Olivetti, E.A., 2018. Value of information analysis for life cycle assessment: Uncertain emissions in the green manufacturing of electronic tablets. J. Clean. Prod. 197, 1540–1545. https://doi.org/10.1016/j.jclepro.2018.06.113

McMichael, A.J., Butler, C.D., Folke, C., 2003. New Visions for Addressing Sustainability. Science (80-.). 302, 1919–1920. https://doi.org/10.1126/science.1090001

McMillan, C.A., Skerlos, S.J., Keoleian, G.A., 2012. Evaluation of the Metals Industry's Position on Recycling and its Implications for Environmental Emissions. J. Ind. Ecol. 16, 324–333. https://doi.org/10.1111/j.1530-9290.2012.00483.x

Medarac, H., Moya, J.A., Somers, J., 2020. Production costs from energy-intensive industries in the EU and third countries, JRC Technical Report. https://doi.org/10.2760/705636

Medina, M., 2013. Global Supply Chains in Chinese Industrialization: Impact on Waste Scavenging in Developing Countries, in: Pathways to Industrialization in the Twenty-First Century. Oxford University Press, pp. 324–342. https://doi.org/10.1093/acprof:oso/9780199667857.003.0012

Merz, M., 2016. Recycling as a Source of Regeneration, in: Merz, M. (Ed.), Scarce Natural Resources, Recycling, Innovation and Growth. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 25–35. https://doi.org/10.1007/978-3-658-12055-9_4

Mesina, M.B., de Jong, T.P.R., Dalmijn, W.L., 2007. Automatic sorting of scrap metals with a combined electromagnetic and dual energy X-ray transmission sensor. Int. J. Miner. Process. 82, 222–232. https://doi.org/10.1016/j.minpro.2006.10.006

Mesina, M.B., de Jong, T.P.R., Dalmijn, W.L., 2005. Scrap stainless steel detection using a pulsed electromagnetic field. Int. J. Miner. Process. 76, 21–31. https://doi.org/10.1016/j.minpro.2004.08.020

Miletic, I., Boudreau, F., Dudzic, M., Kotuza, G., Ronholm, L., Vaculik, V., Zhang, Y., 2008. Experiences in applying data-driven modelling technology to steelmaking processes. Can. J. Chem. Eng. 86, 937–946. https://doi.org/10.1002/cjce.20090

Milios, L., 2018. Advancing to a Circular Economy: three essential ingredients for a comprehensive policy mix. Sustain. Sci. https://doi.org/10.1007/s11625-017-0502-9

Molina-Azorín, J.F., López-Gamero, M.D., 2016. Mixed Methods Studies in Environmental Management Research: Prevalence, Purposes and Designs. Bus. Strateg. Environ. 25, 134–148. https://doi.org/10.1002/bse.1862

Mombelli, D., Dall'Osto, G., Mapelli, C., Gruttadauria, A., Barella, S., 2021. Modeling of a Continuous Charging Electric Arc Furnace Metallic Loss Based on the Charge Mix. Steel Res. Int. 92, 2000580. https://doi.org/10.1002/srin.202000580

Moreno-Sánchez, R.D.P., Maldonado, J.H., 2006. Surviving from garbage: the role of informal waste-pickers in a dynamic model of solid-waste management in developing countries. Environ. Dev. Econ. 11, 371–391. https://doi.org/10.1017/S1355770X06002853

Muchová, L., Eder, P., 2010. End-of-waste Criteria for Iron and Steel Scrap: Technical Proposals, European Commission, Joint Research Centre. https://doi.org/10.2791/43563

Müller, D.B., Wang, T., Duval, B., Graedel, T.E., 2006. Exploring the engine of anthropogenic iron cycles. Proc. Natl. Acad. Sci. 103, 16111–16116. https://doi.org/10.1073/pnas.0603375103

Nakamura, S., Kondo, Y., 2002. Input-Output Analysis of Waste Management. J. Ind. Ecol. 6, 39–63. https://doi.org/10.1162/108819802320971632

Nakamura, S., Kondo, Y., Matsubae, K., Nakajima, K., Tasaki, T., Nagasaka, T., 2012. Quality-and Dilution Losses in the Recycling of Ferrous Materials from End-of-Life Passenger Cars: Input-Output Analysis under Explicit Consideration of Scrap Quality. https://doi.org/10.1021/es3013529

Nakamura, S., Kondo, Y., Nakajima, K., Ohno, H., Pauliuk, S., 2017. Quantifying Recycling and Losses of Cr and Ni in Steel Throughout Multiple Life Cycles Using MaTrace-Alloy. Environ. Sci. Technol. 51, 9469–9476. https://doi.org/10.1021/ACS.EST.7B01683/SUPPL_FILE/ES7B01683_SI_001.PDF

Nicolli, F., Johnstone, N., Söderholm, P., 2012. Resolving failures in recycling markets: The role of technological innovation. Environ. Econ. Policy Stud. 14, 261–288. https://doi.org/10.1007/S10018-012-0031-9/TABLES/6

Noll, R., Bengtson, A., Gurell, J., Chiarotti, U., Grieco, R., Volponi, V., Zani, M., Appell, A., Brunk, M., 2015. Inline elemental characterisation of scrap charging for improved EAF charging control and internal scrap recycling (IPRO). EUR. Research Fund for Coal and Steel 27196.

Oda, J., Akimoto, K., Tomoda, T., 2013. Long-term global availability of steel scrap. Resour. Conserv. Recycl. 81, 81–91. https://doi.org/10.1016/j.resconrec.2013.10.002

Ødegård, H.L., Eidsvik, J., Fleten, S.-E., 2019. Value of information analysis of snow measurements for the scheduling of hydropower production. Energy Syst. 10, 1–19. https://doi.org/10.1007/s12667-017-0267-3

OECD, 2021. Moving to sustainable industrial production, in: Accelerating Climate Action. OECD Publishing, Paris.

Oostenbrink, J.B., Al, M.J., Oppe, M., Rutten-van Mölken, M.P.M.H., 2008. Expected Value of Perfect Information: An Empirical Example of Reducing Decision Uncertainty by Conducting Additional Research. Value Heal. 11, 1070–1080. https://doi.org/10.1111/j.1524-4733.2008.00389.x

Pardo, A., Merino, M.C., Carboneras, M., Viejo, F., Arrabal, R., Muñoz, J., 2006. Influence of Cu and Sn content in the corrosion of AISI 304 and 316 stainless steels in H2SO4. Corros. Sci. 48, 1075–1092. https://doi.org/10.1016/j.corsci.2005.05.002

Parnell, G., 2009. Decision analysis in one chart.

Pauliuk, S., Milford, R.L., Müller, D.B., Allwood, J.M., 2013. The steel scrap age. Environ. Sci.

Technol. Technol. 47, 3448–3454. https://doi.org/10.1021/es303149z

Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A., 2019. Business model innovation for circular economy and sustainability: A review of approaches. J. Clean. Prod. 215, 198–216. https://doi.org/10.1016/j.jclepro.2019.01.036

Pierre, R., Ansseau, O., Pierret, J.-C., Gutierrez, J.A., Frittella, P., Unamuno, I., Milling, O., 2020. Optimization of Scrap Charge Management and Related Process Adaptation for Performances Improvement and Cost Reduction (OPTISCRAPMANAGE): final report. EUR. Research Fund for Coal and Steel 30537.

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring innovation in the product chain - Policy report, PBL Netherlands Environmental Assessment Agency. Utrecht.

Pryshlakivsky, J., Searcy, C., 2013. Sustainable Development as a Wicked Problem, in: Kovacic, S.F., Sousa-Poza, A. (Eds.), . Springer Netherlands, Dordrecht, pp. 109–128. https://doi.org/10.1007/978-94-007-5515-4_6

Raabe, D., 2023. The Materials Science behind Sustainable Metals and Alloys. Chem. Rev. 123, 2436–2608. https://doi.org/10.1021/acs.chemrev.2c00799

Raabe, D., Ponge, D., Uggowitzer, P.J., Roscher, M., Paolantonio, M., Liu, Chuanlai, Antrekowitsch, H., Kozeschnik, E., Seidmann, D., Gault, B., De Geuser, F., Deschamps, A., Hutchinson, C., Liu, Chunhui, Li, Z., Prangnell, P., Robson, J., Shanthraj, P., Vakili, S., Sinclair, C., Bourgeois, L., Pogatscher, S., 2022. Making sustainable aluminum by recycling scrap: The science of “dirty” alloys. Prog. Mater. Sci. 128. https://doi.org/10.1016/j.pmatsci.2022.100947

Raven, P.H., 2002. Science, Sustainability, and the Human Prospect. Science (80-.). 297, 954–958. https://doi.org/10.1126/science.297.5583.954

Read, B.L., 2018. Serial Interviews. Int. J. Qual. Methods 17, 160940691878345. https://doi.org/10.1177/1609406918783452

Reijnders, L., 1996. Environmentally improved production processes, in: Environmentally Improved Production Processes and Products: An Introduction. Springer Netherlands, Dordrecht, pp. 61–92. https://doi.org/10.1007/978-94-009-1596-1_4

Reuter, M.A., 2011. Limits of design for recycling and “sustainability”: A review. Waste and Biomass Valorization 2, 183–208. https://doi.org/10.1007/s12649-010-9061-3

Reuter, M.A., van Schaik, A., Gutzmer, J., Bartie, N., Abadías-Llamas, A., 2019. Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective. Annu. Rev. Mater. Res. 49, 253–274. https://doi.org/10.1146/annurev-matsci-070218-010057

Rigamonti, L., Niero, M., Haupt, M., Grosso, M., Judl, J., 2018. Recycling processes and quality of secondary materials: Food for thought for waste-management-oriented life cycle assessment studies. Waste Manag. 76, 261–265. https://doi.org/10.1016/j.wasman.2018.03.001

Riley, W.D., Brown, R.E., Soboroff, D.M., 1983. Rapid identification and sorting of scrap metals. Conserv. Recycl. 6, 181–192. https://doi.org/10.1016/0361-3658(83)90004-8

Rli, 2015. CIRCULAR ECONOMY: From Wish to Practice, Council for the Environment and Infrastructure.

Rong, A., Lahdelma, R., 2008. Fuzzy chance constrained linear programming model for optimizing the scrap charge in steel production. Eur. J. Oper. Res. 186, 953–964. https://doi.org/10.1016/j.ejor.2007.02.017

Sahamie, R., Stindt, D., Nuss, C., 2013. Transdisciplinary Research in Sustainable Operations - An Application to Closed-Loop Supply Chains. Bus. Strateg. Environ. 22, 245–268.

https://doi.org/10.1002/bse.1771

Sakallı, Ü.S., Baykoç, Ö.F., 2011. An optimization approach for brass casting blending problem under aletory and epistemic uncertainties. Int. J. Prod. Econ. 133, 708–718. https://doi.org/10.1016/j.ijpe.2011.05.022

Sarkis, J., Zhu, Q., 2018. Environmental sustainability and production: taking the road less travelled. Int. J. Prod. Res. 56, 743–759. https://doi.org/10.1080/00207543.2017.1365182

Sasikumar, P., Kannan, G., 2008. Issues in reverse supply chains, part I: end-of-life product recovery and inventory management – an overview. Int. J. Sustain. Eng. 1, 154–172. https://doi.org/10.1080/19397030802433860

Scharun, M., Fricke-Begemann, C., Noll, R., 2013. Laser-induced breakdown spectroscopy with multi-kHz fibre laser for mobile metal analysis tasks - A comparison of different analysis methods and with a mobile spark-discharge optical emission spectroscopy apparatus. Spectrochim. Acta - Part B At. Spectrosc. 87, 198–207. https://doi.org/10.1016/j.sab.2013.05.007

Schlosser, R., Chenavaz, R.Y., Dimitrov, S., 2021. Circular economy: Joint dynamic pricing and recycling investments. Int. J. Prod. Econ. 236. https://doi.org/10.1016/j.ijpe.2021.108117

Solow, R.M., 2009. The Economics of Resources or the Resources of Economics*. J. Nat. Resour. Policy Res. 1, 69–82. https://doi.org/10.1080/19390450802504048

Sovacool, B.K., Ali, S.H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., Mulvaney, D., 2020. Sustainable minerals and metals for a low-carbon future. Science (80-.). 367, 30–33. https://doi.org/10.1126/science.aaz6003

Stachowiak, J., 2016. Does Your Scrap Metal Contain A Trace of the Wrong Material? - Analyzing Metals [WWW Document]. URL https://www.thermofisher.com/blog/metals/does-your-scrap-metal-contain-a-trace-of-the-wrong-material/ (accessed 1.29.19).

Stahel, W.R., 2016. The circular economy. Nature 531, 435–438. https://doi.org/10.1038/531435a

Steffen, W., Crutzen, P.J., McNeill, J.R., 2007. The anthropocene: Are humans now overwhelming the great forces of nature? Ambio 36, 614–621. https://doi.org/10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2

Stephenson, E.T., 1983. EFFECT OF RECYCLING ON RESIDUALS, PROCESSING, AND PROPERTIES OF CARBON AND LOW-ALLOY STEELS. Metall. Trans. A, Phys. Metall. Mater. Sci. 14 A, 343–353. https://doi.org/10.1007/bf02644212

Szaniawski, K., 1967. The value of perfect information. Synthese 17, 408–424. https://doi.org/10.1007/BF00485042

Taszner, Z., Ender, A., Grega, O., 2007. Development of Scrap Evaluation Algorithm to Optimize the Converter Charge Composition. Mater. Sci. Forum 537–538, 701–708. https://doi.org/10.4028/www.scientific.net/MSF.537-538.701

Tercero Espinoza, L.A., Rostek, L., Loibl, A., Stijepic, D., 2020. The promise and limits of urban mining: Potentials, trade-offs and supporting factors for the recovery of raw materials from the anthroposphere. Fraunhofer ISI, Karlsruhe.

Terrell, J., 2019. PMI Technologies_ What's the Difference Between XRF, LIBS, and OES_ - Analyzing Metals.

Tonini, D., Federica, P., Caro, D., Meester, S. De, Garbarino, E., Andrea, G., 2022. Quality of recycling : Urgent and undefined. Waste Manag. 146, 11–19. https://doi.org/10.1016/j.wasman.2022.04.037

Tu, Q., Hertwich, E.G., 2021. A mechanistic model to link technical specifications of vehicle end-of-life treatment with the potential of closed-loop recycling of post-consumer scrap alloys. J. Ind. Ecol. 1–14. https://doi.org/10.1111/jiec.13223

UNEP, 2024. About resource efficiency [WWW Document].

UNIDO, 2019. Development of recycling industries within the UNIDO circular economy approach, United Nations Industrial Development Organization. Vienna.

Valdes, R., 1991. An Analysis of the Factors Affecting Steel Scrap Collection (No. 1).

van der Voet, E., Salminen, R., Eckelman, M., Mudd, G., Norgate, T., Hischier, R., 2013. Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. https://doi.org/10.1227/01.NEU.0000108643.94730.21

Van der Voet, E., Van Oers, L., Verboon, M., Kuipers, K., 2019. Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. J. Ind. Ecol. 23, 141–155. https://doi.org/10.1111/jiec.12722

Vercammen, S., Chalabyan, A., Ramsbottom, O., Ma, J., Tsai, C., 2017. Tsunami, spring tide, or high tide? The growing importance of steel scrap in China, Mckinsey&Company - Metals and Mining Practice.

Vicente, A., Picon, A., Barco, E., 2020. New method for estimating the economic penalties of ferrous scraps in the steelmaking industry due to material degradation during its storage in scrap yards. Ironmak. Steelmak. 47, 473–481. https://doi.org/10.1080/03019233.2020.1748433

Watari, T., Hata, S., Nakajima, K., Nansai, K., 2023. Limited quantity and quality of steel supply in a zero-emission future. Nat. Sustain. 6, 336–343. https://doi.org/10.1038/s41893-022-01025-0

Whiteside, I.R.C., Meilland, R., Ruby-Meyer, F., Tusset, V., Didriksson, R., Bengtson, A., Pissenberger, A., Schuller, M., Noll, R., Wester, R., Vögeli, M., Bohlen, J.M., 2006. Fast characterisation of steel cleanness by advanced mathematical analysis of spark and laser source optical emission data. Luxembourg. https://doi.org/10.1103/PhysRevE.76.041201

Wieczorek, T., Pilarczyk, M., 2008. Classification of steel scrap in the EAF process using image analysis methods. Arch. Metall. Mater. 53, 613–617.

Winterstetter, A., Heuss-Assbichler, S., Stegemann, J., Kral, U., Wäger, P., Osmani, M., Rechberger, H., 2021. The role of anthropogenic resource classification in supporting the transition to a circular economy. J. Clean. Prod. 297. https://doi.org/10.1016/j.jclepro.2021.126753

World Steel Association, 2019a. Steel - The Permanent Material in the Circular Economy [WWW Document]. URL https://circulareconomy.worldsteel.org/ (accessed 11.5.20).

World Steel Association, 2019b. Fact Sheet: Steel and raw materials.

Worldsteel, 2020. STEEL FACTS | worldsteel [WWW Document]. URL https://www.worldsteel.org/about-steel/steel-facts.html (accessed 11.25.20).

Worrell, E., Allwood, J., Gutowski, T., 2016. The Role of Material Efficiency in Environmental Stewardship. Annu. Rev. Environ. Resour. 41, 575–598. https://doi.org/10.1146/annurev-environ-110615-085737

Worrell, E., Faaij, A.P.C., Phylipsen, G.J.M., Blok, K., 1995. An approach for analysing the potential for material efficiency improvement. Resour. Conserv. Recycl. 13, 215–232. https://doi.org/10.1016/0921-3449(94)00050-F

Worrell, E., Reuter, M.A., Meskers, C., 2024. Introduction, in: Handbook of Recycling. Elsevier, pp. 3–14. https://doi.org/10.1016/B978-0-323-85514-3.00008-7

Wulff, S.W., 1985. The future of recycling: The ISIS perspective. Conserv. Recycl. 8, 429–432.

Xylia, M., Silveira, S., Duerinck, J., Meinke-Hubeny, F., 2018. Weighing regional scrap availability in global pathways for steel production processes. Energy Effic. 11, 1135–1159. https://doi.org/10.1007/s12053-017-9583-7

Xylia, M., Silveira, S., Duerinck, J., Meinke-Hubeny, F., 2016. Worldwide resource eficient steel production, in: ECEEE Industrial Summer Study Proceedings. pp. 321–333.

Yamada, H., Daigo, I., Matsuno, Y., Adachi, Y., Kondo, Y., 2006. Application of Markov chain model to calculate the average number of times of use of a material in society: An allocation methodology for open-loop recycling - Part 1: Methodology development. Int. J. Life Cycle Assess. 11, 354–360. https://doi.org/10.1065/lca2006.05.246.1

Yin, R.K., 2009. Case study research : design and methods, 4. ed.. ed, Applied social research methods series, 5. SAGE, London.

Yuzov, O. V., Sedykh, A.M., 2003. World trends in the formation and use of scrap metal. Metallurgist 47, 201–205. https://doi.org/10.1023/A:1025668611528

Zabeo, A., Keisler, J.M., Hristozov, D., Marcomini, A., Linkov, I., 2019. Value of information analysis for assessing risks and benefits of nanotechnology innovation. Environ. Sci. Eur. 31, 11. https://doi.org/10.1186/s12302-019-0194-0

Zhu, Y., Cooper, D.R., 2019. An optimal reverse material supply chain for U.S. Aluminum scrap. Procedia CIRP 80, 677–682. https://doi.org/10.1016/j.procir.2019.01.065