

# VALIDATION OF A RISK APPLICATION MATRIX AND ADDING RECYCLING OF SCRAP STEEL TO THE CERA RAW MATERIALS CERTIFICATION SCHEME

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### *Partners of this thesis work*

This master thesis is done as the final part for the master ‘European Mining Course’ (EMC), followed at Aalto University in Espoo, the Rheinisch-Westfälische Technische Hochschule in Aachen and the Delft University of Technology. The Delft University of Technology is the main University with regard to this master thesis.

This thesis is done in cooperation with DMT GmbH & Co. KG, with a project named the Certification of Raw Materials (CERA). This project was initiated by EIT Raw Materials and funded by the European Institute of Innovation and Technology (EIT), supported by different leading raw materials research institutions and technical service providers.

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## Abstract

The aim of this master thesis is to improve a raw materials certification scheme by checking and validating the application matrix and the coherent hazards developed for the Certification of Raw materials (CERA) project.

The scope of the original application matrix included exploration, mining, physical processing, chemical processing, smelting and refining. The validation in this thesis was focussed on the iron ore value chain. This validation showed that important methods associated with these processes were missing in the application matrix. Two main sections that are absent are recycling and storage and transportation, which have been added to the application matrix including the main methods used within those two sections.

The risks and hazards developed by CERA, associated with the application matrix's processes and methods, are transformed to only hazards. Next to this, new hazards are suggested to make the hazards list more holistically applicable.

After the addition of recycling to the application matrix, an analysis on the addition of recycling to the CERA Performance Standard (CPS) and to the CERA Chain of Custody Standard (CCS) was done. This analysis showed that adding recycling to the Performance Standard deals with few challenges due to it being an industrial activity with many similarities to methods used in processing and smelting. Therefore, with the additions that are proposed in the validation of the matrix and the hazards analysis, recycling can be easily added to the CPS. This is done by including collection centres, recycling facilities and scrap transport in the standard under the general term 'recycling facilities'.

Adding recycled material to the CCS can be done in different ways, this thesis proposes multiple options of which three are viable. First, three types of recyclable materials have been distinguished: Recyclables of which the origin is known (1); Recyclables of which the origin is unknown and no further information is available (2); Recyclables of which the origin is unknown but a due diligence can show that it has sufficient added value to the raw materials value chain with regard to responsibility and sustainability (3). In all cases, CERA should include the certification of recycled material of which the origin is known. The first viable option is to only certify type one with the original CCS certificate and exclude the other two types from the scope. This requires no extra certification or requirements by CERA. The second viable option for CERA would be to also certify type three within the original CCS certification standard, and add a 'recycled label' to materials of type two. The third viable option would be for CERA to develop a 'CCS recycled' certificate for materials of the third type mentioned, and add a 'recycled label' to materials of type two.

CERA should decide which option is best according to their basic criteria and values. If CERA decides to select option one, CERA safeguards their integrity but the option is lacking holistic applicability. If option two is preferred, CERA increases their holistic applicability level, however, the integrity of CERA might be at stake. If CERA decides to select option three, holistic applicability is maximized and their integrity is safeguarded, however, the system of CERA is complicated due to different levels of certifying.

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## Introduction

For many sectors of the economy such as automotive, manufacturing and electronic industries, raw materials are fundamental. The demand for and consumption of these raw materials has risen over the past decades, driven by population growth, urbanization, decarbonization industrialization and development of consumer demand (Bleischwitz, 2007). It is expected that in the coming decades these factors will still lead to a significant increase in global demand for raw materials (EuCommission, 2018) (Organisation for Economic Co-operation and Development, 2018). This has caused and will still cause a rise in production in raw materials worldwide (Reichl & Schatz, 2019) (United States Geological Survey, 2020). The technologies needed for this production growth have been developed greatly (Hartman & Mutmansky, 2002). The extraction of the resources is linked to the usage of large quantities of water and energy, intervention in ecosystems and the production and use of substances that are toxic for the environment. Not only extraction of raw materials but also the transport from remote areas is linked to the intervention of ecosystems (Bleischwitz, 2007). Due to the higher demand and supply, more raw materials are transported and traded all over the world. This is also valid for resources that damage the environment such as fossil resources and high-tech products in which 'conflict minerals' are used. The latter one is especially interesting since technology development that needs these 'conflict minerals' is growing (Baumgartner, et al., 2016) even though they fund wars and drive human rights abuse (TCO, 2020). How does a customer decide between all the possible different raw material value chains, except for price difference, when there are so many different suppliers and aspects to consider.

Besides this, the debate about raw materials was dominated for many years by geostrategic concerns. This is re-emerging, along with other aspects, the awareness of environmental impact and socio economic roles of the production and use of those raw materials (Bleischwitz, 2007). These 'new' awareness issues are gaining importance for decision-making. The problem addressed is that these factors are not clearly determined when looking at the raw material value chain. The certification schemes that are in place, are not holistically applicable for all different raw materials, they are not on global scale and in most cases artisanal small mining (ASM) or recycling is not considered (Kickler & Franken, 2017). This causes companies to have difficulties due to multiple certification standards to choose from. How do these companies know which to trust. Next to this they would have to use different standards for different raw materials, if they produce or trade multiple, which complicates the certification.

For the aforementioned problems and aspects, transparency with regard to the production of the raw materials is more and more important to consumers and also for companies that mine, trade in, process or sell raw materials (CERA, 2019). The CERA project, Certification for Raw Materials, is aiming to decrease these difficulties by developing one standard certification scheme for all different raw materials at once. This CERA certification will aim to ensure environmental, social and economic sustainability of all raw materials through the value chain. This is done by using a combination of four standards. The Readiness Standard (CRS) which looks at the exploration state. The Performance Standard (CPS) which defines a set of criteria for mining, processing and refining. The Chain of Custody Standard (CCS) which refers to the mining product, it guarantees a traceable chain of custody of the sustainably extracted material. Finally the Final product Standard (CFS) which focusses on and certifies the production of the product sold.

The focus of this thesis is on the CERA Performance Standard (CPS) and the CERA Chain of Custody Standard (CCS). The first bricks of the CPS standard have been developed in the past two years with the commodity cobalt. A risk and hazard application matrix was developed.

In this thesis the application matrix is adjusted, extended and validated for the commodity iron ore. Iron ore has been chosen here due to it being one of the most widely utilized metals (Mwanguzi, et al., 2012) and 98% of all iron ore produced is used in metal production (Canadian Government, 2019) which helps to set boundaries for the project. The focus will be on magnetite, hematite and goethite which are the world's most common iron ore minerals (Clout & Manuel, 2015) (Yang, et al., 2014).

Next to the focus on production of iron ore in a sustainable manner and the demand for a certification system, another upcoming important process is recycling. Iron ore is used, up to 98% (United States Geological Survey, 2020), for steel making and, in turn, steel is being recycled to large extent (Shine & Wiener, 2019) since it has a recovery of almost 100% while it maintains its properties (WorldSteel, 2020). Recycling is usually associated with positive features, but not all recycling processes are as sustainable as believed (United Nations, 2019). Electronic scrap yards in Ghana is a well-known example. When specifically looking at iron recycling, the shipyards in Bangladesh are examples of non-sustainable (social, environmental and governmental) recycling practices (Vidal, 2017). How does a certification like CERA define the requirements for recycling practices of material that has been mined, in some cases, decades ago?

The layout of the thesis comprehends a summary of the CERA project and application matrix description (1), after which a broad overview of the iron ore industry and its mining, processing and smelting methods and processes is given (2). These will be evaluated on their hazards regarding the three focus points of CERA, namely environmental, social and economic sustainability (3). After evaluation, the matrix will be adjusted and new items will be added in order to add to the completeness of the matrix for, in the end, all raw materials, where in this thesis iron will be the focus (4). During early stage analysis of the matrix it was found that recycling was only mentioned as one particular risk, 'inadequate recycling management'. Since recycling is very important within the steel making process this is a huge miss in the application matrix and in the CERA project for that matter. Therefore a research is done and an advise is given on how to add recycling to the different CERA standards, focussing on CPS and CCS (5). In the final chapter a conclusion and recommendation is given for the upcoming approach of CERA (7).

Throughout this thesis the research question is: 'How can a raw materials certification standard such as CERA include recycling in the existing elements of the standard?'. This main research question is answered with regard to the case commodity iron by the following sub-questions.

1. What are the main features of the iron ore value chain?
2. What features need to be adjusted or added to the application matrix in order to validate the correctness for the iron ore value chain?
3. What are general hazards applying to the iron ore value chain?
4. What are the characteristics of recycling standards, if any, that are in place?
5. How can recycling processes be added to the Performance Standard described by CERA?
6. How can recycling processes be added to the Chain of Custody described by CERA?
7. How can recycled material/scrap material be traced to their origin?
8. In what way can untraceable materials still enter the CERA certified raw materials value chain?

# 1. CERA Project

Customers expect high quality products and at the same time they are questioning more often the origin and manufacturing conditions (CERA, 2020). Who verifies and guarantees the compliance with sustainability criteria? To define a criteria standard, the CERA certification of raw materials project has been in development since 2015 (European Institute of Innovation & Technology, 2020) and its main focus is to develop a certification standard applicable to all raw materials and all processes in the raw materials value chain (CERA, 2019).

In this chapter the CERA project is explained and worked out in more detail, what the focus of CERA is and why the project has been founded, what the goal is and how this goal is proposed to be achieved in the upcoming years.

## 1.1. Foundation and partners

The CERA project has been funded by EIT Raw Materials since 2017, which is a subgroup of the European Institute of Innovation and Technology (EIT). EIT Raw Materials is the world's largest innovation community in raw materials. The vision of EIT Raw Materials is to develop raw materials into a strength for Europe. They want to achieve this by boosting competitiveness, growth and attractiveness of the raw materials sector of Europe (European Institute of Innovation & Technology, 2020). This is done by increasing of innovation and guided entrepreneurship and in this way support CERA's mission in maintaining the world standard for sustainability in the sector of raw materials (Klosek, 2020). This is important for the European Union since for many materials, including some which are considered critical for the European Union's economy, the EU is dependent on imports (EuCommission, 2018).

The CERA project is led by DMT GmbH & Co. KG, which is an independent engineering and consulting company with their main office in Essen, Germany. The project is run in cooperation with other leading raw materials research institutes and providers of technical service in Europe:

- DMT GmbH & Co. KG
- TÜV NORD CERT GmbH
- Leiden University
- Research Institutes of Sweden
- University of Leoben
- CONFEDEM
- Savannah Resources
- Until 2019: LTU Business AB

Next to the institutes and technical service providers an Advisory Board was formed in order to discuss directions and research opportunities (European Institute of Innovation & Technology, 2020):

- Volkswagen AG
- Euromines
- University of Southern Denmark
- United nations ECE
- EU Joint Research Centre
- European Bank for Reconstruction and Development
- Siemens AG
- Infinity Lithium
- Until 2019: Fairphone

## 1.2. Problem addressed by CERA

In different sectors such as the forestry, food or textile industry a general certification scheme is already in place. These are used for production and transport and have an all-encompassing standard. Unfortunately, this does not exist for mineral resources yet (Brink, 2017). The existing certification schemes fail to be holistically applicable on all raw materials or on the entire value chain for that matter. Besides, they lack a global scale for their standards and in most cases recycling is not considered (CERA, 2019). There are more than 40 different certification schemes for the mining industry alone and this number of schemes increases exponentially when the entire value chain is considered, according to Andreas Hucke, CERA Project Director, head of Raw Material Sustainability at DMT (Jamasmie, 2019). For specific sections this scheme diversification allows for tailor-made solutions. However, information overload, disorientation and scepticism is generated to some extent due to this diversification (Kickler & Franken, 2017). “Existing certification processes are complex, expensive and inconsistent, resulting in a porous and diffuse approach to how sustainability and ethics are defined from country to country, mineral to mineral and company to company” says DMT (Gleeson, 2019).

The problem addressed here is that society has a growing interest in the responsible production of mineral resources while there is only limited global distribution of the standards available, while the value chain of raw materials is global. Next to that these standards often do not include outstanding value chain parts. The interest does not only grow due to pressure from legislation or from the increase in media reporting on mining such as human rights violation and environmental grievances, but it also grows due to newer responsible products offered on the market by different suppliers, for example mobile phones and jewellery (Kickler & Franken, 2017). Moreover, the effort that mining companies are taking to ensure good practice is increasing, due to reputational benefits and the fact that they want to differentiate from other corporations. Benefits with regards to reputational risks are increasingly important for organizations. Reputational risks mainly depend on the available information about companies’ environmental performances (Pineiro-Chousa, et al., 2017). Corporate social responsibility can be used as a differentiation from other corporations by the development of competitive advantage in the form of corporate reputation and organizational commitment (Yalcintas, 2017). In other segments of the value chain, such as manufacturing, pressure is rising as well to the supply chain due diligence due to international legislation and other obligations with for example the EU Regulation on Conflict Minerals (Kickler & Franken, 2017).

## 1.3. Focus and goal

For these reasons, the focus of CERA is to create a standardized certification scheme for all raw materials on a global scale. This way the certification can ensure environmental, social and economic sustainability and it can guarantee traceability of the certified materials. By constructing a standardized certification scheme for all raw materials on a global scale, the level of transparency is increased. This is because a CERA label, no matter what stage of the raw materials value chain, clearly indicates that the company is certified according to regionally and globally accepted regulations and requirements.

CERA aims to be applicable for the whole value chain from greenfield to consumer. Next to that, CERA introduces mechanisms to ensure reliability in the chain of custody (CERA, 2019). Besides its own criteria and certification it tries to harmonize and recognize the already existing standards. CERA focuses on the following three basic criteria:

- a) Corporate Governance
- b) Social Responsibility
- c) Environmental Responsibility

## Principles

Within these three basic criteria, CERA has principles to work according to. These are based on the Sustainable Development Goals of the UN Agenda 2030 and ISO 26000 “Guidance on social responsibility” (CERA, 2019).

*Completeness* – all different raw materials, all techniques for mining and processing at every scale possible and all countries in which it takes place along the value chain are considered. This is done by taking into account the different specific conditions for the raw material in question and creating different implementation details for them.

*Transparency & Trustworthiness* – because of the not-for-profit governance nature of CERA, its independent developing consortium and public consultations it can guarantee maximum credibility. In addition to this, an independent third party does the auditing and consultancy work.

*Comprehensiveness & Recognition* – to reduce workload for some organizations that are aiming for a certification by CERA, the project aims to accept and integrate already existing standards available. This allows for harmonization between existing standards. To aim for recognition, CERA aims to be aligned with well recognized standards. Think about the Sustainability Development Goals set by the United Nations (United Nations, 2020) and standards such as the ISO 26000.

*Traceability* – by using appropriate combinations of traceability methods, i.e. analytical fingerprints, traceability throughout the value chain can be assured with more confidence.

*Participation & Contribution* – stakeholders are asked for their interests and recommendations, these are taken into account, which ensures that the set of standard criteria is comprehensive and well-balanced.

*Flexibility* – the CERA certification is suitable for every type of player within the supply chain, also mentioned within ‘completeness’.

*Competence* – support of leading experts in certification and sustainability together with an interdisciplinary team developing CERA ensures competence work.

## Sustainability Development Goals (SDG)

One of the goals implemented in the CERA project is adding value to the SDGs set by the United Nations shown in Figure 1.1 on the next page. The SDGs provide a blueprint of plans and actions for peace and prosperity for people and planet, with the view on now and on the future. The SDGs are an urgent call for action by developed and developing countries. These align the fact that ending poverty and other deprivations must go together with improving health and education, reducing inequalities and spurring economic growth and at the same time addressing climate change tackling and preservation of oceans and forest to better the world (United Nations, 2020). All of these goals set by the United Nations are touched upon in the CERA project within their basic criteria.

Corporate governance can be linked to SDGs 1,2,4,5,6,8,10,13 and 17. Where environmental responsibility especially touches on the SDGs 11,12,13,14 and 15. And within social responsibility most are applicable, namely SDGs 1,2,3,4,5,7,8,9,10 ,11,12,16 and 17 (CERA, 2019).



Figure 1.1 – Sustainable development goals (United Nations, 2020).

#### 1.4. Approach of CERA

In order to develop a certification system that is as holistic as possible, all value chain elements need to be included. Therefore the CERA project is split into four main sections. They are the four standards within the CERA standard, the CRS, CPS, CCS and CFS as shown in Figure 1.3. In Figure 1.3 it is shown to which part of the value chain the different standards are linked.



Figure 1.3 – CERA structure (CERA, 2019).



Figure 1.3 – Summary of the four different standards and their application field (CERA, 2019).

*CERA Readiness Standard (CRS)* – This standard looks at the phase of exploration, pre-investment and all the planning operations before production starts. The CRS consist of a set of criteria for the evaluation of mineral and ore reserves. This includes studies such as pre-feasibility, feasibility and bankable studies and also the regulations set for exploration with regard to sustainability criteria. So the CRS focusses on the criteria before extraction and thus the output for certification is a responsible extraction plan.

*CERA Performance Standard (CPS)* – This standard is the main focus of this thesis. The CPS focusses on all the steps from mining activities through processing activities into refining activities of the value chain. These steps will be evaluated with regard to sustainability criteria set within the basic criteria mentioned in paragraph 0. Implementing the rules and requirements set by the CPS will contribute to responsible operations. The standard has its focus on the facilities and sequences of operations within the steps mentioned.

*CERA Chain of Custody Standard (CCS)* – This standard has its focus on the displacement of the material along the value chain, it enables traceability of the commodities. To ensure traceability of the commodity, this standard provides the criteria for the appropriate management systems. Within this the run-of-mine, the concentrate produced and primary or secondary raw materials are considered. CCS is not only focussed on CPS certified organisations but an approach for non-CERA-certified organisations will be developed as well.

*CERA Final Product Standard (CFS)* – This standard, as in the name, focusses on the final product of the raw material process and its manufacturing process. The criteria in this certification are focussed on the consumer goods and will enable informed decision-making by issuing various labels. The CFS requires the former standards CPS and CCS to be in place. When the standard is assigned this is indicated by a product label.

#### *Implementation Details*

To clearly describe what a company is supposed to implement in order to be certified by the standards of CERA, each of the four standards is supported by an Implementation Details file. These IDs documents are respective to each of the standards. In order to get the certificate of CERA, the organisation should be conform with the necessary requirements of the standard, for this the Implementation Details of the respective standard need to be fulfilled (CERA, 2019).

The Implementation Details document for the CPS standard is an overview of measures and requirements for specific conditions with regard to e.g. raw materials, company status or processes. This document is created to give an overview for the specifics of the operation based on three aspects. Firstly an exemplary prevention plan for hazards identified is given. Secondly the key performance indicators (KPI) are requested, e.g. amount of material or licence allocations. Thirdly an improvement plan can be developed for the specific company or process.

### 1.5. CERA Performance Standard detailed

As mentioned before, the focus of this master thesis is on the CPS. As shortly mentioned in the previous paragraph, the CERA Performance Standard is implemented in the production, processing and refining elements of the value chain. Within these steps of the value chain the main focus of this certification standard is the basic criteria stated earlier: Corporate governance, Social responsibility and Environmental responsibility. These basic criteria have been worked out in more detail and each of them has a few set rules and requirements to adhere to before being CPS Certified.

An application matrix has been developed that will help customers check and determine the hazards related to the production methods they use. Then, linked to the application matrix, an Implementation



Details document is worked out showing the hazards and their respective preventive and mitigative measures. Also the documentation that is required from the company seeking certification is defined. By fulfilling these details a company can achieve CPS certification by CERA.

In this thesis the application matrix will be extended, with the main research focus on the commodity iron ore. Sections of the matrix will be enlarged and sections are added to make the application matrix as complete as possible. The hazards, corresponding to the methods, developed by CERA will be critically analysed and missing hazards shall be added to the corresponding methods. A separate section on the recycling of raw materials is developed in the later stage of this matrix validation.

## 2. Iron ore – the basics

As mentioned in the introduction, the purpose of this report is to validate the application matrix for the commodity iron ore specifically. This application matrix has originally been developed for the raw commodity cobalt. In order to do this analysis correctly, a research was done thoroughly to understand all the processes with regard to iron ore. This includes the origin, geographic and geologic features, mining, processing and refining processes of iron ore, also the transportation, commodity market and its waste production is studied. Iron ore is a different type of material compared to cobalt, mainly with respect to the scale of operations. Also cobalt is a more valuable material, thus different methods of processing might be viable in comparison to iron ore processing.

The commodity iron ore is interesting because of the scale of operations and the share in the world's market. The element iron is the second most abundant element in the earth's crust (Bell, 2020) and in several various sectors of the economy it is the most widely utilized metal (Mwanguzi, et al., 2012). Besides this, the amount of iron ore mined worldwide has almost doubled over the past 20 years (United States Geological Survey, 2020) as can be seen in Figure 2.9 on page 25 and is expected to grow modestly in future years due to expansions in Brazil and increasing output from India (FitchSolutions, 2019).

### 2.1. Geology

Many different iron ore deposit types exist and have been important for producing iron ore. The most important deposit type is the Banded Iron Formation (BIF) iron ores. The BIF ores are followed by importance by the Channel iron deposits (CIDs), Kiruna-type iron oxide-apatite ores, and some types of copper iron skarn deposits (Clout & Manuel, 2015). More than 90% of iron ore deposits exploited were sedimentary hosted iron ores in 2011, the other 10% covered magmatic and skarn deposits (Ramanidou & Wells, 2014). These sedimentary deposits were formed from chemical precipitates in ancient oceans some 1.8 billion years ago (Gutzmer & Beukes, 1999). These are mainly consistent of the Banded Iron Formations, which are by far the most important deposits. The BIF deposits are mostly sub-divided into 2 different types, the Lake Superior-type and the Algoma type (Skinner, 2019). They were formed by the precipitation of iron oxides in seas or lakes. The Superior-type BIFs were deposited in shallow waters of the continental shelves or sometimes, at that time present sedimentary basins. They are very continuous over long distances. These types of BIFs are mined all around the world. The Algoma type BIFs were formed over a very long period of time, from 3.8 billion to a few hundred million years ago and are formed by submarine volcanic activities. These types are less continuous than the Lake Superior-type and are mined less extensively.

### 2.2. Characteristics

Multiple different iron minerals exist, however, the main two are hematite and magnetite which is why these two will be discussed in more detail. Other less important iron minerals are limonite, siderite, pyrite and more. The industry classifies iron ore as high grade ores (+/- 60% Fe) like hematite and magnetite, and low grade ores (+/- 30% Fe) like taconite. Hematite and magnetite can also be found as lower grade ores. Most of the known deposits contain such low grade ores (Mwanguzi, et al., 2012). The only source of primary iron is iron ore (United States Geological Survey, 2020). Typical gangue minerals such as  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ , and elements such as Phosphorus (P) and Sulphur (S) can be harmful with regards to the production of steel (Xiong, et al., 2015), paragraph 2.4.3 discusses this in more detail.

*Hematite*, with its chemical formula  $\text{Fe}^{+3}_2\text{O}_3$  contains in pure form 70% iron. This mineralization of iron ore was originally called blood stone by the Greeks due to its rust-red colour, although it can also be

found in grey to black. Hematite is commonly of sedimentary origin in Archaean cratons, but can also be found in metamorphic rocks and sometimes even in igneous extrusive rocks. Most red soils are red due to this mineral. Hematite minerals may contain impurities replacing the iron molecules for titanium, aluminium, manganese or water (King, 2020). The dominating type of iron ore today is hematite, since it is easily reduced in blast furnaces (Yang, et al., 2014). The enrichment of Precambrian iron-formations caused the formation of most of the world's high-grade hematite iron ores. However, the processes that cause the enrichment are still unclear. This is mainly due to the monomineralic composition of the ores. The high-grade hematite ores are mainly composed of hematite as microcrystalline hematite and martite, revealing little about its origin due to these mineral's wide stability field and simple chemical composition (Beukes, et al., 2002).

*Magnetite*, with its chemical formula  $Fe^{+2}Fe^{+3}_2O_4$  has in pure form 72% iron. This mineralization of iron ore was originally called lodestone and has a greyish black or iron black colour (Denchi, 2020). It is an iron oxide and it may contain impurities replacing the iron molecules with manganese, zinc, aluminium, magnesium, chromium, titanium, nickel, vanadium or a combination of the mentioned minerals. The magnetic attraction of magnetite is one of its best known properties and magnetite itself can actually be a magnet (Friedman, 2020). To mine Banded Iron Formations as iron ore economically, coarse-grained meta-morphogenic magnetite abounds minerals should be present to easily separate and concentrate the mineral with magnetic separation. It can also be desired to separate by gravitation if the minerals are metamorphosed and later strongly weathered to a coarse-grained iron oxide and quartz (Gutzmer & Beukes, 1999).

### 2.3. Geography

As explained earlier, iron ore is mined around the world in approximately 50 countries. The main areas where these iron ore minerals are found and exploited are Australia, Brazil, China and India. Other iron production countries are for example Russia, South Africa, Northern America (United States Geological Survey, 2020). In 2014, from the ten biggest iron ore mines in the world, seven were located in Australia, two in Brazil and one in South Africa. The mine with the highest yearly production in 2014, the Hamersley mine in the Pilbara region in Australia, had a production of over 160 million tons (Basov, 2015). To give a perspective of size, this one mine produces 1000 times more iron ore than the yearly cobalt production worldwide (United States Geological Survey, 2020). A visualization of the main producing countries and the amount in metric ton is shown in Figure 2.1 (Löf, et al., 2019), in which Australia, Brazil and India are clearly the main producing countries.



Figure 2.1 – Iron ore production in 2018 in metric ton (Löf, et al., 2019).

### 2.3.1. Main iron ore reserves

As mentioned, the main producing countries are Australia, Brazil, China and India. Those countries are shortly elaborated on in this paragraph.

#### *Australia*

Australia is the main iron ore producer and exporter in the world (United States Geological Survey, 2020). At the moment the mining projects in Australia mainly cover hematite deposits, but in the future magnetite projects will make an important contribution to the production of iron ores in Australia as well. These magnetite deposits have higher impurity levels and were thus not yet economical. The iron ore deposits mined currently are high quality ores (58 to 65% Fe content). The most important deposits are the Marra Mamba, which are surface enriched BIF's, and Channel Iron Deposits (O'Brian, 2009).

#### *Brazil*

Brazil is the second-largest iron ore producer in the world. In Brazil, mainly two types of iron ore are mined, the rich superficial deposits and itabirite. The main mineral mined is low impurity hematite ores. They are of fine texture and brittle, this causes high amounts of fines and dust generated during production and transportation. The itabirites are a proto ore and have lower iron content which causes flotation to be a necessary production step (Moraes & Ribeiro, 2018).

#### *China*

In 1995 an Australian report stated that China is expected to rely on imported ore due to the relatively low quality and poor location of its own iron ore deposits (Labson, et al., 1995). Generally, recent resources found were of low grade, +/- 30% iron content. However, large shallow high grade deposits have been discovered as well (Wu, 2012). China mainly relies on import of iron ores to support their steel making industry and the demand of construction material in the country.

#### *India*

India also has as prominent mineralization hematite and magnetite. In India the hematite deposits are thought to be the most important, with mostly high grade ores, over 60% iron content, near the surface. Those deposits are mainly associated with volcano-sedimentary BIFs. In India there are five broad zones where the majority of the iron ore is mined (Gundewar, 2011).

## 2.4. Industry related features

Within the CERA Performance Standard (CPS) the main production steps of iron ore are linked to the basic criteria. The production steps discussed in the CPS are mining, processing, smelting and refining. However, in the application matrix used for certifying, the exploration of potential valuable areas is also discussed. Within this paragraph the processes used during every production step of iron and the production of its products is described in more detail. In this chapter the focus is on the CPS mining, processing, smelting, refining and recycling. However, since exploration is not detailed enough in the application matrix, this will be discussed in this paragraph as well. The information in this chapter is used to check up on and validate the application matrix.

### 2.4.1. Exploration

In chapter three one can see that the exploration section has not been discussed extensively previously. Therefore this paragraph also discusses some exploration processes that are not used with iron ore exploration. Exploration is used to discover mineral deposits that can be profitably extracted. Meaning that the deposit is of significant size for the commodity, its shape is convenient for mining purposes and the mineral content is high enough to pay for the expenses and make a profit. Different types of tools are used during exploration, e.g. topography, geological, geophysical and geochemical maps and information (Roonwal, 2018). For more detailed exploration (bulk) sampling, drilling and

core logging and geophysical and geochemical surveys are used. Due to the magnetic characteristic of some iron ore minerals, magnetic surveys have played a role in the exploration phase of magnetite iron ores specifically (Christiansen, et al., 2018). 'Since economic mineral resources are rare, finding one is challenging and the odds of success of any exploration program are relatively low' (Revuelta, 2018, p. 14).

### *Prospecting*

Finding geologically important bodies and deposits is the first step in the exploration procedure. This is often done by using geological, geophysical, geochemical and topographical maps and models. But before geological mapping is done, satellite imagery and aerial photography is used and is important for easier mapping of terrain elevation, geological structures of large scale e.g. faults. It is also used to plan regional mapping or sampling campaigns for later stages of the exploration procedure (Roonwal, 2018).

### *Preliminary exploration*

After the regional maps have been developed and studied, preliminary exploration is the following stage. Information about the geological set-up and mineral occurrences is collected during this stage. The objective of this stage is to collect all necessary information needed for making a decision on investment. Since exploration practises are relatively expensive, and as mentioned earlier often not resulting in production. Sufficient data should therefore be collected to establish reliability on the occurrence of the mineral deposit. This stage includes the preparation of a contoured survey map, geological appraisal of the deposit, limited subsurface mapping, interpretation of borehole data obtained by drilling, chemical analysis of borehole and other samples and ore dressing tests (Roonwal, 2018, pp. 62 - 64).

Other useful methods are useful as well such as geophysical and geochemical surveys. These types of surveys include airborne geophysical surveys for a cost-effective way of obtaining information about a large area. This can also be done from the ground with methods such as seismic surveys, sampling and drilling.

### *Detailed exploration*

When the preliminary exploration shows promising results, more in depth research on the possible size and quality of the mineral deposit is done by the means of exploration. Similar methods are used but on a more detailed scale and more to the surface and subsurface. This stage includes close interval contour mapping, extended drilling including surveying the boreholes, (bulk) sampling vial trenching or blasting, rock formation data gathering, geological map cross-sections including a preliminary reserve estimation, laboratory testing of borehole samples, collection of ground water data and base line environmental data and possibly a pilot on mineral/ore processing (Roonwal, 2018, pp. 65 - 66).

### *Methods used*

A more detailed explanation is given on the geophysical and geochemical methods used during exploration. These are, as explained earlier, relatively extensive and not only focussed on exploration with regard to iron ore due to the lack of information on exploration within the application matrix.

**Geological Mapping** – With this method of exploration, geological maps are developed by identifying rock or soil types in the area, geological structures are also investigated. This is mainly done by observing the area of interest, the orientation and characteristics of the rocks exposed at the surface. Small samples can be taken to a lab for chemical analysis to increase the details of the exploration. Nowadays geological mapping is also done digitally by comparing or combining information already established in the past (United States Geological Survey, 2004).

**Geophysical Surveys** – Geophysical surveys can be classified into passive methods, measuring naturally existing fields, and active methods, in which the response of the (sub)surface is measured to a signal. Different surveys detect and measure different physical properties. The passive methods usually include measuring magnetic and gravity fields, alpha and gamma radiation and natural electrical fields. Other methods, such as electrical and electromagnetic techniques, seismic methods and some downhole methods are part of the active geophysical survey methods (Milsom, 2006).

Milsom (2006) separates between six main different geophysical surveying methods. The first, being magnetic surveys. This surveying method is used for the detection of naturally magnetic deposits, for example magnetite deposits. It measures the magnetic field of the rocks, by flying over them with a high sensitivity caesium vapor magnetometer. The second method mentioned is the gravity survey, which is based on the change in gravity field by variations in the subsurface. Due to the effects being minimal the gravity meters are extremely sensitive. The third method is radiometric surveying, which is based on the principle of natural radioactive decay. The particles emitted by this decay can be measured and different radiation spectres allow for distinction between compositions, however this is difficult and expensive. The fourth method is resistivity, where electrical properties are characterized. Some minerals, for example graphite, conduct very good and therefore reduce the rock resistivity. This is a method conducted at the surface and sometimes in boreholes. The fifth method discussed is seismic surveying. This is mainly used in the gas and oil industry and little used in mineral exploration. This is due to the lack of coherent layering in many igneous and metamorphic rocks. However, some placer deposits can be defined using seismic surveys. The last method mentioned is ground penetrating radar (GPR) surveying. The results from this type of surveying is similar to seismic surveying, only it is limited to the top few tens of meters. One useful characteristic is that the radar shows a very strong reflection of the water table.

**Sampling/Geochemical Surveys** (Whateley & Scott, 2006) – After a first interpretation of the subsurface and promising results, geochemical surveys can be used to determine more in depth information. It usually involves the collection and preparation of samples, which are sent to laboratory for analysis of the mineral composition. Samples should be clearly labelled and contained in non-metallic containers to avoid contamination. Methods regularly used are neutron activation analysis, x-ray fluorescence, atomic absorption spectrophotometry, inductively coupled emission spectrometry and inductive coupled mass spectrometry. For a more extensive sampling method, trench sampling can be used where a series of samples are collected along an excavated line, which results in densely spaced samples. Sampling for geochemical analysis is sometimes done in bulk, but only in advanced exploration projects (Gill, 2009).

**Exploration Drilling** – In order to get a more specific image of the rocks in the subsurface, exploration drilling is used. Drilling however is an expensive method and thus is done in later stages of the exploration phase. The aim of exploration drilling is to bring back samples from down the drillhole and analyse those samples. First the cores are quickly analysed on site to determine whether this hole is to be continued or not, the samples are then sent to a field base. Here more detailed core logging and chemical analysis is done for a greater geological understanding and to analyse the mineralization of the sample core (Whateley & Scott, 2006). Sometimes the drillhole, when empty, is analysed by so called ‘down hole’ surveys measuring density, porosity, strength and other characteristics (Milsom, 2006).

**Iron ore specific methods** (Roonwal, 2018) – For the exploration of iron ore specifically certain methods are of greater interest than others. A main determining factor in this is the large scale of iron ore deposits. Topography study is of great use for many iron ore deposits. This is due to the fact that almost all iron ore deposits occur on top or ridges and other topographical land marks. Iron ores are

also known to have gravitational influence on gravity instruments. Thus gravity surveys may be of interest with iron ore deposits. In a similar way, magnetic surveys might be of interest to the exploration of magnetite due to the magnetic characteristics. Besides these airborne surveys, trenching and pitting have been used extensively within the exploration of iron ore. Besides these bulk sampling methods, exploratory mining can be used if the previously mentioned methods do not provide enough information about the deposit in question. This is only done when confidence about the ore body is already relatively high.

*Evaluation*

After exploration, evaluation of the data received from exploration, in the form of (pre-) feasibility studies, should provide an answer on whether to go into production or not. Often during a technical evaluation, making use of different methods e.g. polygons, inverse distance weighted, triangulation and contour methods, information found is connected and an estimation of tonnage and grade is developed, the quantity and quality of the deposit. An economic and socioeconomic evaluation is done as well, determining the accessibility and value of a deposit. Net present value, internal rate of return or payback period calculations are often part of the economic evaluation. (Revuelta, 2018, pp. 16 - 17)

These evaluations will define the deposit as resource or reserve, in which factors such as geological knowledge and confidence, and economic viability are used. The definitions have been defined by the JORC code, and shown in Figure 2.2. These definitions are thus also dependent on the mining, processing, metallurgical methods, as well as on economic, infrastructure, marketing, legal, environmental, social and governmental factors, known as the ‘Modifying Factors’ (Joint Ore Reserves Committee, 2012).

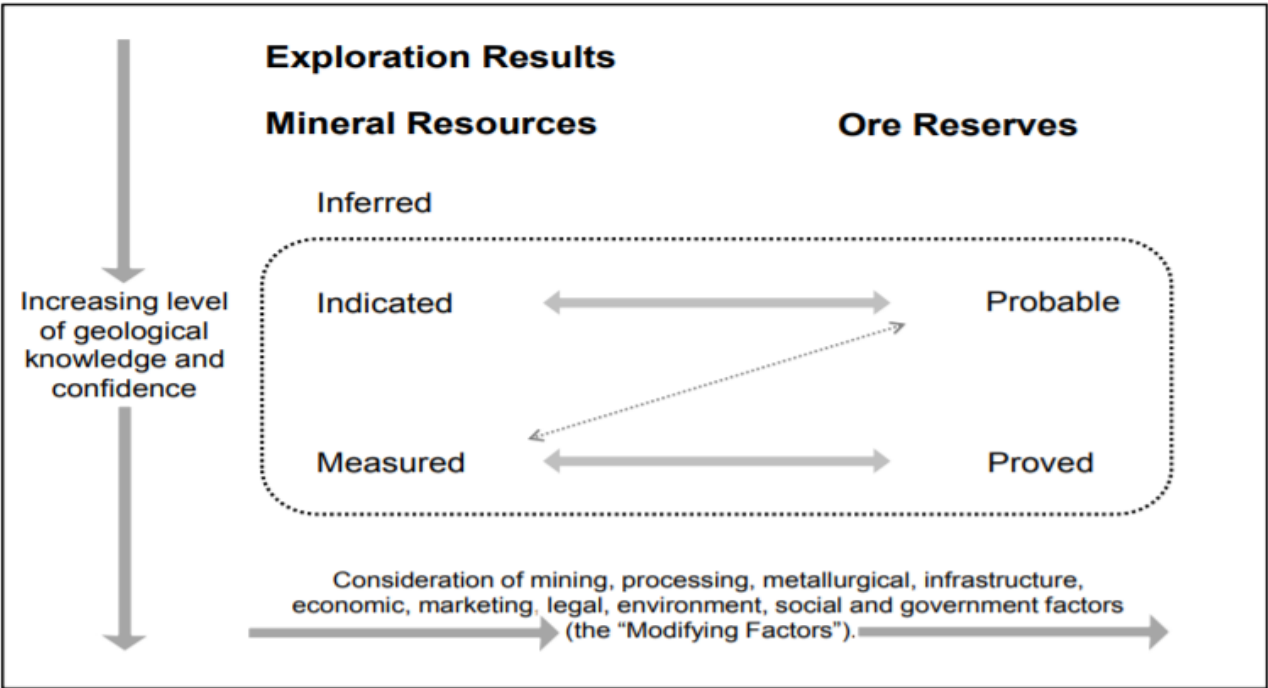


Figure 2.2 – Relationship between Exploration Results, Mineral Resources and Ore Reserves (Joint Ore Reserves Committee, 2012).

2.4.2. Mining

During the mining phase of a project the pre-defined deposit, from the feasibility study, is supposed to be brought to the production phase. The main division in mining methods is between open pit mining and underground mining (Hartman & Mutmansky, 2002).

### *Open pit mining*

For the production through the means of an open pit mine, the top soil and overburden need to be taken away before access can be granted to the deposit. This can withhold anything from a meter till a hundred meters, depending on the size of the deposit and its value. In larger open cast coal mines the overburden removal can be quite significant if the coal seam has a significant thickness. With an eye to the iron ore deposits discovered and produced nowadays, the grade is relatively low, so a deposit should not have a too thick overburden to be processed by open pit mining. The open pit mining method depends on the rock characteristics in situ. In hard rock conditions, such as in Scandinavia, the main mining method is drilling and blasting. The rocks are too hard to actually mine by shovel so it needs to be fragmented before it can be removed. In other cases the ground conditions are favourable for a truck and shovel combination for loading and hauling without blasting.

A section within open pit mining is aqueous mining. This includes the mining of placer deposits with the use of dredging. This is mainly done with stream and beach placer deposits. These deposits are sluiced and valuable materials are separated with the use of gravitational separation (Smith, 2019). An example of such a deposit with regards to iron are titanium magnetite sands offshore north Taiwan and south Kyushu, which are mainly mined for their iron content (Wang, et al., 2014).

Another sub-method used and defined under open pit mining is in situ mining (Hartman & Mutmanský, 2002). In situ mining or solution mining is the mining of a material underground by not physically accessing it. Where the main process is making use of hydrometallurgical properties to extract the metals directly as a solution (Seredkin, et al., 2016). Water is pumped down and certain minerals dissolve and are pumped up again. This is mainly done for salt deposits, where it is called solution mining/borehole mining.

### *Underground mining*

If the overburden or conditions for open pit mining are too thick or harsh respectively, the operations can take place in an underground mining environment. This means an opening is created in order to access the ore at a lower level. The access ramp or shaft is created just next to the deposit or minable area in order to be protected from mining activities close by such as drilling and blasting. The opening of an underground mine is usually a costly project, due to the constructions needed to access the valuable material. Underground mining is almost always done with drilling and blasting and supporting the blasted area. Within the drilling and blasting method, multiple different methods are possible, for example block caving, back fill mining (upwards and downwards), sub-level stoping and sub-level caving. With large planar underground coal mines longwall mining is used where a shearer is used to take away the coal.

These mining methods bring different types of risks and hazards with it (Donoghue, 2004). This means that for all different iron ore mining methods the different risks and hazards need to be separately worked out. A common hazard for underground mining is unstable ground conditions whereas in open pit mining slope stability is a common hazard. This will be worked out in more detail in chapter 4.

The two mining methods mentioned can be divided into different sub methods again. For open pit mining 8 different methods are defined and for underground 10 different methods are defined. These are visualised in Figure 2.3 on the next page. These methods will not be discussed into more detail since the activities and hazards associated to them are relatively equal to the activities and hazards of the overall terms of open pit, underground, placer and in situ mining. In the analysis of the application



matrix some of the methods are highlighted due to separate hazards associated to them. These will be discussed in chapter 3 and chapter 4.

Open pit Mining		Underground		
Mechanical	Aqueous	Unsupported	Supported	Caving
Open pit	Hydraulicking	Room and Pillar	Cut and fill	Longwall
Quarrying	Dredging	Stope and Pillar	Stull stoping	Sublevel caving
Open cast	Borehole	Shrinkage	Square set	Block caving
Auger	Leaching	Sublevel stoping		

Figure 2.3 – Open pit and underground mining methods designed from (Hartman & Mutmansky, 2002).

2.4.3. Processing

In order to deliver the correct quality of material, the ore is send to the processing facility. The raw iron ore is processed and refined into a concentrate before it can be smelted into steel sheets or other types of products.

Gangue minerals

Iron ore production is associated with different gangue minerals. The mineralogical characteristics become more and more important due to the depletion of high grade ore deposits (Kadhe, et al., 2016). It is important to know the gangue minerals when liberating the iron minerals during processing and especially during flotation. There are four main gangue minerals associated to iron ores (Pattanaik & Venugopal, 2018). The first is silica with its most important elemental form quartz, but also chert, kaolinite and others can be found. The second gangue mineral is alumina, found as gibbsite, kaolinite and other alumina bearing gangues like ferruginous clay, found in lower quantities. A third gangue mineral commonly found is phosphorous in the form of apatite, hydroxylapatite, fluapatite, chlorapatite, vollophane and bromapatite. The last, one of the most common gangues, is sulphur in the form of pyrite, marcasite and pyrrhotite. Later in this chapter the processes of liberating the iron minerals from these gangue minerals are explained, these include but are not limited to crushing, grinding, (magnetic) separation and froth flotation.

Due to the gangue minerals present in the raw iron ore, processing the ore is a crucial step in the value chain. The gangue minerals mentioned have different influences on the final product. The influence of aluminium on the further process of steel making is mainly associated to the high melting temperature of aluminium. Its high temperature for melting negatively influences the induration furnace and the process becomes more energy intensive (Kadhe, et al., 2016). The presence of high quantities of alumina cause the reduction degradation index to increase (RDI), which is negatively effecting the process in the blast furnace (Lu, et al., 2015). High silica contents in the iron ore results in a high slag volume, which has a negative impact on the iron ore smelting process (Okvist, et al., 2000). Operations that have high slag volumes demand high fuel rates and it decreases the productivity. The silica content together with the alumina content should preferably be lower than 5% in pellets or concentrates, providing a low volume of slags and a high production rate (Lu, et al., 2015). Phosphorus and sulphur content should preferably be kept at a minimum. This is due to both being deleterious elements, they result in brittleness of the steel products (Rudyk, et al., 1974).

### Crushing, sintering/pelletizing and upgrading

Whenever the ore quality is high enough to be fed to the blast furnace immediately, only crushing and grinding to the right size is needed. This is only for high grade ores, with 60% iron content or higher, with low impurities (Muwanguzi, et al., 2012). These high grade, low impurity ores can be directly shipped to the steel manufacturer. The iron ore that has been blasted contains lumps of rock in different sizes, ranging from one meter to one millimetre. The blasted material is screened and the larger particles are fed to a crusher. Screening out the smaller particles improves the crushers productivity. The larger sized material is crushed via a primary crusher, sometimes with an in pit crusher, and sometimes even into a secondary crusher which can be a gyratory crusher, cone crusher or another type of crusher. The material is crushed to be reduced to a size suitable for blast furnaces, since the blast furnace process requires a good permeability. Usually these lumps have a size between 6.3 mm and 31.5 mm (Jankovic, 2015). Particle sizes that are too small (<6.3 mm) need to be sintered in order to create the correct particle sizes. Sintering is the heating of a layer of small particles to obtain a state of partial melting which fuses individual ore particles together. A grain size below 5 mm is the most suitable for sintering (Frohlichova, et al., 2018).

Nowadays the grade of the iron ore mined is usually not the desired quality, since high grade ores are depleting and thus ores with higher impurity levels are being mined (Battle, et al., 2014). When the composition of the ore is not optimal for feeding it to the furnace, it is upgraded after crushing and grinding. This is done to increase the iron content in the product and to reduce the content of harmful gangue minerals. For this processing step the material needs to be milled to such a small particle size that the iron bearing particles can be separated from the non-iron-bearing particles. Separation can be done by gravity or magnetic separation techniques. Methods making use of gravity separation are for example dense media separation (DMS) (Grewal, et al., 2019) and jig separation (Falconer, 2003). These methods make use of the different specific gravities of minerals, by letting the heavier minerals settle and the lighter minerals 'float' in water or suspensions depending on the specific gravities. These two stream are thus separated and can therefore be used separately.

Due to the ferromagnetic nature of magnetite it can be separated with a low magnetic field intensity, whereas hematite may require a higher magnetic field intensity in order to be separated as required (Battle, et al., 2014). Magnetic separation is illustrated in Figure 2.4 by two of the possible separators used in processing. Hydrocyclones are used to separate on gravitational characteristics.

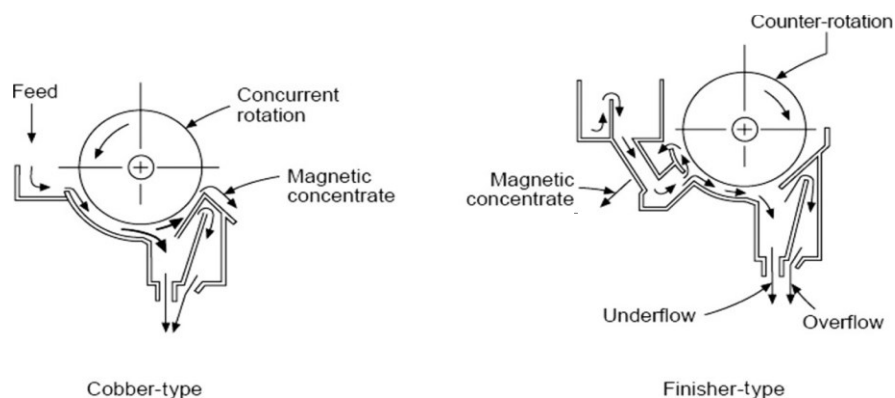


Figure 2.4 – Schematic of a magnetic separator (Nakhaei & Irannajad, 2017).

The particle size after this process is too small for feeding to the furnace, therefore the material is agglomerated by pelletizing. Pelletizing is the creation of small balls that have the ideal size and shape for the blast furnace. This is done by adding a binding agent, which for iron ore is bentonite, the most commonly used, in order to make the pellets stick together (Forsmo, et al., 2006). This bentonite is added to the concentrate and moistened, where after the material is rolled in a balling drum to form soft pellets of typically 10 to 15 millimetres in diameter. These are screened and if the pellets are too large they are crushed and rolled again. The soft pellets are moved to a furnace for drying and preheating. These pellets typically have 60-65 percent iron content and have different ranges of other minerals present depending on the original composition and the requirements (S&PGlobal, 2020) (JindalSteel, 2014) (Battle, et al., 2014). The requirements for standard pellet chemistry is shown in Table 2.1. In some cases the pelletizing takes place on a different location than the processing of the ore. This mostly results in the mixing and blending of different iron concentrates to obtain uniform, high-quality pellets (Nakhaei & Irannajad, 2017). These final pellets will be transported via train or ship to the customers or to an ore dock where they will be re-distributed for the production of steel in a blast furnace.

Parameter	Units	BF Pellets	DR Pellets
Fe	wt%	63–65	65–68
SiO <sub>2</sub>	wt%	2.5–5.3	1.0–3.0
Al <sub>2</sub> O <sub>3</sub>	wt%	0.4	0.2–3.0
MgO	wt%	0.3–1.5	0.2–0.9
CaO	wt%	0.6–3.6	0.4–1.2
Pellet size	mm	9–16	9–16
Compression strength	N	2850–3190	2500–3000
Tumble index	% + 6.15 mm	95–96	92–95
Reducibility index	wt%	91–97	92–95

Table 2.1 – Characteristics of typical iron oxide pellets (Nakhaei & Irannajad, 2017).

### Flotation

In the case that the iron bearing minerals are not liberated properly by the use of magnetic and gravitational separation, froth flotation is used. Due to the increase of impurities in iron ores, froth flotation has become an internationally and industrially used processing method, especially when it comes down to the direct reduction coupled with electric arc furnace production (Ma, 2012). In some cases the content of the ore has such characteristics that extra treatment is needed. This is typically used for hematite ores (Battle, et al., 2014). It is for example commercially used as a method to remove pyrite and pyrrhotite from iron sulphides and it is used in combination with gravity and magnetic separation in order to effectively remove sulphur and other impurities (Nakhaei & Irannajad, 2017).

For iron ore flotation five major routes can be specified namely; cationic or anionic flotation of iron oxide, cationic/anionic flotation of quartz, or a combination of these. The most widely used is the reverse cationic flotation route, but the direct and reverse anionic flotation routes are also used in the industry. Direct flotation is still desirable for some low grade iron ores with a vast amount of quartz. With this process hematite ores can be upgraded from 36.5% Fe to 65.4% Fe in Michigan, U.S.A., with an iron recovery of 82.5%. In order to enhance the flotation process, collectors and additives are used. The collector acts as a coat around the mineral that is supposed to float on the water, making it hydrophobic. A frother is added to make sure that stable air bubbles and froth are formed. These chemicals can be fatty acids, normal types of acids, sodium sulphates or many other chemicals (Bruckard, et al., 2015) (Ma, 2012). After separation the concentrated material is dried and pelletized or sintered before being transported to the steel making facilities.

### Flow sheet

In Figure 2.5, on the next page, a process flowchart is shown to illustrate the steps explained in this paragraph. The main processing line starts with crushed material, being the fresh feed. This material goes through a milling section and through screens. Particles that are too large are fed back to the mill and particles that pass the screens continue to a magnetic separator. After which the material is sent through hydrocyclones. This material is then again sent through a magnetic separator after which it follows to the flotation cells. After the flotation the useful part of the material is sent to filters so it can be dried and pelletized.

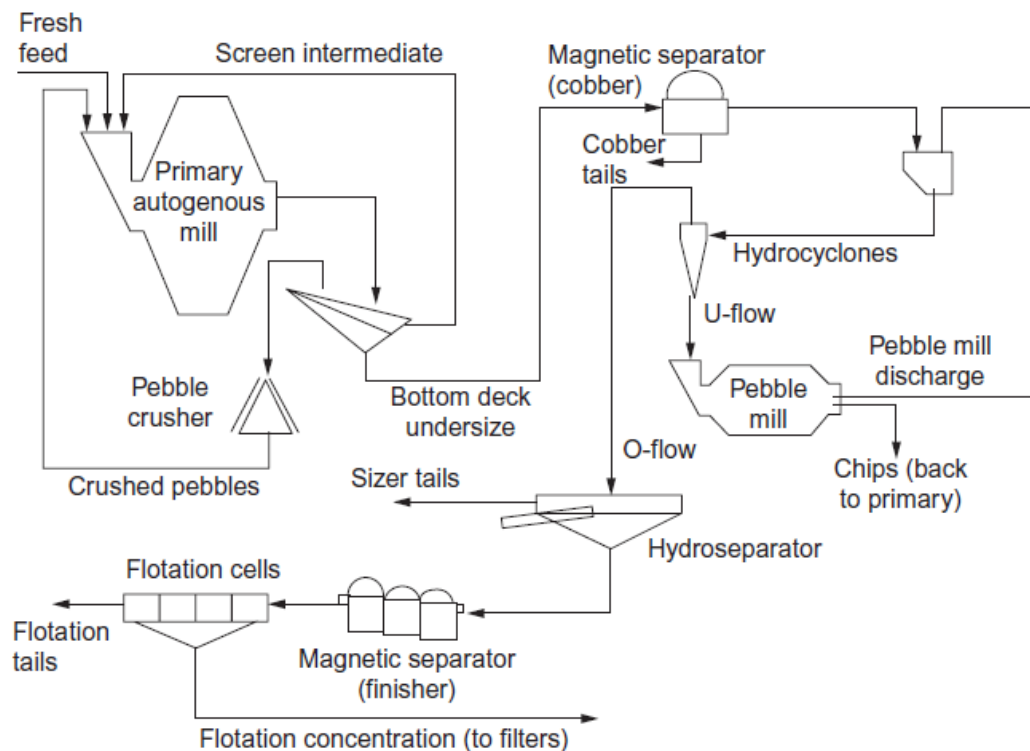


Figure 2.5 – Typical grinding and concentrating line (Jankovic, 2015).

#### 2.4.4. Smelting and refining

For the production of steel, raw materials such as hot metal/pig iron and steel scrap are used. Steel scrap originates from the downgrading of constructions or other methods of recycling. The production of hot metal or pig iron is mainly done via the blast furnace process. The blast furnace process accounts for 93% of the pig iron production, the other 7% is produced via the direct reduction process. Blast furnaces use three main forms of 'raw' iron used for ironmaking, these are sinter, lumps and pellets (Battle, et al., 2014). Other materials used are coke and pulverized coal to reduce the iron oxides, also used as a heat source. Next to that lime or limestone is used as fluxing agents (Yang, et al., 2014).

From the pig iron created, in the blast furnace and direct reduction furnaces, steel is produced. There are two main furnaces used for the production of steel. Mostly a typical basic oxygen furnace (BOF) is used to purify the pig iron. Another furnace used is the electric arc furnace (EAF), especially for scrap recycling. In Figure 2.6, on the following page, the full cycles of smelting raw iron ore to steel is shown.

The blast furnace route is the oldest iron melting route but is still the main one used, with a production of 66% of the total crude steel. The electric arc furnace route accounts for 31% and the other 3% is produced via blast furnace-open hearth process (Yang, et al., 2014).

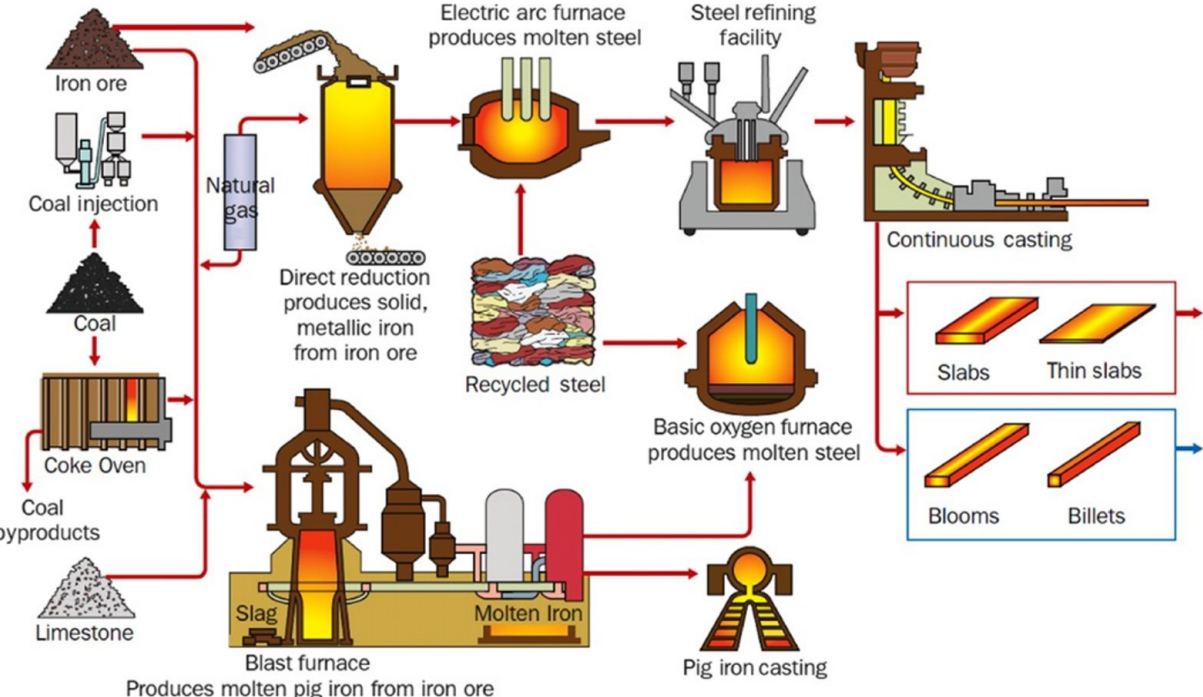


Figure 2.6 - Steel production flow sheet (Yang, et al., 2014).

*Process of blast furnace*

The process in a blast furnace is a continuous process making use of a heat and mass transfer process. From the top of the furnace alternating layers of cokes and raw iron products, mentioned in the previous paragraph, are charged. Due to gravity the material will slowly go down the tall structure. In the lower part of the furnace hot oxygen is injected through tuyeres. The hot oxygen reacts with the cokes in the furnace, which forms carbon monoxide. This gas rises through the raw iron products reducing the iron-oxides in them to metallic iron. At the bottom of the blast furnace the pig iron is extracted. Since the formed slag is lighter than the hot metal, it will float on top and thus can be extracted separately. In Figure 2.7 the process within a common blast furnace is illustrated.

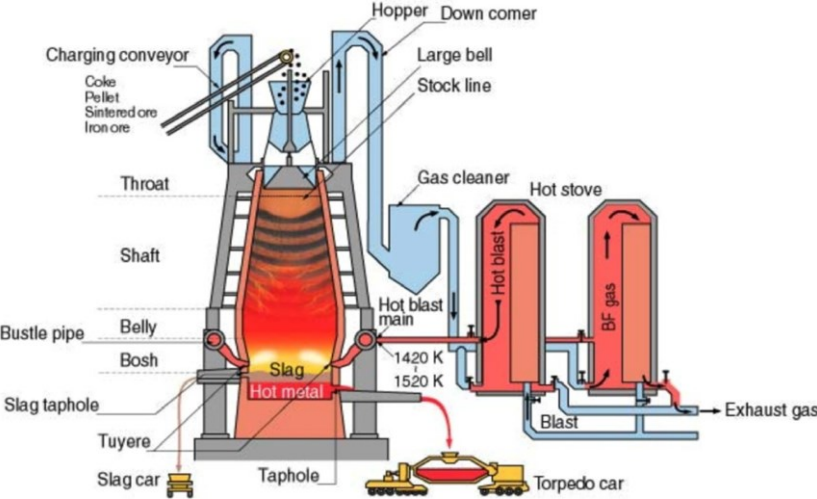
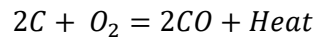


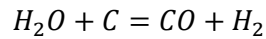
Figure 2.7 – Blast furnace process illustration (Yang, et al., 2014).

The chemical reactions inside the blast furnace are shown in the following reactions (Yang, et al., 2014).

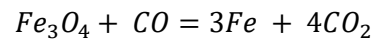
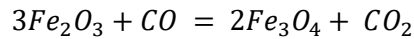
First the cokes react with the oxygen blown through the system.



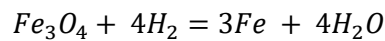
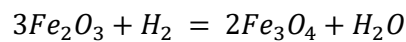
In a similar way, the water vapor present reacts with the coke.



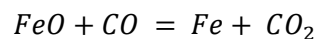
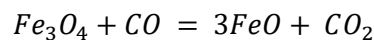
After charging the raw iron containing materials they are preheated rapidly by the rising heated gases in the furnace, causing the following reactions below 570 degrees Celsius:



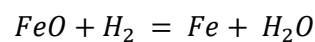
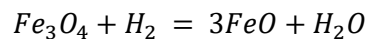
The iron oxides can also react with the hydrogen gases with similar reaction schemes:



When the charged material reaches a temperature higher than 570 degrees Celsius, the reactions are as follows:



Similar reactions occur when reacting with hydrogen gases:



After this the temperatures rise to around 1000-1100 degrees Celsius causing the charged material to soften. This also separates the iron and the slag. The slag that is formed still contains iron oxides in the form of FeO. These can be reduced further in the direct reduction furnace.

#### *Process of direct reduction*

Direct reduction of iron is defined as the conversion of iron ore to metallic ore in the solid state. The significant disadvantage of direct reduction is the fact that there is almost no possibility for removing impurities since the material is not melted. This causes a problem for the main customer of direct reduced iron, the electric arc furnaces, since they can usually not handle the extra slag load created due to the impurities. Therefore these impurities need to be treated and removed in the mineral processing phase. This causes the feed to the direct reduction 'furnace' to be more expensive.

A standard natural gas-based direct reduction method is performed in a shaft furnace. While the iron ore is fed from the top of the shaft furnace, a reducing gas is fed from the bottom of the furnace going upwards, counter current of the iron ore. This natural gas needs to be reformed into a mix of carbon monoxide and hydrogen just like the reactions in the standard blast furnace. Usually steam and/or carbon dioxide are used. To optimize this process a nickel-based catalyst is used. Research has been going on to use the CO<sub>2</sub> produced by the reduction process as its own injection gas repeatedly, lowering the amount of gas used.

### *Process of Electric Arc Furnace*

The electric arc furnace (EAF) is mainly used for recycling steel scrap, but it can handle all sorts of iron materials such as pig iron, hot metal, direct reduced iron or hot briquetted iron. Also it is versatile in its products: long and flat, carbon and alloyed and both continuous and ingot casting. At the moment 29% of the crude steel production in the world is via the EAF process (Madias, 2014). The EAF uses a high electric current to melt down the iron products. Electrodes are lowered into a 'pile' of iron materials mentioned earlier and melts the first layers, these will run down to the bottom of the furnace and create a 'pool' of molten metal. The electrodes are lowered until they touch the molten metal and from there on rise with the level of the molten metal. This method uses a much higher temperature than normal furnaces, namely up to 3500 degrees Celsius. The downside of this method is that it uses a considerably large amount of electricity, also it requires a certain feed to work effectively just like with the other processes (Flournoy, 2018).

#### *2.4.5. Alloys*

Steel is produced with different qualities and characteristics. For example stainless steel is produced by adding chromium as an alloy. With generally containing between 10-20% chromium, the corrosion resistance can be 200 times higher. These alloying commodities are added after the primary melting of the iron ore. Within the stainless steel production, three different groups can be identified based on their crystalline structure, austenitic, ferritic and martensitic stainless steel (Bell, 2019). The main additives to the iron are chromium, nickel, carbon and sometimes aluminium, molybdenum or titanium, depending on the quality desired.

Next to stainless steel, multiple different steel types are produced. One example is 'tool steel' which often contains tungsten, molybdenum, cobalt and vanadium in different quantities depending on the final desired heat resistance and durability. This type of steel is ideal for cutting and drilling equipment. Different quantities of alloys are added to change the characteristics of the produced steel (Mackie, 2019).

#### *2.4.6. Coating*

After the product has been cast it is often coated. Common coating methods are hot-dip galvanizing, electrochemical coating, vapor deposition and thermal spraying (YenaEngineering, 2019).

Galvanizing is the most common method for coating metal surfaces. Before a metal can be coated it needs to be cleaned thoroughly in order to obtain a high bond between the coat and the metal. Cleaning is done by dipping the metal in hot alkali solution to remove common dirt, then dipping the metal in pickling solution to remove rust and scales. After these cleaning steps, the final step is fluxing to remove surface oxides so that the metal is protected from oxidation. When the metal is clean, it is dipped into a zinc bath to obtain the coating. This zinc layer protects the metal from corrosion by acting as an anode whenever it gets damaged.

Another method is electrochemical coating, which makes use of charged particles attaching to an electrode. This means that a metal is lowered into a solution bath (cleaned beforehand) and a current is created through this solution. The desired charged particles in the solution bath will be attracted by the electrodes, which is the metal, therefore coating the metal.

With the third method, vapor deposition, the desired metal coating is first evaporated to later condensate on the metal surface. Two different groups are distinguished, the chemical and the physical vapor deposition. With physical vapor deposition the evaporated metals are 'sprayed' on the metal surface under high pressure to enable high adhesion. With chemical vapor deposition the

dissolved material in the vapor is adsorbed by the metal surface due to chemical properties and coats it with a thin layer.

Thermal spraying is the last method discussed and is based on the principle of spraying the substance for coating on the metal surface under heated conditions. This type of coating can be applied in a thicker layer.

*2.4.7. Waste production and handling*

During mining, waste production can be classified into different groups: solid mining, processing and metallurgical wastes and mine waters as shown in Figure 2.8 (Lottermoser, 2010).

Examples of mining wastes are waste rocks and overburden, mining water and atmospheric emissions such as carbon dioxide. Examples of processing wastes are tailings, sludges, milling water and atmospheric emissions. Examples of metallurgical wastes are slags, ashes, dusts, leached ores process water and atmospheric emissions. Waste water includes all the water used for e.g. cooling of machinery or dust suppression.

These wastes are not necessarily a danger to the environment or social communities, but that depends on the characteristics of the wastes, which in turn depends on the mineralogy of the deposit mined or material processed. Whether something is defined as a waste depends on the value of the mineral. Sometimes by-products can be processed if the value is high enough instead of put to the wastes.

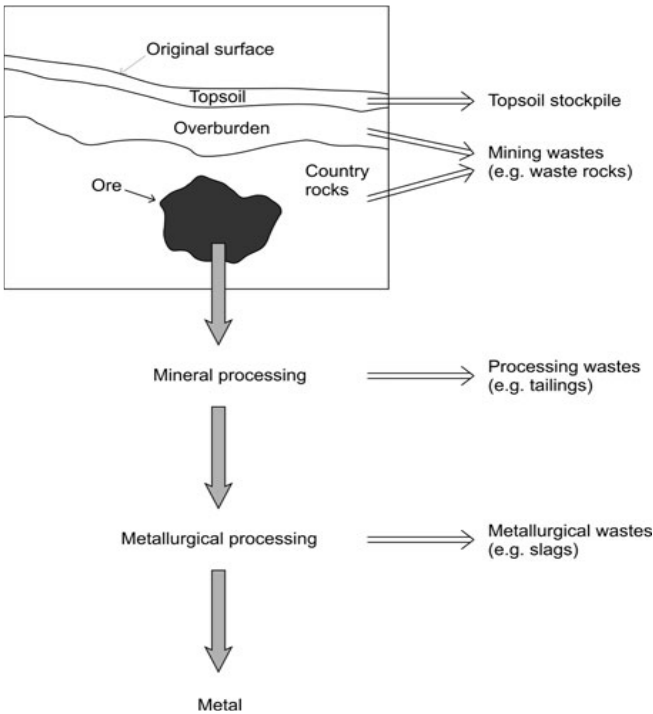


Figure 2.8 – Scheme of waste streams from metal mining industry (Lottermoser, 2010).

Mine wastes have potential environmental impacts due to the release of harmful elements. In some cases the release of those mine waste elements have impact on the local ecosystems. Which is why regulations have taken form to prevent mining and other companies on the value chain to dispose their waste into nature without any measures taken. Nowadays this even includes the development of a mine closure and rehabilitation plan before operations can start.

*Waste dumps*

Especially with iron ore mining the wastes can account for enormous amounts of wastes being dumped. These waste dumps are storage locations for the nonvaluable material that has been mined in order to reach the subsurface deposit. Within those wastes, especially sulfidic wastes can be problematic due to its weathering characteristics. This is due to the fact that mining exposes the sulphides to oxygen which causes the materials to be chemically unstable. When exposed to atmospheric conditions, the material wants to oxidize and sulfuric acid is a product of this reaction. The hazard of this is the seeping of this acid into hydraulic systems causing acid mine drainage. Iron ore is often associated to sulphides, for example pyrite and pyrrhotite, and is therefore a concern for certification due to the large environmental hazards.



### *Tailings*

After crushing, grinding and flotation, a processing facility is left with two products, one is the concentrate of the valuable material and the other is a slurry of all the unwanted material called tailings. To dispose of all the tailings, large tailing ponds are developed. The unwanted minerals are mainly the gangue minerals named in the beginning of this chapter, such as silica and phosphorus. There are also sulphides and oxides, depending on the mineralogy of the material. Within the tailings, the process chemicals used during beneficiation are present as well. At some metal mines the tailings can be the most voluminous wastes due to the low grade ores that are mined. With iron ore this is not necessarily the case due to higher grades being used. When the slurry is in the tailings for longer period of time, the solid particles can settle and some dissolved minerals can even precipitate due to evaporation of water. In Brazil such tailing ponds have caused environmental disasters, e.g. the failure of the Brumadinho iron mine in 2019 and Mariana's tailings dam rupture in 2015 resulting in the exposure of the near environment to 11 million cubic meters and 43 million cubic meters of toxic mud respectively (Rotta, et al., 2020).

#### *2.4.8. Recycling*

In the past decade, recycling scrap metal has become a significant resource to the steel industry. The steel industry is named the 'world champion' in closing the material cycle due to its recycling rates (Stahl, 2020). Steel is recycled the most of all materials and the recycled steel is used in all new steel manufacturing (TataSteel, 2020). Even though the main supplier of iron ore is still the mining sector, since nearly 40% of the steel production worldwide is done with recycled steel (LeBlanc, 2019). Due to the fact that steel recycling is efficient and economical the scrap steel has become valuable, resulting in recovering it wherever it can be.

Steel recycling comes with the following 'production steps', namely the collection, sorting, processing, shredding, melting, purification, solidifying and the transportation of the steel (Rinkesh, 2020). Most of the recycling is done via Electric Arc Furnaces (EAF) (Madias, 2014).

Other new developments that can be cited under 'recycling' is, for example, the extraction of hematite from tailings. This has been made possible due to technological advances and increases the recovery percentage (Tang, et al., 2019). Recycling will be worked out into more detail in the analytical analysis of the addition of recycling to the CERA project in chapter 5 of this thesis. It will also be handled in the application matrix and hazards analysis.

## 2.5. Iron ore market

Iron ore is produced almost globally due to its abundance in the earth crust, with estimated resources of 800 billion tons of crude ore that contains 230 billion tons of iron. The largest estimated reserves are located in Australia, Brazil, China, India and Russia. Which are also the largest producers of iron ore, with especially Australia producing the most (United States Geological Survey, 2020). Production numbers provided by the USGS in January 2020 are shown in Table 2.2.

Mine production in:	Usable ore (ton)	Iron content (ton)	Reserves (ton)	
	2019	2019	Crude ore	Iron content
<b>United States</b>	48.000.000	31.000.000	3.000.000.000	1.000.000.000
<b>Australia</b>	930.000.000	580.000.000	48.000.000.000	23.000.000.000
<b>Brazil</b>	480.000.000	260.000.000	29.000.000.000	15.000.000.000
<b>Canada</b>	54.000.000	33.000.000	6.000.000.000	2.300.000.000
<b>Chile</b>	14.000.000	9.000.000	NA	NA
<b>China</b>	350.000.000	220.000.000	20.000.000.000	6.900.000.000
<b>India</b>	210.000.000	130.000.000	5.500.000.000	3.400.000.000
<b>Iran</b>	38.000.000	25.000.000	2.700.000.000	1.500.000.000
<b>Kazakhstan</b>	43.000.000	12.000.000	2.500.000.000	900.000.000
<b>Mexico</b>	23.000.000	14.000.000	NA	NA
<b>Peru</b>	15.000.000	10.000.000	NA	NA
<b>Russia</b>	99.000.000	59.000.000	25.000.000.000	14.000.000.000
<b>South Africa</b>	77.000.000	49.000.000	1.100.000.000	690.000.000
<b>Sweden</b>	37.000.000	23.000.000	1.300.000.000	600.000.000
<b>Ukraine</b>	62.000.000	39.000.000	6.500.000.000	2.300.000.000
<b>Other countries</b>	62.000.000	35.000.000	18.000.000.000	9.500.000.000
<b>Rounded world total</b>	<b>2.500.000.000</b>	<b>1.500.000.000</b>	<b>170.000.000.000</b>	<b>81.000.000.000</b>

Table 2.2 – Production of mines per country in tons of ore, iron content and the respective reserves (United States Geological Survey, 2020).

The production in the past decades has grown rapidly due to the enlarging population and the need for more industrialization. This can be seen in Figure 2.9. In Table 2.3 the production of usable ore from the year 2015 until 2019 is shown. The values in both visualisations are reported in usable ore, which means that the ore has a typical Fe content of 58 – 65% (Tuck, et al., 2017).

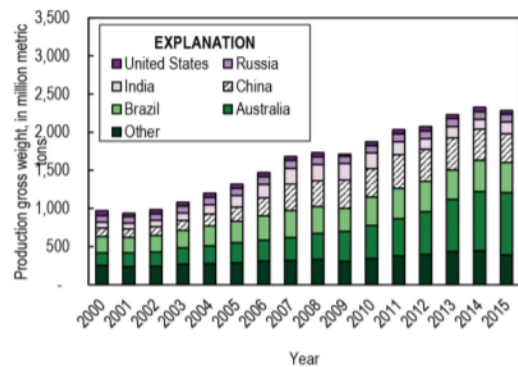


Figure 2.9 – Usable iron ore production from year 2000 to 2015 (Tuck, et al., 2017).

USGS	2015	2016	2017	2018	2019
<b>World production usable ore</b>	2.280.000.000	2.350.000.000	2.430.000.000	2.460.000.000	2.500.000.000
<b>World production iron content</b>	1.400.000.000	1.450.000.000	1.500.000.000	1.470.000.000	1.500.000.000

Table 2.3 – Production of usable ore and iron content amount in Metric Tons from 2015 to 2019 (United States Geological Survey, 2020).

The growth in production can be explained due to the demand that increased largely due to steel production in China to support their major growth. The growth in China caused steel production to almost double since 2000 (Holmes & Lu, 2015).

All of these iron ores are produced by large companies, the three main iron ore producers, Vale, Rio Tinto and BHP Billiton, were responsible for 74% of the production in 2013 (Holmes & Lu, 2015). These three companies are the top three mining companies with regards to market capitalization in 2018 (PricewaterhouseCoopers, 2018).

According to Investopedia (2020) the prices of a ton of iron ore has fluctuated around a price of 100 USD, with highest values at the beginning of 2011 at 187\$/ton and lowest values in the end of 2015 at 41\$/ton (Investopedia, 2020). The price fluctuation over the past years is shown in Figure 2.10.

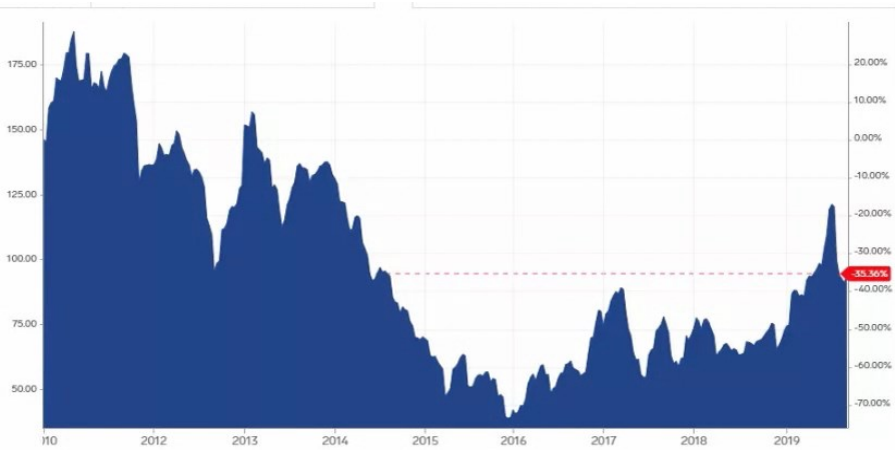


Figure 2.10 – Price fluctuation of a ton of ore in USD (Investopedia, 2020).

Most of the price fluctuation is due to the market demand in China since they have by far the largest portion of import of iron ore in the world, with 69.1% of the gross total which is also shown in Figure 2.11 on the next page (Garside, 2020).

*Steel production*

China’s import requirements are this high since its own iron ore production of 14% global share, can’t match its steel production. China is at the moment the main producer of steel with a crude steel production of over 900 million tonnes in the year 2018 (WorldSteel Association, 2019), which is more than half of the worlds crude steel production. In Figure 2.12 on the next page, one can observe the growth of crude steel production in the world over the years. Since 98% of iron ore is used for steel making this graph nearly follows the iron ore production trend. In 2018 the top three steel maker companies were ArcelorMittal (96.42Mt), China Baowu Group (67.43Mt) and Nippon Steel Corporation (49.22Mt).

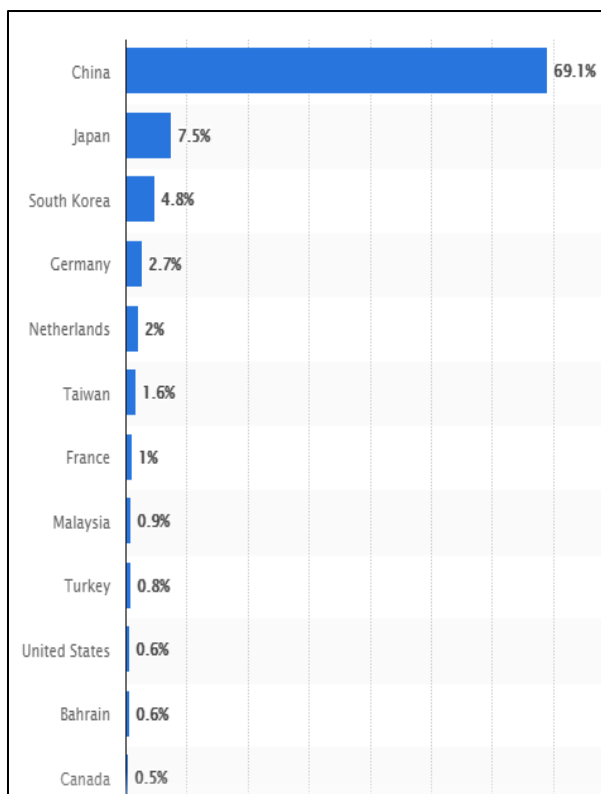


Figure 2.11 – import of raw iron ore per country (Garside, 2020).

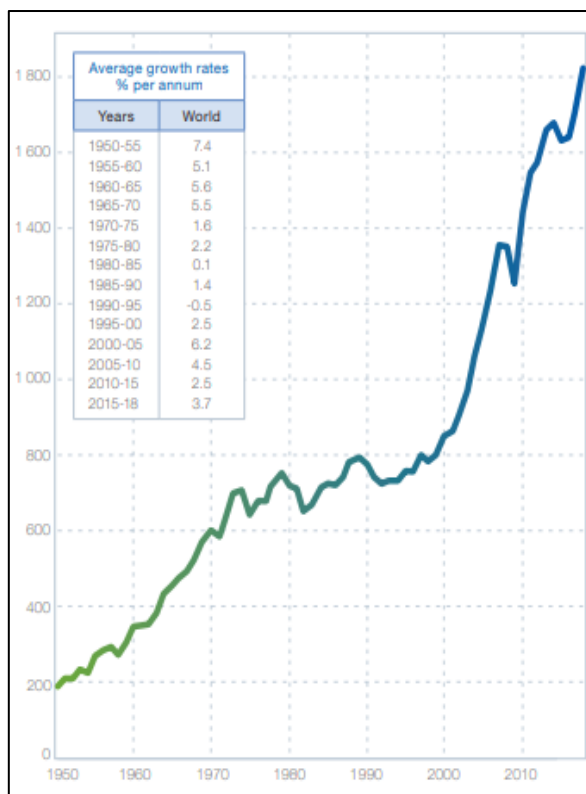


Figure 2.12 – crude steel production worldwide in million tonnes (WorldSteel Association, 2019).

## 2.6. Transportation

Iron ore is mined in large quantities which is associated to hazards during the transport of the material. Since the commodity in terms of size is much larger than the already investigated commodity cobalt (United States Geological Survey, 2020), this is an interesting subject to keep an extra eye on during the validation of the application matrix. Mostly the ores are processed on site and the product, either concentrate or pellets, is transported to a port for overseas transportation. This first bit of transportation is, if available, by train. If the deposit, mine, processing plant or refinery is large enough, a railway network can be constructed for cheaper and quick transportation to the port.

In most cases the ores are seaborne traded to other countries. In order to load the shipment a code has been developed, the International Maritime Solid Bulk Cargoes (IMBSC) Code. In this document the traders need to provide all information with regards to the shipment, information on the safety of the personnel and the ship, technical information on stowage factors and more (Federal Ministry of Transport and Digital Infrastructure, 2020). This code will be taken into account later in the validation process.

In Figure 2.13 on the next page the main transportation routes are shown. Main importers of iron ore are China, Japan and the EU and main exporters of iron ore are Australia and Brazil (Löf, et al., 2019). Examples of other exporters are Finland, Argentina, Canada, Chile, Germany, Russia and Oman. Examples of other importers are the Netherlands, Germany, United States and Indonesia. (Chatam House, 2018)



Figure 2.13 – Iron ore trade in 2017 in metric ton (Löf, et al., 2019).

### Haulage

Transportation of ores within a mine is also an important sector for the mining industry. After drilling and blasting, haulage is done with trucks or conveyer belts. The use of haulage trucks is mainly important for open pit production (Burmistrov, et al., 2017). The hauling of material and the maintenance of the machinery needed, accounts for a significant section of the costs of a mining operation (Nunes, et al., 2019). Next to that, the number of fatal accidents with haulage trucks is relatively high in comparison to other mining equipment (Zhang, et al., 2014).

Besides truck and shovel combination, In-Pit Crusher Conveyor (IPCC) systems have been developed in recent years for iron ore mining as well, in for example the Pilbara region in Australia. Here the material is either directly fed to an IPCC system or the excavators load a small fleet of trucks that bring the material to the IPCC system. The material is crushed closer to the mining location and transported via an overland conveyor. This offers higher productivity due to fewer operators and maintenance personnel and more efficient energy use due to electrically powered conveyors that are more efficient in energy use than trucks driving on diesel (QueenslandUniversity, 2016).

Underground mines usually have conveyer belts in combination with a hoisting skip system that brings up the ore. Other systems can be used such as inclined shafts or drifts in combination with truck haulage or a rail mounted system (Haldar, 2013). It is important to select the correct haulage system for the mining method used and type of material mined.

### 3. Application matrix analysis

The analysis of the application matrix was done by comparing the matrix in place with the information found during the literature study. During the validation the focus is on the processes and methods used within the iron ore value chain. By comparing the literature and the existing matrix, differences are determined. A more clear structure is created and missing sections are added to include them in the matrix.

#### *Application matrix conclusion*

The matrix in place was relatively extensive in certain sections of the value chain, whereas in other parts the matrix was lacking methods that are being used in the raw material value chain. Especially with regard to the iron ore value chain, some methods are very important that were absent or not sufficiently detailed. Many changes are proposed, some of them more important than others.

### 4. Risk and Hazard Analysis

In this chapter the many risks and hazards that have been developed by CERA are analysed and reflected on. This is done by comparing information on the methods mentioned and defined in chapter 3. By comparing literature to the existing list, the list is extended and made more comprehensive at the same time. Besides this, the newly added methods to the matrix are discussed into more detail, in order to determine the risks and hazards associated to them.

#### *Definition*

To analyse the risks and hazards and transform them into correctly formulated hazards, the definition of a hazard needs to be specified. The definition for a hazard used within the CERA project and this thesis is from the ISO-45001 definitions list (International Organization for Standardization, 2018).

‘A hazard is any situation, substance, activity, or event that could potentially cause harm to people, property or the environment.’ In this thesis this includes situations or events that are harmless until something happens, e.g. slope instability is a hazard, since if something happens an earthquake for example, it has the potential to cause harm due to a possible landslide.

#### *Suggested Hazards Conclusion*

The hazards list developed by CERA is extended with suggested new hazards. These hazards have been linked to the basic criterion stated by CERA.

### 5. Recycling within CERA Certification

In the previous chapters the application matrix created by CERA and the hazards associated to the methods in the matrix have been observed and critically analysed. After which recommendations were made suggesting additions and changes to the matrix and its content. In this chapter the importance of recycling for CERA is discussed and different options for including recycling in CERA are discussed and proposed.

## 6. Recommendations and discussion

This recommendations section is split in three parts, the application matrix analysis, the hazards development and the addition of recycling and recycled materials to CERA's standards.

### *Application matrix*

The application matrix in its original form is not sufficient for a raw materials certification body such as CERA. The application matrix lacks major methods used within the raw materials value chain and insufficient interlinkage between different types of commodities is missing.

The changes made to the application matrix have been decided based on information acquired with the literature research. Methods might have been overlooked or misinterpreted. Therefore the suggested changes to the application matrix in this thesis should be critically looked at and analysed whether they should be added for CERA's purpose. Furthermore the matrix should be checked on with organizations to see if the structure is correctly working. When new commodities are added to CERA's certification scope, the methods used within those commodities should be analysed just the same way as was done for iron ore in this thesis. This will eliminate the risk of missing methods for other commodities.

Besides the discussed application matrix's build-up and the advised changes and additions, CERA should decide on the upcoming commodities to be added to the matrix. It would be a great addition for CERA to think more about interlinked commodities. Iron ore and manganese for example since they are mined for use in the steel making industry for 98% and 97% respectively. Therefore when CERA implements both these commodities in the application matrix, it is easier to check up on it with value chain actors in the steel industry.

### *Hazards associated*

Hazards and risks are often used interchangeable, which makes it hard to define the correct wording of the hazards for CERA. Most have been defined as general as possible, however, for CERA this might not always be the best since the hazards have to be audited. Therefore, the suggested new hazards and changes to existing hazards and risks should be evaluated critically before adjusting the hazards list accordingly. This is especially valid for the newly developed hazards developed.

## Bibliography

- Adagunodo, T. et al., 2018. Radioactivity and radiological hazards from a kaolin mining field in Ifonyintedo, Nigeria. *MethodsX*, 16 April, Volume 5, pp. 362-374.
- African Mining Legislation Atlas, 2017. *AMLA Guiding Template*, Africa: AMLA.
- Akcil, A. & Koldas, S., 2006. Acid Mine Drainage (AMD): causes, treatment and case studies. *Cleaner Production*, Volume 14, pp. 1139 - 1145.
- Ash, P., 2013. *Demand for Resources Drives African Rail Boom*. [Online]  
Available at: [https://www.railjournal.com/in\\_depth/demand-for-resources-drives-african-rail-boom](https://www.railjournal.com/in_depth/demand-for-resources-drives-african-rail-boom)  
[Accessed on 4 December 2020].
- Babich, A. & Senk, D., 2015. Recent developments in blast furnace iron-making technology. In: L. Lu, red. *Iron Ore*. Oxford: Elsevier, Woodhead Publishing, pp. 505-547.
- Basov, V., 2015. *True giants of mining: World's top 10 iron ore mines*. [Online]  
Available at: <https://www.mining.com/true-giants-of-mining-worlds-top-10-iron-ore-mines/>  
[Accessed on 23 September 2020].
- Battle, T. et al., 2014. The Direct Reduction of Iron. In: S. Seetharaman, red. *Treatise on Process Metallurgy*. Oxford: Elsevier, pp. 89-176.
- Baumgartner, T., Hatami, H. & Valdivieso, M., 2016. *The new world of sales growth*. [Online]  
Available at: <https://www.mckinsey.com/business-functions/marketing-and-sales/our-insights/the-new-world-of-sales-growth>  
[Accessed on 19 June 2020].
- Bell, T., 2019. *Steel Grades and Properties*. [Online]  
Available at: <https://www.thoughtco.com/steel-grades-2340174>  
[Accessed on 19 June 2020].
- Bell, T., 2020. *Metal Profile: Iron*. [Online]  
Available at: <https://www.thoughtco.com/metal-profile-iron-2340139>  
[Accessed on 19 June 2020].
- Bernechea, E. J. & Viger, J. A., 2013. Design optimization of hazardous substance storage facilities to minimize project risk. *Safety Science*, 51(1), pp. 49-62.
- Beukes, N., Gutzmer, J. & Mukhopadhyay, J., 2002. *The Geology and Genesis of High-Grade Hematite Iron Ore Deposits*. Perth, Iron Ore Conference.
- Björkman, B. & Samuelsson, C., 2014. Recycling of Steel. In: B. Björkman & C. Samuelsson, red. *Handbook of recycling*. Lulea: Elsevier, pp. 65 - 82.
- Bleischwitz, R., 2007. International Raw Materials Markets: Rising Prices and Growing Conflict Potential. In: T. Debiel, D. Messner & F. Nuscheler, red. *Global Trends 2007 - Vulnerability and Human Security in the 21st Century*. Bonn: Foundation for Development and Peace (SEF), pp. 65-78.
- Blondes, M. S. & Demas, A., 2019. *Making Minerals-How Growing Rocks Can Help Reduce Carbon Emissions*. [Online]  
Available at: <https://www.usgs.gov/news/making-minerals-how-growing-rocks-can-help-reduce-carbon-emissions>  
[Accessed on 31 August 2020].
- BMT, 2020. *Cargo Handbook Scrap Metal*. [Online]  
Available at: [https://www.cargohandbook.com/Scrap\\_metal](https://www.cargohandbook.com/Scrap_metal)  
[Accessed on 8 November 2020].
- Briggs, D. F., 2015. *Recovery of Copper by Solution Mining Methods*, Tucson Arizona: Arizona Geological Survey Contributed Report.
- Brink, S. v. d., 2017. *CERA - Certification of Raw Materials*. [Online]  
Available at: <https://www.universiteitleiden.nl/en/research/research-projects/science/cml-cera---certification-of-raw->



materials

[Accessed on 29 April 2020].

Britannica, 2014. *Contact dermatitis*. [Online]

Available at: <https://www.britannica.com/science/contact-dermatitis> (Retrieved on 25-08-2020)

[Accessed on 10 August 2020].

Bruckard, W., Smith, L. & Heyes, G., 2015. Developments in the physiochemical separation of iron ore. In: L. Lu, red. *Iron ore: Mineralogy, Processing and Environmental Sustainability*. Cambridge: Elsevier Woodhead Publishing, pp. 339 - 353.

Burmistrov, K., Osintsev, N. & Shakshakpaev, A., 2017. Selection of Open-Pit Dump Trucks during Quarry Reconstruction. *Procedia Engineering*, Volume 206, pp. 1696-1702.

Calam, C., 2017. *Types of Land Surveys Utilized by Mining Operations*. [Online]

Available at: <https://www.thermofisher.com/blog/mining/types-of-land-surveying-utilized-by-mining-operations/#:~:text=Using%20surveying%20minimizes%20the%20risk,of%20miners%20and%20the%20industry.>

[Accessed on 3 July 2020].

Canadian Government, 2019. *Natural Resources Canada*. [Online]

Available at: <https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/iron-ore-facts/20517>

[Accessed on 18 June 2020].

Celik, M. & Suner, F., 1995. A thermodynamic analysis of the decrepitation process. *Thermochimica Acta*, Volume 254, pp. 167-174.

CERA, 2019. *CERA Manual*. [Online]

Available at: <https://www.cera-standard.org/>

[Accessed on 28 April 2020].

CERA, 2019. *Performance Standard*. [Online]

Available at: <https://www.cera-standard.org/>

[Accessed on 27 April 2020].

CERA, 2020. *CERA Certification of Raw Materials*. [Online]

Available at: [https://www.youtube.com/watch?time\\_continue=36&v=7Z3Kjw6jxFY&feature=emb\\_title](https://www.youtube.com/watch?time_continue=36&v=7Z3Kjw6jxFY&feature=emb_title)

[Accessed on 28 April 2020].

Chaigneau, R., 2020. *Processes in iron ore production; Email to Olaf van der Meer* [Interview] (3 august 2020).

Chatam House, 2018. *ResourceTrade.Earth*. [Online]

Available at: <https://resourcetrade.earth/data?year=2018&category=157&units=weight>

[Accessed on 24 September 2020].

ChemWatch, 2008. *Aluminum Hydroxide*. [Online]

Available at: <http://datasheets.scbt.com/sc-214529.pdf>

[Accessed on 10 August 2020].

Christiansen, R., Kostadinoff, J., Bouhier, J. & Matrinez, P., 2018. *Exploration of iron ore deposits in Patagonia, Insights from gravity, magnetic and SP modelling*. [Online]

Available at: <https://onlinelibrary.wiley.com/doi/epdf/10.1111/1365-2478.12678>

[Accessed on 2 August 2020].

CLEAPSS, 2019. *Student Safety Sheet, Iron and its Compounds*. [Online]

Available at: <http://science.cleapss.org.uk/Resource/SSS038-Iron-and-its-compounds.pdf> - Retrieved on 31-8-2020

[Accessed on 9 August 2020].

Clout, J. & Manuel, J., 2015. Mineralogical, chemical, and physical characteristics of iron ore. In: L. Lu, red. *Iron Ore: Mineralogy, Processing and Environmental Sustainability*. Cambridge: Elsevier Woodhead Publishing, pp. 45-84.

ControlUnion, 2020. *GRS-Global Recycle Standard*. [Online]

Available at: <https://certifications.controlunion.com/en/certification-programs/certification-programs/grs-global-recycle-standard#:~:text=The%20GRS%20is%20an%20international,environmental%20practices%20and%20chemical%20restriction>

s.

[Accessed on 28 October 2020].

- Cooper, D., 2013. *Reuse of steel and aluminium without melting*, Cambridge: University of Cambridge.
- Cova, T. J. & Conger, S., 2003. Transportation Hazards. In: M. Kutz, red. *Transportation Engineers Handbook*. Utah: University of Utah.
- Dalbert, 2012. *Quartz risk sheet*, Pego Abrantes: Agglomerated Stone Association of Europe.
- Dastidar, M. G., Sarkar, B. K., Mitra, M. K. & Dey, R., 2017. Effect of alkali on different iron making processes. *Material Science and Engineering International Journal*, 2(Special), pp. 304 - 313.
- Dauce, P. D., Castro, G. B. d., Lima, M. M. F. & Lima, R. M. F., 2018. Characterisation and magnetic concentration of an iron ore tailings. *Journal of Materials Research and Technology*, 31 August, 8(1), pp. 1052 - 1059.
- Davila, R. B., Fontes, M. P. F., Pacheco, A. A. & Ferreira, M. d. S., 2019. Heavy metals in iron ore tailings and floodplain soils affected by the Samarco dam collapse in Brazil. *Science of the Total Environment*, 12 December, Volume 709, pp. 136-151.
- Denchi, M. L., 2020. *Magnetite*. [Online]  
Available at: <https://www.mindat.org/min-2538.html>  
[Accessed on 26 June 2020].
- Donoghue, A., 2004. Occupational health hazards in mining: an overview. *Occupational Medicine*, 54(5), pp. 283-289.
- Edward, L., McHugh & Girard, J. M., 2002. *Evaluating Techniques for Monitoring Rock Falls and Slope Stability*, Spokane: National Institute for Occupational Safety and Health.
- Edwards, R., 2014. *The fatal dangers of working in the recycling industry*. [Online]  
Available at: <https://www.etui.org/topics/health-safety-working-conditions/hesamag/waste-and-recycling-workers-at-risk/the-fatal-dangers-of-working-in-the-recycling-industry> (Retrieved on 19-8-2020)  
[Accessed on 14 August 2020].
- Elton, S., 2016. *Severe weather response plan*, Hertfordshire: East and North Hertfordshire Clinical Commissioning Group.
- Environmental Protection Agency, 2020. *EPA Recycling Basics*. [Online]  
Available at: <https://www.epa.gov/recycle/recycling-basics>  
[Accessed on 5 November 2020].
- EuCommission, 2018. *Securing raw materials for the future*. [Online]  
Available at: <https://ec.europa.eu/jrc/en/news/securing-raw-materials-future>  
[Accessed on 13 May 2020].
- European Automobile Manufacturers Association, 2017. *Fact sheet: Trucks*. [Online]  
Available at: <https://www.acea.be/publications/article/factsheet-trucks>  
[Accessed on 4 December 2020].
- European Commission, 2020. *REACH*. [Online]  
Available at: [https://ec.europa.eu/environment/chemicals/reach/reach\\_en.htm](https://ec.europa.eu/environment/chemicals/reach/reach_en.htm)  
[Accessed on 25 September 2020].
- European Institute of Innovation & Technology, 2020. *CERA project: a universal standard for ethics, sustainability and environmental impact*. [Online]  
Available at: <https://eitrawmaterials.eu/cera-project-a-universal-standard-for-ethics-sustainability-and-environmental-impact/>  
[Accessed on 29 April 2020].
- European Institute of Innovation & Technology, 2020. *EIT Raw Materials about*. [Online]  
Available at: <https://eitrawmaterials.eu/about-us/>  
[Accessed on 11 November 2020].
- EuroStat, 2019. *Road freight transport by type of goods*. [Online]  
Available at: [https://ec.europa.eu/eurostat/statistics-explained/index.php/Road\\_freight\\_transport\\_by\\_type\\_of\\_goods#Road\\_freight\\_transport\\_by\\_type\\_of\\_goods](https://ec.europa.eu/eurostat/statistics-explained/index.php/Road_freight_transport_by_type_of_goods#Road_freight_transport_by_type_of_goods)  
[Accessed on 4 December 2020].

Falconer, A., 2003. Gravity Separation: Old Technique/New Methods. *Physical Separation in Science and Engineering*, 12(1), pp. 31 - 48.

Federal Ministry of Transport and Digital Infrastructure, 2020. *International Maritime Solid Bulk Cargoes (IMSBC) Code*. [Online]

Available at: <https://www.deutsche-flagge.de/en/safety-and-security/cargo/imsbc/imsbc>  
[Accessed on 2 June 2020].

FitchSolutions, 2019. *Global Iron ore Mining Output*. [Online]

Available at: <https://www.fitchsolutions.com/corporates/metals-mining/global-iron-ore-mining-outlook-17-05-2019>  
[Accessed on 5 December 2020].

Fleschen, D., 2018. *A possible future of steelmaking: Hisarna*. [Online]

Available at: <https://www.market-steel.com/news-details/a-possible-future-of-steelmaking-hisarna.html>  
[Accessed on 18 July 2020].

Flournoy, B., 2018. *How does an Electric ARC Furnace Work*. [Online]

Available at: <https://www.hunker.com/12608288/how-does-an-electric-arc-furnace-work>  
[Accessed on 21 July 2020].

Forsmo, S., Apelqvist, A., Bjorkman, B. & Samskog, P.-O., 2006. *Binding mechanisms in wet iron ore green pellets with a bentonite binder*. [Online]

Available at: <https://www.sciencedirect.com/science/article/pii/S003259100600338X>  
[Accessed on 14 June 2020].

Foulke, E. G., 2008. *Guidance for the Identification and Control of Safety and Health Hazards in Metal Scrap Recycling*, US: OSHA Occupational Safety and Health Administration.

Friedman, H., 2020. *The mineral Magnetite*. [Online]

Available at: <https://www.minerals.net/mineral/magnetite.aspx>  
[Accessed on 17 May 2020].

Frohlichova, M. et al., 2018. The effect of concentrate/iron ore ratio change on agglomerate phase composition. *Metals*, 8(973), pp. 1-11.

Garside, M., 2020. *Distribution of global iron ore imports in 2019, by major country*. [Online]

Available at: <https://www.statista.com/statistics/270008/top-importing-countries-of-iron-ore/>  
[Accessed on 2 September 2020].

Gill, S.-J., 2009. *The nugget effect*. [Online]

Available at: [researchgate.net/publication/316878381](https://www.researchgate.net/publication/316878381) The nugget effect  
[Accessed on 14 June 2020].

Gleeson, D., 2019. *CERA blockchain certification program to track raw material sustainability credentials*. [Online]

Available at: <https://im-mining.com/2019/10/30/cera-blockchain-certification-program-to-track-raw-material-sustainability-credentials/>  
[Accessed on 27 May 2020].

GovernmentofCanada, 2010. *Health Risks Associated with Use of Miracle Mineral Solution*. [Online]

Available at: <https://healthycanadians.gc.ca/recall-alert-rappel-avis/hc-sc/2010/13510a-eng.php>  
[Accessed on 13 August 2020].

Grewal, I., Lundt, M., Wong, D. & Tse, W., 2019. *Recent Developments in Preconcentration using Dense Media Separation*. [Online]

Available at: <https://labs.seprosystems.com/wp-content/uploads/2019/08/Recent-Developments-in-Preconcentration-Using-Dense-Media-Separation-2014.pdf>  
[Accessed on 8 December 2020].

Griffiths, H. & Bromley, M., 2009. *Air transport and destabilizing commodity flows*, Stockholm: SIPRI.

Gundewar, C., 2011. *Iron and Steel vision 2020*, Nagpur: Indian Bureau of Mines.

Gutzmer, J. & Beukes, N. J., 1999. *Geology, Iron and manganese ore deposits: mineralogy, geochemistry, and economic geology*. Rand Afrikaans University, South Africa: EOLSS.

- Gwin, P., 2014. The Ship-Breakers. *National Geographic*, May, Issue May.
- Haldar, S. K., 2013. *Mineral Exploration Principles and Applications*. Oxford: Elsevier.
- Haldar, S. K., 2018. Exploration Geochemistry. In: S. K. Haldar, red. *Mineral Exploration, Principles and Application*. Oxford: Elsevier, pp. 85-101.
- Hartman, H. L. & Mutmanský, J. M., 2002. *Introductory Mining Engineering*. Hoboken, New Jersey: John Wiley & Sons.
- Health and Safety Executive, 2014. *Health and Safety Executive Safe work in confined spaces*. 3rd red. London: Crown.
- Holmes, R. & Lu, L., 2015. Introduction: overview of the global iron ore industry. In: L. Lu, red. *Iron Ore*. Cambridge: Elsevier, pp. 1 - 42.
- Institute of Scrap Recycling Industries, 2020. *ISRI Scrap Specifications Circular*, Washington: ISRI.
- International Organization for Standardization, 2018. *ISO 45001 Occupational health and safety management systems — Requirements with guidance for use*, sl: ISO.
- International Standard Organisation, 2019. *Biological evaluation of medical devices - part 23: Tests for irritation*, Geneva: ISO.
- Investopedia, 2020. *How the Iron Ore Market Works*. [Online]  
Available at: <https://www.investopedia.com/articles/investing/030215/how-iron-ore-market-works-supply-market-share.asp>  
[Accessed on 21 May 2020].
- Jamasmie, C., 2019. *Europe-led global certification scheme for raw materials expected in 2020*. [Online]  
Available at: <https://www.mining.com/europe-led-global-certification-scheme-for-raw-materials-expected-in-2020/>  
[Accessed on 3 May 2020].
- Jankovic, A., 2015. Developments in iron ore comminution and classification technologies. In: L. Lu, red. *Iron Ore*. Cambridge: Elsevier Woodhead Publishing, pp. 251-282.
- JindalSteel, 2014. *Pellet Brochure*. [Online]  
Available at: [https://www.jindalsteelpower.com/product\\_broucher/Pellet\\_Brochure\\_AW\\_CTC.pdf](https://www.jindalsteelpower.com/product_broucher/Pellet_Brochure_AW_CTC.pdf)  
[Accessed on 8 June 2020].
- Joint Ore Reserves Committee, 2012. *The JORC Code*, Australia: AusIMM.
- Kadhe, D. et al., 2016. *Optimization of pelletization process for iron ore with high alumina by use of high silica fluxes*, Toranagallu: TATA Consultancy Services.
- Karhula, M., 2013. *The transport needs of the mining industry*, Helsinki: Finnish Transport Agency.
- Kaufman, W. W. & Ault, J. C., 2001. *Design of Surface Mine Haulage Roads - A Manual*, Pittsburgh: WMC Resources.
- Kenton, W., 2018. *Bre-X Minerals Ltd.*. [Online]  
Available at: <https://www.investopedia.com/terms/b/bre-x.asp>  
[Accessed on 26 August 2020].
- Kickler, K. & Franken, G., 2017. *Sustainability Schemes for Mineral Resources: A Comparative Overview*, Hannover: Federal Institute for Geosciences and Natural Resources.
- King, N., 2020. *Hematite*. [Online]  
Available at: <https://www.mindat.org/min-1856.html>  
[Accessed on 24 May 2020].
- Klossek, A., 2020. *EIT Raw Materials*. [Online]  
Available at: <https://eitrawmaterials.eu/cera-project-a-universal-standard-for-ethics-sustainability-and-environmental-impact/>  
[Accessed on 20 April 2020].
- Krewski, D. et al., 2007. Human health risk assessment for aluminium, aluminium oxide, and aluminium hydroxide.. *Journal of toxicology and environmental health Part B*, 11(10), pp. 1-269.

Labson, S., Gooday, P. & Manson, A., 1995. *China Steel, China's emerging steel industry and its impact on the world iron ore and steel market*, Canberra: ABARE Research Report 95.4.

LeBlanc, R., 2019. *An Introduction to Metal Recycling*. [Online]  
Available at: <https://www.thebalancesmb.com/an-introduction-to-metal-recycling-4057469>

Löf, A., Ericsson, M. & Löf, O., 2019. Iron Ore Market Review 2018. *Engineering and Mining Journal*, Volume 17, pp. 4 - 9.

Lottermoser, B. G., 2010. *Mine Wastes, Characterization, Treatment and Environmental Impacts*. 3rd ed. Townsville: Springer.

Lottermoser, B. G., 2011. Recycling, Reuse and rehabilitation of mine Wastes. *Elements*, December, Volume 7, pp. 405-410.

Lu, L., 2015. *Iron Ore: Mineralogy, Processing and Environmental Sustainability*. Collaboration: Elsevier Woodhead.

Lu, L. & Ishiyama, O., 2015. Iron ore Sintering. In: L. Lu, red. *Iron ore, Mineralogy, Processing and Environmental Sustainability*. Oxford: Elsevier Woodhead Publishing, pp. 395-433.

Lu, L., Pan, J. & Zhu, D., 2015. Quality requirements of iron ore for iron production. In: L. Lu, red. *Iron Ore*. Cambridge: Elsevier Woodhead Publishing, pp. 475-505.

Mabey, P. T., Li, W., Sundufu, A. J. & Lashari, A. H., 2020. Environmental Impacts: Local Perspectives of Selected Mining Edge Communities in Sierra Leone. *Sustainability*, 12(14), p. 5525.

Mackie, C., 2019. *Types of steel and how they are made*. [Online]  
Available at: <https://www.buildingsguide.com/blog/types-steel-and-how-they-are-made/>  
[Accessed on 9 June 2020].

Madias, J., 2014. Electric Furnace Steelmaking. In: S. Seetharaman, red. *Treatise on Process Metallurgy*. Buenos Aires: Elsevier, pp. 271-301.

Ma, M., 2012. *Froth Flotation of Iron Ores*, Clayton Victoria: Scientific & Academic Publishing.

Marks, D., 2017. *Recycling centers: Worker safety, Risks to watch for*. [Online]  
Available at: <https://bergmill.com/2017/06/13/top-5-health-safety-risks-faced-recycling-workers/>  
[Accessed on 3 September 2020].

Matinde, E., Ndlovu, S. & Simate, G. S., 2018. Mining and metallurgical wastes: a review of recycling and re-use practices. *The Journal of the Southern African Institute of Mining and Metallurgy*, Volume 118, pp. 825-844.

McCall, B., 2020. *Fairmined Gold vs. Recycled Gold: Which is More Ethical & Sustainable?*. [Online]  
Available at: <https://valleyrosetudio.com/blogs/journal/fairmined-gold-vs-recycled-gold-which-is-better>  
[Accessed on 10 October 2020].

McCarthy, P., 2017. *Feasibility studies for Mining Projects*. [Online]  
Available at: <https://amcconsultants.com/experience/feasibility-studies-for-mining-projects/>  
[Accessed on 18 July 2020].

Miller, B. G., 2005. The Effect of Coal Usage on Human Health and the Environment. In: B. G. Miller, red. *Coal Energy Systems 1st Edition*. sl:Elsevier, pp. 77-122.

Miller, K. A., Thompson, K. F., Johnston, P. & Santillo, D., 2018. *An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts and Knowledge Gaps*. [Online]  
Available at: <https://www.frontiersin.org/articles/10.3389/fmars.2017.00418/full>  
[Accessed on 3 August 2020].

Milsom, J., 2006. Geophysical Methods. In: M. K. W. A. M. E. Charles J. Moon, red. *Introduction to Mineral Exploration*. Malden; Oxford; Carlton: Blackwell Publishing, pp. 127-153.

Mindat, 2020. *Minnesotaite*. [Online]  
Available at: <https://www.mindat.org/min-2722.html>  
[Accessed on 10 July 2020].

- Mindat, 2020. *Stilpnomelane*. [Online]  
Available at: <https://www.mindat.org/min-3789.html>  
[Accessed on 16 August 2020].
- Mining Safety, 2020. *Vehicle Overloading*. [Online]  
Available at: <https://www.miningsafety.co.za/dynamiccontent/25/Overloading-of-Mining-Vehicles>  
[Accessed on 11 September 2020].
- Mining Technology, 2018. *Samarco dam Disaster: dealing with the fallout of a tragedy*. [Online]  
Available at: <https://www.mining-technology.com/mining-safety/samarco-dam-disaster-dealing-fallout-tragedy>  
[Accessed on 5 October 2020].
- Ministry of Mines, 2014. *Brazilian Mining Code - Licence Procedures*, Brussels: Frederico Bedran Oliveira.
- Moraes, S. d. & Ribeiro, T., 2018. Brazilian Iron Ore and Production of Pellets. *Mineral Processing and Extractive Metallurgy Review*, 40(1), pp. 16-23.
- Moraes, S. L. d., Lima, J. R. B. d. & Ribeiro, T. R., 2018. *Iron Ore Pelletizing Process: An Overview*. [Online]  
Available at: <https://www.intechopen.com/books/iron-ores-and-iron-oxide-materials/iron-ore-pelletizing-process-an-overview>  
[Accessed on 28 July 2020].
- Muwanguzi, A. J., Karasev, A. V., Byaruhanga, J. K. & Jonsson, P. G., 2012. *Characterisation of the Physical and Metallurgical Properties of Natural Iron Ore for Iron Production*, Stockholm; Kampala: ISRN Materials Science.
- Muwanguzi, A. J., Karasev, A. V., Byaruhanga, J. K. & Jonsson, P. G., 2012. *Characterization of Chemical Composition and Microstructure of Natural Iron Ore from Muko Deposits*, Stockholm: International Scholarly Research Network.
- Nakhaei, F. & Irannajad, M., 2017. Sulphur removal of iron ore tailings by flotation. *Journal of Dispersion Science and Technology*, 38(12), pp. 2-11.
- Nourali, H. & Osanloo, M., 2015. *Prediction of Essential Amount of Exploration Drilling in Primary Stage of Open Pit Mine Planning*, Tehran: Elsevier.
- NSW, 2019. *Common Ground Exploration*. [Online]  
Available at: [commonground.nsw.gov.au/#!/exploration-methods](http://commonground.nsw.gov.au/#!/exploration-methods)  
[Accessed on 27 May 2020].
- Nunes, R. A. et al., 2019. A decision-making method to assess the benefits of a semi-mobile in-pit crushing and conveying alternative during the early stages of a mining project. *International Engineering Journal*, 72(2), pp. 285-291.
- O'Brian, R., 2009. *Australia's Iron Ore Product Quality*, sl: Geoscience Australia.
- Occupational Safety and Health Administration, 2002. *Materials Handling and Storage 2236*, Boston: OSHA.
- Occupational Safety and Health Administration, 2019. *Crystalline Silica*. [Online]  
Available at:  
[https://www.osha.gov/dsg/topics/silicacrystalline/health\\_effects\\_silica.html#:~:text=Breathing%20in%20very%20small%20\(%22respirable,COPD\)%2C%20and%20kidney%20disease.\(Retrieved%20on%2018-8-2020\)](https://www.osha.gov/dsg/topics/silicacrystalline/health_effects_silica.html#:~:text=Breathing%20in%20very%20small%20(%22respirable,COPD)%2C%20and%20kidney%20disease.(Retrieved%20on%2018-8-2020))  
[Accessed on 23 August 2020].
- Occupational Safety and Health Administration, 2020. *Ventilation Hazard Recognition*. [Online]  
Available at: <https://www.osha.gov/ventilation/hazards>  
[Accessed on 14 August 2020].
- OccuSafe, 2015. *Health Hazards of Oxy-Acetylene Cutting & Welding*. [Online]  
Available at: <https://occusafeinc.com/newsletter/health-hazards-of-oxy-acetylene-cutting-welding-june-2015/#:~:text=Eye%20injuries%2C%20such%20as%20discomfort,e.g.%20slag%20and%20cutting%20sparks.-Retrieved%20on%2010-9-2020>  
[Accessed on 21 August 2020].
- Okvist, L. S., Zuo, G. & Ma, J., 2000. *Influence of Basic Fluxes on Slag Formation in A Blast Furnace Using LKAB Pellets*, Tunnsplat Sweden: LKAB.

- Organisation for Economic Co-operation and Development, 2005. *Glossary of Statistical Terms*. [Online]  
Available at: <https://stats.oecd.org/glossary/detail.asp?ID=2260#:~:text=OECD%20Statistics,converted%20into%20new%20iron%20products>.  
[Accessed on 5 November 2020].
- Organisation for Economic Co-operation and Development, 2018. *Global Material Resources Outlook to 2060, Economic drivers and environmental consequences*. [Online]  
Available at: <https://www.oecd.org/environment/waste/highlights-global-material-resources-outlook-to-2060.pdf>  
[Accessed on 7 September 2020].
- Oshokoya, P. & Naidoo, S., 2014. The relevance of surveying content in mining engineering education. *South African Journal of Geomatics*, 3(2), pp. Vol. 3, No. 2.
- Pain, D., Sanchez, A. & Meharg, A., 1998. The Donana ecological disaster: contamination of a world heritage estuarine marsh ecosystem with acidified pyrite mine waste. *Science of the Total Environment*, 222(1-2), pp. 45-54.
- Pattanaik, A. & Venugopal, R., 2018. *Investigation of Adsorption Mechanism of Reagents (Surfactants) System and its Applicability in Iron Ore Flotation - An Overview*, Dhandbad, India: Elsevier.
- Pereira, A. C. & Papini, R. M., 2015. Processes for phosphorus removal from iron ore - a review. *Revista Escola de Minas*, 68(3), pp. 331-335.
- PHPfamily, 2019. *PHP Family Ship Recycling*. [Online]  
Available at: <https://phpfamily.co/businesses/ship-recycling/>  
[Accessed on 29 October 2020].
- Pineiro-Chousa, J., Vizcaino-Gonzalez, M., Lopez-Cabarcos, M. A. & Romero-Castro, N., 2017. Managing Reputational Risk through Environmental Management and Reporting: An Options Theory Approach. *Sustainability*, 9(376), pp. 1 - 15.
- Pourjavad, E. & Shirouyehzad, H., 2013. Selecting maintenance strategy in mining industry by analytic network process and TOPSIS. *Industrial and Systems Engineering*, 15(2), pp. 171-192.
- PricewaterhouseCoopers, 2018. *Mine 2019 Resourcing the Future*. [Online]  
Available at: <https://www.pwc.com/mx/es/publicaciones/archivo/2019/06/20190604-pwc-mx-mine-report-2019.pdf>  
[Accessed on 7 May 2020].
- PubChem, 2020. *Manganese Dioxide*. [Online]  
Available at: <https://pubchem.ncbi.nlm.nih.gov/compound/14801>  
[Accessed on 27 August 2020].
- QueenslandUniversity, 2016. *Mining Methods and Equipment*. [Online]  
Available at: <https://www.mechmining.uq.edu.au/mining-methods-and-equipment>  
[Accessed on 9 December 2020].
- Rahimi, B., Sharifzadeh, M. & Feng, X.-T., 2020. Ground behaviour analysis, support system design and construction strategies in deep hard rock mining. *Journal of Rock Mechanics and Geotechnical Engineering*, 12(1), pp. 1-20.
- Ramanaidou, E. & Wells, M., 2014. Sedimentary Hosted Iron Ores. In: H. Holland & K. Turekian, red. *Treatise on Geochemistry. 2nd ed.*. Oxford: Elsevier, pp. 313 - 355.
- Recycling Industry Operating Standard, 2018. *About RIOS*. [Online]  
Available at: <http://www.rioscertification.org/about-rios>  
[Accessed on 26 October 2020].
- Reichl, C. & Schatz, M., 2019. *World Mining Data 2019*, Vienna: Minerals Production.
- Renay, D., 2003. *Overloading mining trucks affects production, safety and costs*. [Online]  
Available at: [https://www.miningweekly.com/article/overloading-mining-trucks-affects-production-safety-and-costs-2003-11-14/rep\\_id:3650#:~:text=The%20powertrain%20life%20is%20related,trucks%20in%20the%20market%20place.-](https://www.miningweekly.com/article/overloading-mining-trucks-affects-production-safety-and-costs-2003-11-14/rep_id:3650#:~:text=The%20powertrain%20life%20is%20related,trucks%20in%20the%20market%20place.-)  
Retrieved on 2-9-2020  
[Accessed on 30 August 2020].
- Revueita, M. B., 2018. *Mineral Resources*. Cham, Switzerland: Springer Nature.

Rinkesh, 2020. *Metal Recycling*. [Online]

Available at: <https://www.conserve-energy-future.com/recyclingmetal.php>

[Accessed on 23 August 2020].

Rodvalho, E., Passos, A. O., Tomi, G. d. & Tenorio, J. A. S., October 2019. Sequential glory hole approach as a new mining method for sustainable operations. *Journal of Materials Research and Technology*, 8(5), pp. 4788-4796.

Roonwal, G., 2018. *Mineral Exploration: Practical Application*. Singapore: Springer Nature.

Rotta, L. H. S. et al., 2020. The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil. *International Journal of Applied Earth Observation and Geoinformation*, Volume 90, pp. 102 - 119.

Rout, B. & Sidar, B., 2017. Hazard Identification, Risk Assessment, and Control Measures as an Effective Tool of Occupational Health Assessment of Hazardous Process in an Iron Ore Pelletizing Industry. *Indian Journal of Occupational & Environmental Medicine*, 21(2), pp. 56-76.

Rudyk, S., Fel'dman, E., Chernov, E. & Korobeinik, V., 1974. Effect of sulfur and phosphorus on the properties of steel 18B. *Metal Science Heat Treatment*, Volume 16, pp. 1056-1059.

S&PGlobal, 2020. *Specifications guide Iron ore*. [Online]

Available at: [https://www.spglobal.com/platts/plattscontent/\\_assets/\\_files/en/our-methodology/methodology-specifications/ironore.pdf](https://www.spglobal.com/platts/plattscontent/_assets/_files/en/our-methodology/methodology-specifications/ironore.pdf)

[Accessed on 3 July 2020].

Sanchez, L., Silva-Sanchez, S., Neri, A. & Souza, M. N. d., 2014. *Guide For Mine Closure Planning*, Brasilia: IBRAM - Brazilian Mining Association.

Seredkin, M., Zabolotsky, A. & Jeffress, G., 2016. In situ recovery, an alternative to conventional methods of mining: exploration, resource estimation, environmental issues, project evaluation and economics. *Ore Geology Reviews*, Volume 79, pp. 500-514.

Seyring, N. et al., 2015. *Assessment of separate collection schemes in the 28 capitals of the EU*, Brussels: European Commission.

Shine, B. & Wiener, R., 2019. *Recycling Industry Yearbook*, Washington D.C.: International Scrap Recycling Industry.

Silva, A. M. et al., 2009. *Overview of the long distance iron ore slurry pipeline from angelo ferrous Brazil*. Rio, Brazilian Petroleum, Gas and Biofuels Institute.

Singh, K. A., 2013. *Synthetic Chemicals used in Mining Operations: A Proposed Risk Management Framework*, London: Imperial College London.

Skinner, B. J., 2019. *Britannica: Iron deposits*. [Online]

Available at: <https://www.britannica.com/science/mineral-deposit/Iron-deposits>

[Accessed on 5 June 2020].

Smith, B., 2019. *A Guide to the Four Main Methods of Mining*. [Online]

Available at:

<https://www.azom.com/article.aspx?ArticleID=18547#:~:text=There%20are%20four%20main%20methods,to%20profitably%20extract%20the%20resource.>

[Accessed on 22 September 2020].

Soracchi, J.-M., 2020. *The Iron Ore Transportation Process*. [Online]

Available at: [https://usatruckloadshipping.com/the-iron-ore-transportation-process/#How is Iron Ore Transported to Processing Plants](https://usatruckloadshipping.com/the-iron-ore-transportation-process/#How%20is%20Iron%20Ore%20Transported%20to%20Processing%20Plants)

[Accessed on 12 13 2020].

Stahl, 2020. *Steel recycling: Old made new*. [Online]

Available at: <https://en.stahl-online.de/index.php/topics/energy-and-environment/recycling/>

[Accessed on 24 June 2020].



Statsenko, L. & Melkounian, N. S., 2014. Modelling Blending Process at Open-Pit Stockyards: A Norther Kazakhstan Mining Company Case Study. In: C. Drebenstedt & R. Singhal, red. *Mine Planning and Equipment Selection*. Cham: Springer, pp. 1017-1027.

Steel Recycling Institute, 2020. *Steel is the World's Most Recycled Material*. [Online]  
Available at: <https://www.steelsustainability.org/recycling>  
[Accessed on 11 November 2020].

Tang, C., Li, K., Ni, W. & Fan, D., 2019. Recovering Iron from Iron Ore Tailings and Preparing Concrete Composite Admixtures. *Minerals*, 15 April, 9(232), p. Nr 232.

TataSteel, 2020. *Recyclable and recycled*. [Online]  
Available at:  
<https://www.tatasteeleurope.com/en/sustainability/steel%E2%80%93for%E2%80%93a%E2%80%93sustainable%E2%80%93future/the-life-cycle-of-steel/recyclable-or-recycled>  
[Accessed on 14 July 2020].

TCO, 2020. *Conflict minerals used in IT products fund wars and drive human rights abuses*. [Online]  
Available at: [tcocertified.com/conflict-minerals/](https://tcocertified.com/conflict-minerals/)  
[Accessed on 11 September 2020].

ThermoFisher, 2020. *Safety Data Sheet Pyrite*. [Online]  
Available at:  
<https://www.fishersci.com/store/msds?partNumber=AA4263303&productDescription=PYRITE+NATRLLY+OCCURRNG+MIN+1G&vendorId=VN00024248&countryCode=US&language=en>  
[Accessed on 17 August 2020].

Thompson, A. R. H., 2015. *Sacred Mountains: A Christian Ethical Approach to Mountaintop Removal*. 1st red. Lexington: The University Press of Kentucky.

Topf, A., 2016. *Canadian rare earths mine to transport ore using airships*. [Online]  
Available at: <https://www.mining.com/canadian-rare-earths-mine-transport-ore-using-airships/>  
[Accessed on 7 December 2020].

Tuck, C. A., Xun, S. & Singerling, S. A., 2017. Global iron ore production data, clarification of reporting from the USGS. *Mining Engineering*, February, Volume February, pp. 20-23.

United Nations, 2007. *Industrial Development for the 21st Century: Sustainable Development Perspectives*, New York: United Nations.

United Nations, 2011. *Recycling Rates of Metals: A status Report*, sl: UNEP & International Resource Panel.

United Nations, 2019. *A New Circular Vision for Electronics*, Geneva: World Economic Forum.

United Nations, 2020. *Review of Maritime Transport 2020*, New York: United Nations Conference on Trade and Development.

United Nations, 2020. *United Nations Development Goals*. [Online]  
Available at: <https://sustainabledevelopment.un.org/?menu=1300>  
[Accessed on 6 May 2020].

United States Geological Survey, 2004. *Introduction to Geological Mapping*. [Online]  
Available at: [https://www.usgs.gov/core-science-systems/national-cooperative-geologic-mapping-program/science/introduction-geologic?qt-science\\_center\\_objects=0#qt-science\\_center\\_objects](https://www.usgs.gov/core-science-systems/national-cooperative-geologic-mapping-program/science/introduction-geologic?qt-science_center_objects=0#qt-science_center_objects)  
[Accessed on 22 September 2020].

United States Geological Survey, 2020. *Iron and Steel Scrap*, U.S.: USGS.

United States Geological Survey, 2020. *Iron Ore Statistics and information*. [Online]  
Available at: <https://www.usgs.gov/centers/nmic/iron-ore-statistics-and-information>  
[Accessed on 19 May 2020].

- United States Geological Survey, 2020. *Mineral Commodities Summary*. [Online]  
Available at: <https://www.usgs.gov/centers/nmic/mineral-commodity-summaries>  
[Accessed on 23 May 2020].
- Valdes-Dapena, M., 2019. *Metal Recycling: will digitalisation solve key industry challenges?*. [Online]  
Available at: <https://en.amcsgroup.nl/newsroom/blog/metal-recycling-will-digitalisation-solve-key-industry-challenges/>  
[Accessed on 8 December 2020].
- Vidal, J., 2017. *'This is the world's cheapest place to scrap ships' - but in Chittagong, it's people who pay the price*. [Online]  
Available at: <https://www.theguardian.com/global-development/2017/dec/02/chittagong-shipbreaking-yards-legal-fight>  
[Accessed on 6 October 2020].
- Wang, P., Li, Q. & Li, C.-F., 2014. Hydrocarbon and Mineral Resources. In: *Earth and Life Processes Discovered from Subseafloor Environments 1st edition*. Amsterdam: Elsevier.
- Weisgerber, G. & Willies, L., 2000. *The Use of Fire in Prehistoric and Ancient Mining : Firesetting*. [Online]  
Available at: [https://www.persee.fr/doc/paleo\\_0153-9345\\_2000\\_num\\_26\\_2\\_4715](https://www.persee.fr/doc/paleo_0153-9345_2000_num_26_2_4715)  
[Accessed on 10 August 2020].
- Whateley, M. K. & Scott, B. C., 2006. Evaluation Techniques. In: C. Moon, red. *Introduction to Mineral Exploration*. Malden; Oxford; Carlton: Blackwell Publishing, pp. 199 - 252.
- World Health Organization, 2020. *World Health Organization*. [Online]  
Available at: <https://www.who.int/>  
[Accessed on 4 September 2020].
- WorldSteel Association, 2019. *World steel in figures 2019*, Brussels: Worldsteel association.
- WorldSteel Association, 2020. *Life Cycle Thinking*. [Online]  
Available at: <https://www.worldsteel.org/steel-by-topic/life-cycle-thinking.html>  
[Accessed on 15 November 2020].
- WorldSteel, 2020. *WorldSteel Association Steel Recycling*. [Online]  
Available at: <https://www.worldsteel.org/steel-by-topic/sustainability/materiality-assessment/recycling.html>  
[Accessed on 10 November 2020].
- Wu, R., 2012. *Iron Ore Resources and Supply in China: Current Situation and Prospect Forecast*. [Online]  
Available at:  
<https://www.metalbulletin.com/events/download.ashx/document/speaker/6519/a0ID000000X0jOEMAZ/Presentation#:~:text=In%20western%20China's%20Xinjiang%2C%20the,of%20over%201.5%20billion%20tons.&text=All%20these%20regions%20have%20a,easy%20for%20mining%20and%2>  
[Accessed on 25 September 2020].
- Wu, Z. H., Hu, Y. J. & Lee, D. J., 2010. Dewatering and Drying in Mineral Processing Industry: Potential for Innovation. *Drying Technology*, 28(7), pp. 834-842.
- Xiong, D., Lu, L. & Holmes, R., 2015. Developments in the physical separation of iron ore: magnetic separation. In: L. Lu, red. *Iron Ore*. sl:Elsevier, pp. 285 - 286.
- Yalcintas, M., 2017. *Corporate Social Responsibility as a Differentiation Tool to Achieve Competitive Advantage; Cases from Turkish Private Sector*. New York, Institute of Research Engineers and Doctors, USA.
- Yang, Y., Raipala, K. & Holappa, L., 2014. Ironmaking. In: S. Seetharaman, red. *Treatise on Proces Metallurgy*. Oxford: Elsevier, pp. 2 - 88.
- YenaEngineering, 2019. *Coating Methods for Metal Surfaces*. [Online]  
Available at: <https://yenaengineering.nl/coating-methods-for-metal-surfaces/>  
[Accessed on 16 May 2020].
- Zhang, M., Kecojevic, V. & Komljenovic, D., 2014. Investigation of haul truck-related fatal accidents in surface mining using fault tree analysis. *Safety Science*, Volume 65, pp. 106-117.