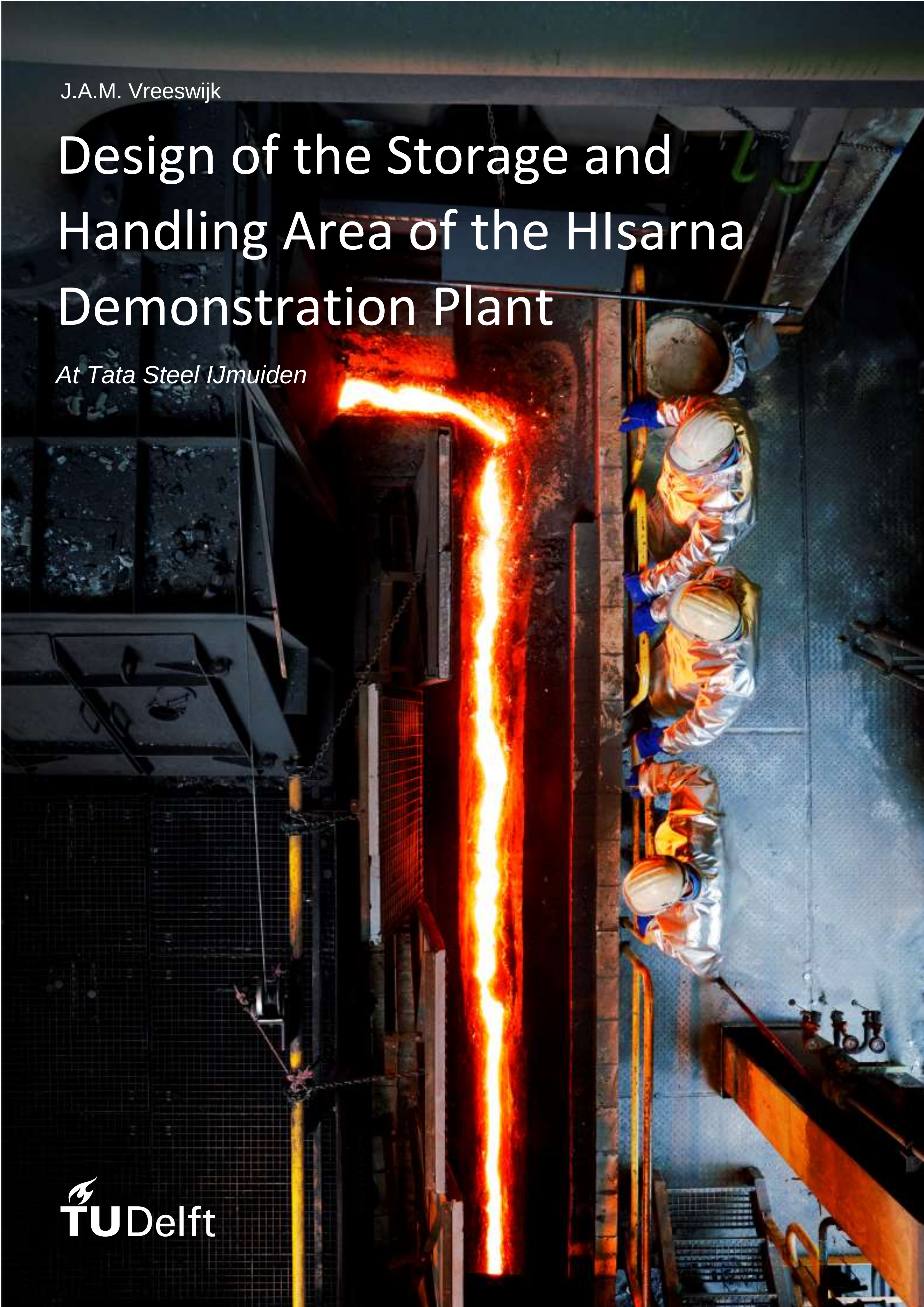
J.A.M. Vreeswijk

Design of the Storage and Handling Area of the HIsarna Demonstration Plant

At Tata Steel IJmuiden



TU Delft

Design of the Storage and Handling Area of the HIsarna Demonstration Plant

At Tata Steel IJmuiden

By

J.A.M. Vreeswijk

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TU Delft

Acknowledgments

This thesis forms part of my graduation project as a Master of Science in the field of Transport Engineering and Logistics at the Delft University of Technology. The subject of my research has been the design of the storage and handling area of the future HIsarna demonstration plant at Tata Steel IJmuiden. I was particularly interested because of the challenge of finding a logistic solution and at the same to contribute to a more sustainable way of ironmaking.

First of all, I would like to thank Tata Steel for allowing me the opportunity to conduct this research at their premises. I am very thankful for being accepted as a member of the HIsarna and R&D teams. Especially, I am indebted to my supervisors at Tata Steel, Johan van Boggelen and Maarten Ouwehand, for their assistance during this project. Furthermore, I would like to thank Hans Hage, Pieter Broersen and Koen Meijer for their additional support.

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Jorien Vreeswijk
Delft, May 2018

Abstract

Currently, Tata Steel IJmuiden is developing a new ironmaking process, called HIsarna. This technique will result in a significant reduction of carbon emissions, allow for more flexible input requirements for materials, and lead to a reduction of processing costs as well. In 2010, Tata Steel IJmuiden built a pilot plant to test and develop the technology of HIsarna. The next step is an industrial scale installation: the HIsarna demonstration plant. The design of the storage and handling area of this new plant is the subject of this research. At this area, the materials are stored and pre-processed before they will be injected into HIsarna.

Thus far, Tata Steel has been working on the first design phase of the demonstration plant. Nevertheless, the design of the storage and handling area is missing. Consequently, the required quantities and necessary pre-processing steps of materials are unknown. Moreover, the existing storage and handling area at the HIsarna pilot plant cannot directly be used for the demonstration plant, because the new plant must meet HIsarna's annual capacity requirements of around one million mt, be able to process iron-rich waste materials (also called reverts), and comply with HIsarna's green ambitions.

First, an analysis of materials is performed to establish the suitable materials and their properties for processing at the HIsarna demonstration plant. This analysis is essential to identify how these properties may affect the design of the storage and handling area. Second, the storage and handling area of the HIsarna pilot plant is analysed, particularly to identify the necessary processing steps and potential future bottlenecks of the HIsarna demonstration plant. Next, a design of the storage and handling area is created by using multi-criteria analyses and information obtained from literature. A simulation model, created in Simio® software and verified using several techniques, is used to examine the performance of the design, but also to investigate the affecting parameters; these are found by performing a fractional factorial design. Based on these results, optimal parameter settings are found to optimise the design.

According to analyses performed, the suitable materials for HIsarna (besides the standard materials such as iron ore and coal) are by-products of the blast furnaces and the oxy steel plant: BF sludge, currently produced BOF sludge and historic BOF sludge. These materials are particularly interesting because of the high levels of iron, carbon and zinc. Less positive are the high moisture level, the stickiness and the inhomogeneity of composition. These might result in problems during processing. The following design is created: iron ore and coal will be transported by conveyor belt to the storage and handling area, historic BOF sludge by truck,

and BF and currently produced BOF sludge by pipeline. Both the raw and handled materials will be stored in enclosed storage systems. Each material will be pre-processed at a dedicated handling line; all materials within the storage and handling area are transported by conveyor belt. The raw material storage of iron ore, coal and BOF sludge has a capacity for two days; and that of BF and currently produced BOF sludge for seven days. In addition, all handled material storages have a capacity of three days.

Based on the results of the fractional factorial design, three designs for the storage and handling area are proposed. Each of the designs has a different starting point. The second design option provides the highest reliability and is recommended if financial resources are not a restrictive factor. The third design is an interesting choice when fewer financial resources are available but still an adequate reliability is aimed at. Finally, the first design results in the lowest reliability. This option may only be suggested when funds are limited. In all cases, redundancy can be added to the storage and handling area, increasing the reliability and decreasing the required storage capacity. All designs fit the selected location at the Tata Steel site, IJmuiden.

Nomenclature

Glossary

BF sludge	By-product of the ironmaking process in the blast furnace, wet treatment of the off-gas, three different fractions can be distinguished, which are different in for example the zinc level. This thesis is focussed on zinc rich BF sludge, defined as BF sludge.
Blast furnace	The traditional ironmaking plant of Tata Steel where sinter or pallet (ore) and cokes (coal) are transformed into hot metal. The used abbreviation for the oxy steel plant in this thesis is BF.
BOF sludge	A by-product of the steelmaking process in the oxy steel plant.
Fractional factorial design	One of the types of design of experiments, it is an efficient tool to investigate the parameter effects on response variables.
Response variable	The variable output of an experiment about which the researcher is asking for, it responds to other factors being studied. Another commonly used term is a key performance indicator.
Flux	Additional material that are used to control the slag composition and the ironmaking process; typical flux materials are limestone, dolomite and bauxite.
Reverts	The material residue separated in the preparation of various products. At Tata Steel these materials are also called iron rich waste materials, examples are BF sludge, historic BOF sludge and currently produced BOF sludge.
HIsarna	The new ironmaking process at Tata Steel IJmuiden.

Abbreviations

BF	Blast furnace
MCA	Multi-criteria analysis
BOF	Basic oxygen furnace
BoD	Basic of design
OEM	Original equipment manufacturer, such as the automobile industry
MTBF	Mean time between failure
MTTR	Mean time to repair (a failure)
mt	Metric ton

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Chapter 1
Introduction

The subject of this master thesis is the design of the storage and handling area for the HIsarna demonstration plant at Tata Steel, IJmuiden. HIsarna (the name derives from “Isarna”, the ancient Celtic word for iron, and “HIsmelt”, the name of the melting vessel) is a new ironmaking process where iron ore and coal could almost be directly used to produce hot metal, resulting in a significant reduction of Tata Steel’s carbon footprint. Tata Steel has performed several tests with a pilot plant to prove the technique of HIsarna. The next step is to design and establish a HIsarna plant on an industrial scale: the HIsarna demonstration plant.

First, this introduction will provide the background information about Tata Steel and HIsarna in paragraph 1-1. Next, in paragraph 1-2, the problem definition will be presented. The objective of the research is elaborated upon in paragraph 1-3; this includes the formulation of the main question and the sub-questions derived from it. Then, the boundaries of the research will be set in paragraph 1-4. Finally, paragraph 1-5 describes the methodology used during in this research.

Figure 1-1: Tata Steel IJmuiden

1-1 Background

1-1-1 Tata Steel IJmuiden

Tata Steel IJmuiden, formerly Corus BV and Koninklijke Hoogovens, produces high-quality strip steel for various customers, such as the packaging, automotive and construction industries. It is part of Tata Steel Europe and its parent company Tata Group, India. The integrated steelmaking site of Tata Steel IJmuiden is shown in Figure 1-1 and produces seven-million mt (metric ton) steel annually. It is approximately 750 hectares stretches across three municipalities: Beverwijk, Heemskerk and Velsen Noord. Figure 1-2 shows the complete steelmaking process at Tata Steel IJmuiden. It includes the sinter and cokes plants, blast furnaces, the oxygen steel plant, (hot and cold) rolling mills, and the casting and coating departments.

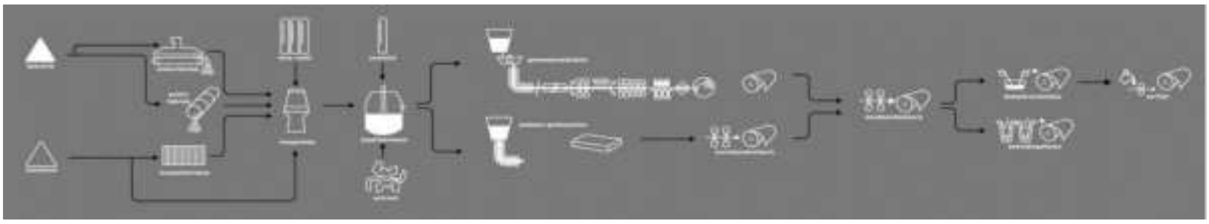

Figure 1-2: Complete production process at Tata Steel IJmuiden [1]

1-1-2 HIsarna

Currently, Tata Steel IJmuiden is using traditional blast furnaces to produce hot metal. For this manner of ironmaking, raw materials (mainly iron ore and coal) need to be pre-processed, as shown in Figure 1-3. The preparatory steps are the agglomeration of iron ores into sinter and pellets, and the carbonization of coal into cokes. The carbon emissions from these processes are significant [2]. At this point, Tata Steel IJmuiden contributes to around 7% of the national CO_2 emissions [3]. In order to comply with the latest climate agreements, the aim of Tata Steel is to reduce its carbon footprint by at least 50% in 2050 [3]. HIsarna is one of the technologies to achieve this significant reduction. It is an alternative ironmaking process, developed by, among others, Tata Steel.

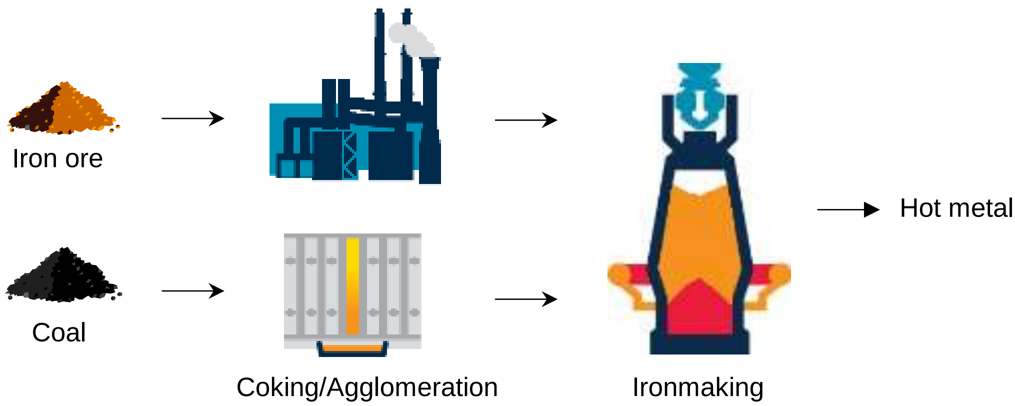

Figure 1-3: Traditional ironmaking process using blast furnaces [2]

HIsarna is a process where fine iron ore and non-coking coal can (almost) be directly used to produce hot metal. This means that agglomeration and carbonization steps in pellet and coke plants are no longer needed, as is shown in Figure 1-4. This results in a CO_2 and energy reduction of already 20% compared to the traditional blast furnace process [2]. Moreover, Tata Steel plans to recycle the CO_2 from the off-gas of HIsarna by implementing a carbon capture and storage (CCS) system [3]. This will lead to a total reduction of carbon emissions of 80% [3].

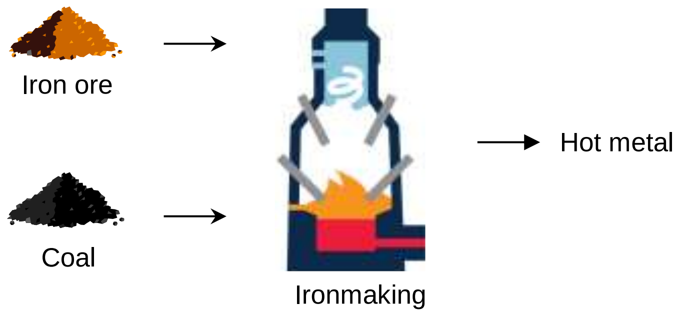

Figure 1-4: Alternative ironmaking process using HIsarna [2]

Besides sustainable improvement, HIsarna results in a reduction of processing costs as well [2]. For instance, this technology requires fewer processing steps, since a complete production stage can be omitted, namely the processes (formerly) taking place in the coking, sinter and pellet plants. Furthermore, HIsarna allows for more flexible input requirements for raw materials. Due to the high temperature involved, HIsarna is able to remove and concentrate impurities such as lead, zinc and cadmium from the off-gas. [3]. As a result, this method enables the production of hot metal from cheaper iron ore and coal. Moreover, HIsarna can be used to recycle waste material rich in iron.

As mentioned before, the raw materials do not need any agglomeration and coking steps. However, some pre-processing steps are still necessary to meet the input requirements of HIsarna. For instance, the raw materials need to be dried in order not to exceed the maximum allowable moisture level. In addition, it can be necessary to screen the raw materials on particle size. These steps take place at the raw material storage and pre-processing area, the focus of this research project.

In 2010, Tata Steel IJmuiden built a pilot plant to test and develop the technology of HIsarna [2]. Since 2011, several campaigns have been performed at the pilot plant to prove the success of HIsarna. If the test runs prove successful, HIsarna can enter the next stage: the design, construction and testing of an industrial scale installation, the HIsarna demonstration plant [2]. This plant should have an increased capacity of around one million mt hot metal per year, instead of a maximum capacity of approximately 60,000 mt per year of the pilot plant. This is planned for 2020.

1-2 Problem statement

As mentioned in paragraph 1-1-2, after successful completion of campaign F, Tata Steel IJmuiden will build an industrial scaled HIsarna plant to continue the study around HIsarna. Two problems become apparent: firstly, the incomplete design of both the storage and handling area and the HIsarna demonstration plant itself. Secondly, the storage and handling area of the HIsarna pilot plant will initially not be available, for the following reasons:

Insofar, Tata Steel has been working on the first design phase of the demonstration plant; the main requirements have been established, and a first concept of the plant has been developed by Tata Steel Consulting [4]. Nevertheless, the design and the arrangement of the storage and handling area are missing. Furthermore, data required for the design of the HIsarna demonstration plant are incomplete and much information is undetermined. For instance, Tata Steel has not completely established which additional materials will be processed at the demonstration plant. As a result, the required and available amounts and necessary pre-processing steps are as yet unknown. Also, it is unclear where the location of the HIsarna demonstration plant is planned, as well as the layout of the storage and handling area.

Moreover, the existing storage and handling area at the HIsarna pilot plant cannot directly be used for the demonstration plant, because the new plant must comply with three important requirements. First, the new plant should have an increased capacity compared to the pilot plant: a capacity of around one million mt hot metal per year, instead of an annual capacity of approximately 60,000 mt. Furthermore, the demonstration plant must be suitable for processing iron-rich waste materials (also called reverts), besides the standard raw materials such as iron ore and coal. This means that also the reverts need to be stored and pre-processed at the HIsarna demonstration plant, whereas these materials may have different material properties. Finally, the demonstration plant will be designed to be operative for the next 20 years. This will have a marked effect on environmental measures to be taken, as it may be expected that environmental requirements will become more and more strict.

1-3 Research objective

The goal of this research is to create a feasible design of the storage and handling area for the HIsarna demonstration plant. This area must meet several requirements. Firstly, the capacity of hot metal to be produced by the HIsarna demonstration plant should be increased compared to the pilot plant. Secondly, the industrial version of HIsarna must be able to produce hot metal from iron-rich waste materials, such as waste materials coming from other plants at Tata Steel IJmuiden. This means that the storage and handling area must be suitable for these materials as well. Furthermore, the pre-processing area must meet environmental requirements in order to offer true competition to the traditional way of producing hot metal by means of blast furnaces. Based on the above, the following main research question can be formulated:

What is the best design of the storage and handling area of the HIsarna demonstration plant to meet the capacity, material and environmental requirements?

Before being able to deal with this mean research question, the following sub-questions need to be answered:

1. Which reverts are most promising and suitable for use at the HIsarna demonstration plant and what are their properties?
2. How is the storage and handling area of the pilot plant arranged, which bottlenecks can be found and what alterations are required for the HIsarna demonstration plant?
3. How can each of the aspects (location, transport, layout and storage) of the storage and handling area be designed to meet the criteria?
4. How can the storage and handling area of the HIsarna demonstration plant be modelled and verified?
5. Which input parameters of the storage and handling area affect the response variables and what combination of parameters results in the best design for the storage and handling area?

1-4 Scope

Due to a reduced time-schedule for this research, as a result of the fact that no more than 35 ECTS points were allocated to the project, I was forced to limit the scope of my research. This limitation implies that this research will focus on the following aspects:

- The **design** of the storage and handling area, including the design aspects: *location*, *transport*, *layout* and *storage*. Note that the detailed design of the pre-processing area and equipment are not included.
- The design is created by using information obtained from the performed **material and system analyses**, literature and Tata Steels expertise. The scope of the storage and handling area and the materials are elaborated on more specifically below.
- The **evaluation and optimisation of the design**, by using a **simulation model**. Note that, at this point, the demonstration plant of HIsarna does not exist yet, which implies that the validation of the simulation model is kept outside the scope.

Storage and handling area

As mentioned above, this research focusses on the storage and handling area of the HIsarna demonstration plant. The scope of the process is depicted in Figure 1-5, and includes:

- The transport to the storage and handling area.
- Storage (of both raw and handled materials) and handling prior to transport and injection into HIsarna.

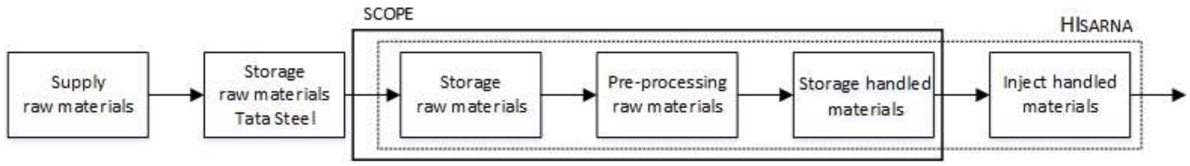

Figure 1-5: Schematic overview of the scope of the master assignment

Material boundaries

The goal of the HIsarna demonstration plant is to process both standard materials, like iron ore and coal, and iron-rich waste materials (also called reverts), such as by-products of Tata Steel. Regarding the standard materials, this study is focused on iron ore and coal. More materials are not taken into consideration. Moreover, the scope of the reverts is also narrowed down, since the materials that can be found worldwide fit to be used at HIsarna, are too numerous to deal with. On the one hand, this research focuses on materials that can be collected from the Tata Steel site at IJmuiden, on the other hand on materials that close the zinc cycle of Tata Steel.

1-5 Methodology and thesis outline

1-5-1 Methodology

The methodology used is listed in Figure 1-6. The blocks at the left of the graph show the steps to be taken in order to arrive at a feasible design, the blocks at the right indicate the resources to be used for each step.

First, an analysis of raw materials is made to establish which materials are suitable for processing at HIsarna. This is done by using internal reports and results of analyses already made at Tata Steel, site viewing and staff expertise. This analysis is essential to identify the properties of the materials, both in quality and quantity, and how these properties may affect the design of the storage and handling area.

Second, the current system, in this case the existing storage and handling area of the HIsarna pilot plant, is analysed. This analysis includes the process flow, characteristics and bottlenecks found at this area. The necessary information is obtained by interviewing staff, site viewing and using internal reports of Tata Steel. By using the information thus obtained, the requirements of the HIsarna demonstration plant can be defined, and the necessary processing steps can be determined. In addition, potential future bottlenecks can be identified.

Subsequently, a design for the storage and handling area of the demonstration plant can be created by using the information of both analyses. The design of this area is divided into the following four design aspects: *location*, *layout*, *transport* and *storage*. For each of these aspects the best possible solutions are identified by using information obtained from literature and expertise of Tata Steel. The best alternatives are selected by means of multicriteria analyses (MCA). Except for the *storage* part, this selection is based on literature.

The performance of the design thus created is studied by using a simulation model of the storage and handling area. In addition, a fractional factorial design is performed to investigate the affecting parameters, which result in optimal parameter settings for the design of the storage and handling area. Furthermore, the feasibility of the location is studied, in order to check if the design fits the selected location at the Tata Steel site, IJmuiden.

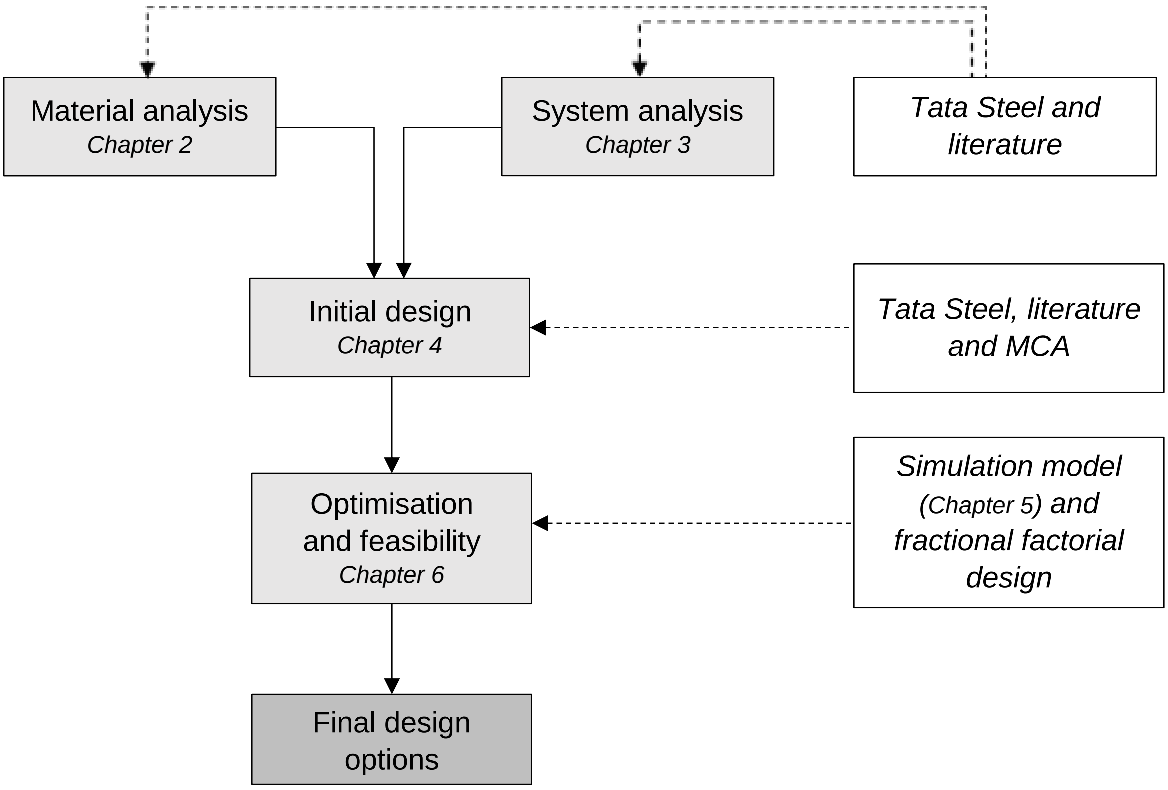

Figure 1-6: Methodology master thesis

1-5-2 Thesis outline

This master thesis will provide the answer to the main research question, based on the answers to the sub-questions as defined in paragraph 1-3. Each of the following chapters covers one sub-question.

Subsequently, the materials to be processed at the HIsarna demonstration plant will be discussed in **Chapter 2**. First, the requirements for the processed materials will be presented in paragraph 2-1 (general, chemical and physical requirements). In this chapter, a description of the materials will be given, distinguishing between standard materials and reverts. These distinctions will be further elaborated upon in paragraphs 2-2 and 2-3, providing information as to the chemical and physical characteristics. Lastly, the second sub question will be answered in Paragraph 2-4.

Chapter 3 provides an analysis of the storage and handling area of HIsarna. First, paragraph 2-1 will deal with the storage and handling area at the HIsarna pilot plant. This includes the process flow, the characteristics and the bottlenecks identified. Next, the objective, requirements and bottlenecks of the storage and handling area at the HIsarna demonstration plant will be discussed in paragraph 3-2. Finally, paragraph 3-3 will give the answer to the first sub-question.

Next, in **Chapter 4** the design of the storage and handling area of the HIsarna demonstration plant will be presented. As mentioned earlier, the design of the storage and handling area is divided into four design aspects: *location*, *transport*, *layout* and *storage*. The *location* of the storage and handling area will be discussed in paragraph 4-2. This will include the various alternatives, the criteria that must be met and the selection of the best design option. Similarly, *transport* and *layout* will be dealt with in paragraphs 4-3 and 4-4 respectively. The design of the *storage* will be elaborated on in paragraph 4-5, including the pros and cons of either open or enclosed storage, the selection and the capacity required. Finally, paragraph 4-7 will provide the answer to the third sub-question.

In **Chapter 5** a description will be given of the simulation model of the storage and handling area of the demonstration plant. First, the conceptual model is elaborated in paragraph 5-1, including the objective of the model, the model content and the assumptions. Next, the results of entering the data of the conceptual model in Simio® software will be discussed in paragraph 5-2. This paragraph will also give a description of the software used, the simulation model applied and model verification. Lastly, the fourth sub-question will be answered in paragraph 5-3.

Subsequently, **Chapter 6** elaborates the performance and optimisation of the design of the storage and handling area. First, the methodology used will be discussed in paragraph 6-1, including among others the response and input parameters and an explanation of the fractional factorial design. The performance of the initial design as well as the affecting parameters will be studied in paragraph 6-2. Subsequently, three design options will be proposed in paragraph 6-3, which are based on the optimal parameter settings as found in paragraph 6-2. Moreover, several options for redundancy will be provided in paragraph 6-4. The feasibility of the location will be checked in paragraph 6-5. Finally, the last sub-question will be answered in paragraph 6-6.

Finally, the study to the design of the storage and handling area of the HIsarna demonstration plant will be concluded in **Chapter 7**, by answering the main research question. In addition, recommendations will be given for further research to the design of the storage and handling area.

Chapter 2

Material analysis

The materials required for traditional ironmaking are iron ore, coal and additional materials (also called flux), like limestone, dolomite and bauxite. Besides these standard materials, the technology of HIsarna can be used to process and recycle rich waste materials (in this thesis also referred to as reverts). In order to create a feasible design for the storage and handling area of the HIsarna demonstration plant, the materials required for HIsarna need to be identified. In addition, the suitable reverts must be selected and analysed.

First, this chapter discusses the materials required for the HIsarna demonstration plant, comprising both chemical and physical requirements (paragraph 2-1). Subsequently, the standard materials are described in more detail, providing information about the required amount and the chemical and physical characteristics of the materials discussed (paragraph 2-2). Similarly, the reverts are elaborated on (paragraph 2-3).

2-1 Requirements

This paragraph defines the requirements for the materials processed at the HIsarna demonstration plant. It is important to meet these requirements in order to achieve a successful iron production at HIsarna, since even a temporary shutdown will result in high costs. The requirements are divided into two parts: chemical and physical requirements, discussed in respectively paragraph 2-1-1 and 2-1-2.

Besides the actual requirements, in some instances preferences are defined for the selection of reverts. This has been done in consultation with employees of HIsarna. First, it is preferred to focus on processing by-products of Tata Steel IJmuiden itself. Mainly, these are materials that currently cannot be reused at the Tata Steel site or need expensive pre-processing outside the site before reuse. For instance, zinc-rich blast furnace sludge is currently landfilled below cost because of the high zinc content. It speaks for itself that Tata Steel will prefer to use these zinc-rich reverts, even more so since HIsarna can process these materials without a problem, thus closing the zinc cycle of Tata Steel and its customers (Appendix C). This will benefit the environment, and enhance profit and customer satisfaction. Another preference of Tata Steel is to select materials that result in the largest profit.

2-1-1 Chemical requirements

The chemical requirements of the materials mainly depend on the required chemical composition of hot metal and slag. Slag is a by-product of the ironmaking process, as depicted in Figure 2-1. It is important to keep the chemical composition and where possible also the size and distribution of particles as constant as possible to achieve a stable quality of hot metal. It must be noted that, besides the composition of materials, other aspects, such as the temperature and viscosity inside the reactor are significant as well, but these do not fall within the scope of this research.

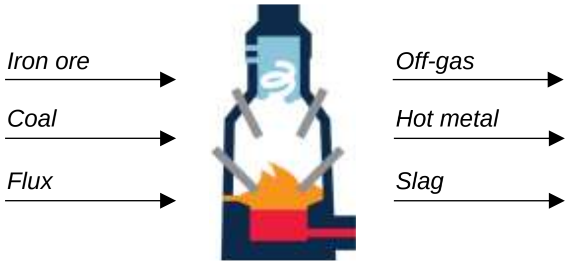

Figure 2-1: Schematic representation of the material flow of ironmaking

The following main elements are necessary to produce hot metal: iron and a reduction agent (for which carbon is used in IJmuiden). Hot metal consists for the largest part of iron and is mainly obtained from iron ores. Carbon ensures the supply of energy and is mainly gained from coal. Besides iron and carbon, the materials contain contaminants, like silicon, manganese and sulphur. These have a negative influence on the quality of hot metal [1], [5]. On the other hand, and in contrast to the traditional blast furnace, HIsarna is able to remove contaminants, like zinc, cadmium, and phosphor, from hot metal. This means that the restrictions for these materials do not apply to HIsarna. Even more important is the fact that HIsarna can be used to recycle these elements. In view of this, materials that are high in iron, carbon and contaminants such as zinc are preferred for the production at HIsarna.

A good slag quality is required to obtain a high quality of hot metal. In addition, the slag composition also has an effect on the stability of the ironmaking process. Slag consists of four main components: aluminium, silicon, calcium and magnesium. The ratio between these components is crucial. For this reason, great accuracy of the process and dosage of the materials is required at the storage and handling area of the HIsarna demonstration plant.

2-1-2 Physical requirements

The supply of materials into HIsarna is done using pneumatic transport. This results in the most important physical requirement: materials must be suitable for pneumatic injection. This is already true for the HIsarna pilot plant (see 3-1). Based on literature and the data obtained from the HIsarna pilot plant, the handled materials must meet the following physical characteristics [6]:

- The materials must be free-flowing.
- The particle size of the materials must be below two millimetres.
- The moisture content of the materials must be below two percent.

2-2 Standard materials

The materials required for traditional ironmaking are iron ore, coal and flux materials. The flux materials are used to control the slag composition and the process in the HIsarna plant; typical flux materials are limestone, dolomite and bauxite. But as mentioned in paragraph 1-4, the flux materials do not form part of this study. The materials iron ore and coal are dealt with in this paragraph, including both the chemical and physical properties of the materials.

2-2-1 Iron ore

Iron ore is one of the main materials required for the production of hot metal, because of high iron content. The typical composition of iron ore is listed in Table 2-1. These figures were obtained by chemical analysis performed by Tata Steel for a commonly used type of iron ore. Note that only the main components are represented. The physical properties of iron ore are given in Table 2-2.

Iron ore is transported to Tata Steel IJmuiden by dry bulk vessels, from suppliers in countries all over the world, such as Brazil, Australia and China. Iron ore is stored at the Tata Steel's general open storage area located near to IJmuiden harbour. The ironmaking process at the blast furnaces uses a blend consisting of several types of iron ore. Contrastingly, the HIsarna process will probably use only one type of ore. Currently, the pilot plant is using iron ore designated for the blast furnaces. This results in HIsarna being dependent on the material selection for the blast furnaces and thus is using materials that are more expensive than needed.

2-2-2 Coal

Besides iron ore, coal is also one of the main materials required for ironmaking. Table 2-1 provides the typical composition of coal. As can be seen in the table, coal is rich in carbon. This element is primarily needed as a reductant and secondarily to create the necessary high process temperature. That apart, outside the reactor the chemical reaction between carbon and oxygen can lead to spontaneous combustion of coal. This is a generally known fire hazard. Therefore, coal needs to be kept in low-oxygen storages. The physical properties of coal are listed in Table 2-2. Similar to iron ore, coal is also transported by dry bulk vessels and stored at the general storage area of Tata Steel IJmuiden.

Table 2-1: Chemical composition of standard materials [7]

Element		**Iron ore**	**Coal**
Symbol	**Description**	[*%*]	[*%*]
C	Carbon	0	82
Fe	Iron	62	6

Table 2-2: Typical physical properties of standard materials [4]

Property	**Iron ore**	**Coal**
Bulk density [mt/m^3]	2.2 ± 0.1	0.8 ± 0.1
Moisture content [*%*]	8	12
Handling losses [*%*]	4	4

2-3 Reverts

As mentioned before, and in contrast to the traditional blast furnace, HIsarna can be used to process and recycle iron-rich waste materials. This is because HIsarna is able to eliminate impurities from the process, such as zinc and silver. Tata Steel has a high preference to recycle these reverts, especially the zinc-rich materials; this makes it possible to close the zinc cycle of Tata Steel and its customers. The zinc cycle is discussed in more detail in Appendix C. The advantages (and disadvantages) of processing reverts are listed in Table 2-3. In addition, the potential economic benefits are provided in Table 2-4. As can be seen, the benefit for zinc oxide is quite significant.

Reverts can be found all over the world, for instance as part of tailings from the mining industry, jarosite from zinc refineries, and zinc-rich scrap from the automobile industry. But reverts can also be found at the site of Tata Steel IJmuiden itself, for instance as by-products of the steelmaking plant. As mentioned in Section 2-1, Tata Steel prefers to focus first on reverts that can be found at Tata Steel IJmuiden. These reverts are identified and all information required is collected. The reverts that will be processed at the HIsarna demonstration plant are the following: blast furnace sludge, historic oxy sludge and currently produced oxy sludge, and they are discussed in this chapter. These are the most interesting by-products at Tata Steel IJmuiden, because of the high zinc content and the withdrawal of these reverts from landfilling. The zinc-rich materials worldwide are discussed in Appendix C.

Table 2-3: (Dis)advantages of processing reverts

Advantages	**Disadvantages**
Recycle iron- and zinc- rich waste materials	Difficult to handle (high moisture content, sticky, inhomogeneous)
Closing the zinc cycle of Tata Steel	Disturb the production process
Lower material costs	
Develop a secondary source of zinc oxides	
Recycle zinc-rich scrap from automobile industry	

Table 2-4: Potential economic benefit for each element [8]

Material element	**Benefit** [*€/mt*]
Carbon	100
Iron	25
Iron oxide (FeO)	75
Calcium	22
Zinc (65 %)	200
Avoided landfilling	35

2-3-1 Currently produced BOF sludge

Currently produced BOF sludge is one of the by-products of the steelmaking process at the Basic Oxygen Furnace (BOF) steelmaking plant. Off-gas is released during the production of steel, containing polluted particles and gasses, like carbon monoxide (CO) and carbon dioxide (CO_2). In accordance with environmental regulations, the off-gas needs to be treated. This results in the following by-products: currently produced BOF sludge and gas, as shown in Figure 2-2. The processing steps of slurry into sludges are described in Figure 2-4.

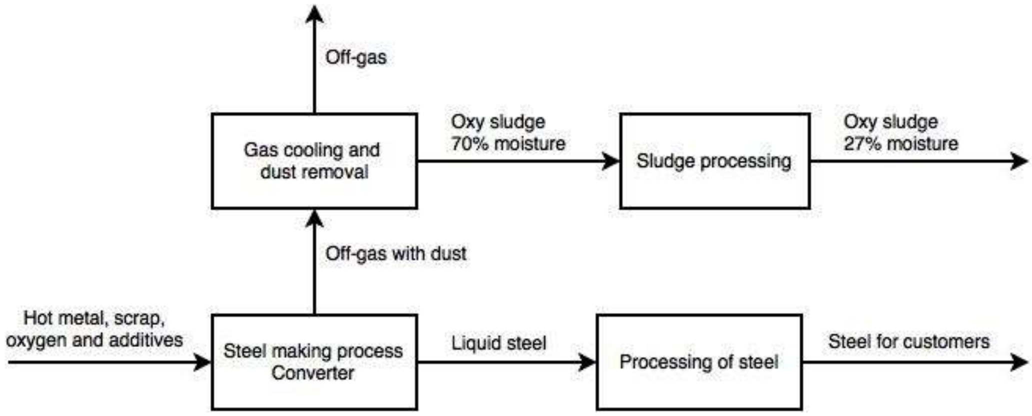

Figure 2-2: Off-gas flow basic oxy steel furnace

It is assumed that every year 83,000 mt of BOF sludge is produced. The typical composition of currently produced BOF sludge is listed in Table 2-5. The figures are based on a chemical analysis performed by Tata Steel. This revert is particularly interesting because of the high percentage of iron and calcium, in addition to zinc. The physical properties are provided in Table 2-6 and are based on an analysis by Tata Steel and site viewing. As can be seen, this moisture content of this revert is higher compared to the standard materials.

Currently produced BOF sludge is stored at an open storage area, as can be seen in Figure 2-3, close to the department where currently produced BOF slurry (with higher moisture content) is processed into BOF sludge (with lower moisture content). The process of handling slurries into sludges is explained in Figure 2-4. Currently, currently produced BOF sludge is reused at the sinter plant, since it contains an interesting percentage of iron and an acceptable level of impurities such as zinc. However, Tata Steel prefers to recycle this material at HIsarna, since this process can remove the zinc particles from the process.

Figure 2-3: Open storage of currently produced BOF sludge

Table 2-5: Composition of reverts in percentages [7]

Element [*%*]		**Currently produced BOF sludge**	**Historic BOF sludge**	**BF sludge**
Symbol	**Description**			
C	Carbon	0	0	37
Fe	Iron	65	44	22
Ca	Calcium	8	19	3
Zn	Zinc	0.4	3	6.9

Table 2-6: Physical properties of reverts [7]

Property	**Currently produced BOF sludge**	**Historic BOF sludge**	**BF sludge**
Bulk density [mt/m^3]	1800	1700	1800
Moisture content [*%*]	24	12	46
Handling losses [*%*]	2	4	2
Other properties	Sticky	Sticky, inhomogeneous	Very sticky

Table 2-7: Available amount of reverts per year

[redacted]

Table 2-8: (Dis)advantages reverts

Material	**Advantages**	**Disadvantages**
Currently produced BOF sludge	High iron content	High moisture content
	High zinc content	Sticky
Historic BOF sludge	High iron content	Flammability
	High calcium content	High moisture content
		Inhomogeneous
		Sticky
BF sludge	High zinc content	Very high moisture content
	High carbon content	Very sticky
		Flammability

Processing slurries into sludges at Tata Steel IJmuiden

Slurries from the blast furnace and oxygen steel plant are processed into sludges by using the following resources: clarifiers, cyclones, and a slurry filter press. Between these steps, the slurries are transported by pipeline. After the slurry filter press, the reverts are called sludges. This is done by means of waste materials BF and currently produced BOF sludge.

Figure 2-4: Processing slurries into sludges

2-3-2 Historic BOF sludge

On the site of Tata Steel IJmuiden, a stockpile of around 1.2 million mt historic BOF sludge is available (also known as historic oxy sludge, abbreviated as HOKS). A part of the stockpile is shown in Figure 2-5. This material is a by-product of the steelmaking plant and has been stored over a period of 40 years. Since historic BOF sludge is stored over a long period of time and the process at the oxy plant has changed during the years, this material is inhomogeneous. For instance, the historic oxy sludge contains a high variation in zinc content; it varies between 0.15 and 6.0%. In addition, the BOF sludge has agglomerated in time, as shown in Figure 2-6 [9]. The typical composition of historic BOF sludge and the physical properties are provided in Table 2-5 and Table 2-6.

Currently, this material is not suitable for recycling at Tata Steel because of the high content of zinc. Besides, due to the zinc content, this material needs to be stored under controlled conditions. The high contents of iron, zinc and calcium, however, make it an interesting material to process at HIsarna. According to Tata Steel, a reasonable expected period for processing the available IJmuiden stock is 20 years.

[redacted]

Figure 2-5: Part of the stockpile of historic BOF sludge

[redacted]

Figure 2-6: Agglomerated lumps of historic BOF sludge

2-3-3 BF sludge

Blast furnace sludge (BF sludge) is one of the by-products of the ironmaking process at the blast furnace. Similar to currently produced BOF sludge, BF sludge is a residual of the off-gas. Off-gases produce particles in various fractions, like: BF dust, zinc-poor sludge and zinc-rich sludge. Currently, BF dust and zinc-poor sludge are reused at the sinter plant. Zinc-rich sludge, on the other hand, is landfilled at considerable costs, because of the high proportion of zinc. This, however, makes it an interesting revert for processing at HIsarna. It is assumed that each year an amount of 26,000 mt is landfilled. From here on, the term ‘BF sludge’ will refer to the zinc-rich BF sludge.

The typical composition of BF sludge is represented in Table 2-5. As can be seen, this material contains an interesting percentage of zinc, carbon and iron particles. In addition, the environment will benefit, since this revert will no longer have to be part of the landfilling process. On the other hand, as can be seen in Figure 2-7, the moisture content of BF sludge is quite significant, which makes this revert very sticky. This might lead to problems during processing at the storage and handling area. The physical properties of BF sludge are provided in Table 2-6.

Figure 2-7: BF sludge

2-4 Conclusion

The first sub-question has been answered by this chapter:

Besides the standard materials such as iron ore and coal, the HIsarna demonstration plant will be used to process and recycle iron-rich waste materials (in this thesis also referred to as reverts). To date, Tata Steel has not established which materials these will be. Therefore, an analysis of materials was performed to establish which reverts are suitable for processing at the HIsarna demonstration plant. This analysis has been essential to identify the properties of the reverts, and how these properties affect the design of the storage and handling area.

First, the requirements for the reverts have been defined, both chemical and physical. Chemically, materials that are high in iron, coal, calcium and/or zinc contents are particularly interesting. Physically, it must be possible to process them by pneumatic injection at the end of the storage and handling area. This implies that the moisture content of the materials must be below 2% and particle size must be smaller than 2 mm. In addition to these requirements, it is preferred to focus on zinc-rich by-products of Tata Steel IJmuiden itself. This is beneficial for closing the zinc cycle, the satisfaction of customers, the environment and, last but not least, profit.

Second, the following reverts have been selected: currently produced BOF sludge, historic BOF sludge and BF sludge. Both the chemical and the physical properties of these materials are analysed, an overview is shown in Table 2-9. The materials are mainly interesting because of the high levels of iron, carbon, calcium and/or zinc. On the other hand, these reverts have some disadvantages, e.g. the high moisture level, sticky properties and inhomogeneity of composition, which might result in problems during processing. Moreover, the components of each revert may result in unforeseen chemical reactions when more than one reverts are used simultaneously.

Table 2-9: Overview material properties

Material	**Chemical properties**			**Physical properties**	
	Fe [%]	C [%]	Zn [%]	Moisture level [%]	Others
Iron ore	62	0	-	8	-
Coal	6	82	-	12	-
Historic BOF sludge	44	0	0.15 – 6	24	Sticky and inhomogeneous
Recent BOF sludge	65	0	0.4	12	Sticky
BF sludge	22	37	6.9	46	Sticky

Chapter 3

System analysis

The goal of the research is to form a feasible design for the storage and handling area of the HIsarna demonstration plant. Therefore, it is necessary to perform a system analysis, both of the existing HIsarna pilot plant and the projected demonstration plant. Information is obtained from internal reports of Tata Steel, interviewing employees and site viewing at the plant. As mentioned before, the storage and handling area is part of the HIsarna plant. An overview of the HIsarna pilot plant is shown in Figure 3-1, where nos. 12-14 indicate the site of the storage and handling area.

First, the storage and handling area of the HIsarna pilot plant is described in paragraph 3-1. This includes the process flow, characteristics and bottlenecks of the area. Subsequently, paragraph 3-2 elaborates on the storage and handling area of the HIsarna demonstration plant, focusing on the same points as for the pilot plant in paragraph 3-1. Finally, the answer on the first sub-question is given in paragraph 3-3.

Figure 3-1: 3D overview of the HIsarna pilot plant at Tata Steel IJmuiden [2]

3-1 Storage and handling area HIsarna pilot plant

Figure 3-2 gives a simplified representation of the storage and handling area of the pilot plant. This area consists of the following parts: a storage area for incoming materials, a mixing system, two pre-processing lines, one for iron ore and one for coal, and storage facilities for the handled materials. The pre-processing steps comprise screening, drying and milling. The main function of the storage and handling area is, on the one hand, storing materials to ensure an uninterrupted availability of materials, so as not to endanger the continuity of the process of making hot metal, on the other hand, transforming raw materials into pre-processed materials, in order to meet the input requirements of HIsarna. The materials include iron ore, coal and additional materials (also called flux), such as limestone and bauxite, as described in Chapter 2.

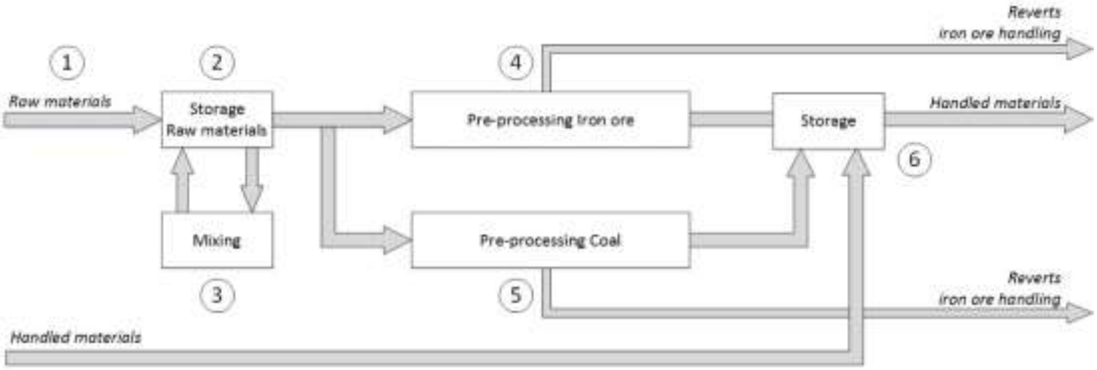

Figure 3-2: Main processes of the storage and handling area of the HIsarna pilot plant

As mentioned in paragraph 1-1, the HIsarna pilot plant is used to develop and validate the technology of HIsarna. At this point, the pilot plant cannot produce hot metal for uninterrupted periods of time, since errors occur frequently during the production runs. A long-lasting failure might result in a shutdown of HIsarna, meaning that the hot metal must be removed from the reactor. Such a shutdown will cost a lot of time (and money); in the worst case the hot metal may have to be removed manually, and valuable time is consumed in the process of cooling and heating the hot metal. Moreover, even more time is lost in between production runs, when the cause of the failure is investigated.

At the moment of writing, building the handling line for coal has not been completed. This means that coal can as yet not be handled at the storage and handling area of HIsarna at all. As a consequence, Tata Steel IJmuiden outsources this handling process to a company in Limburg (in the far south of the country), which involves considerable time loss and costs. In addition, the absence of a handling line for coal at the pilot plant makes it impossible to identify possible bottlenecks.

3-1-1 Process flow

Figure 3-3 represents the process flow of the storage and handling area of the HIsarna pilot plant, including all processes and activities inside the scope. The processes are elaborated on in more detail below.
Three different flows are distinguished: the logistic, the material and the resource flow. These are based on the seven flows of Lean Manufacturing, by Koskela [10]. The logistic flow encompasses all processes and activities that take place at the storage and handling area; the material flow covers all materials that are handled during the processes, and the resource flow deals with the resources required to process the materials.

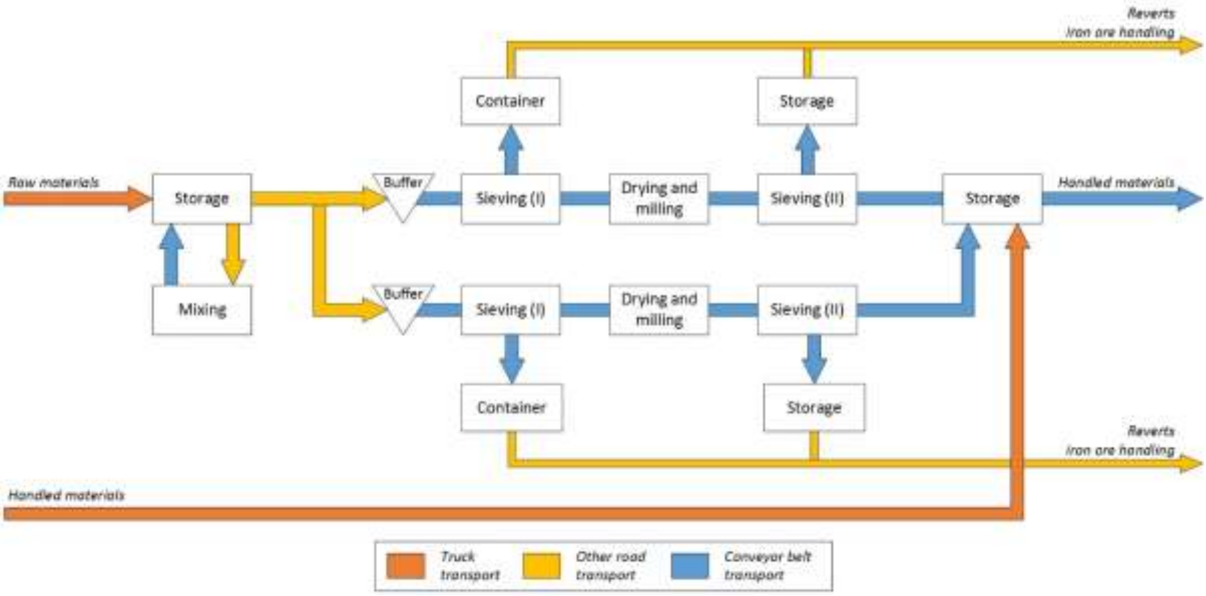

Figure 3-3: Process flow of the storage and handling area of the HIsarna pilot plant

Transport of raw materials

The raw materials processed at the HIsarna pilot plant are transported by truck, from the general raw material storage of Tata Steel IJmuiden to the raw material storage area of HIsarna. Once arrived at HIsarna, the truck unloads the raw materials at the dedicated storage area (described below). As stated in paragraph 3-1, there is no functioning handling line for coal. Therefore, at present trucks with (already) handled coal are transported directly to the storage area for processed materials. An overview of this process step is given in Table 3-1.

Table 3-1: Process flow – Transport of raw materials

Logistic flow	Transport materials from the supplier to the raw material storage area of the HIsarna pilot plant
Material flow	Input: Raw materials such as raw iron ore, coal and flux Output: Raw materials
Resource flow	Truck

Raw material storage

After transportation, the raw materials are stored at the raw material storage area of the HIsarna pilot plant, depicted in Figure 3-4. The following materials are stockpiled: raw iron ore, coal, and in addition flux materials. Each material is stored in one or two separated open storage areas, depending on the consumption of the material. As can be seen in Figure 3-4, the storages are separated by bricks and each material can be recognised by a colour code. The capacity of the raw material storage area is approximately one day of production. The arrangement of the storage area and the capacity of each storage are fixed. Referring to what has been mentioned earlier, obviously coal is at present not stored at this storage area. Table 3-2 provides an overview of the three process flows.

Table 3-2: Process flow – Storage of raw materials

Logistic flow	Store materials at the raw material storage area of the HIsarna pilot plant
Material flow	Input: Raw materials (raw iron ore, coal and flux) Output: Raw materials
Resource flow	Open storage areas, each material has a dedicated area (Figure 3-4)

Figure 3-4: Raw material storage

Mixing of materials

For ironmaking additional materials are required. Currently, these materials are pre-processed together with iron ore. For this, iron ore and flux need to be blended, which is done using a mixing system at the storage area of the HIsarna pilot plant. First, a shovel transports the materials to the mixing system; then the system blends these materials and transports the blend by conveyor belt to a designated storage area. An overview of the mixing process is presented in Table 3-3.

Table 3-3: Process flow – Mixing materials

Logistic flow	Mixing materials before entering pre-processing line
Material flow	Input: Raw iron ore and flux materials Output: Mixture of raw iron ore and flux materials
Resource flow	Shovel and mixing system (including conveyor belt)

Handling of iron ore

Handling iron ore involves the following activities: screening on contamination, drying, and screening on particle size. First, the raw materials are transported into the bunker by means of a shovel, to provide a buffer during processing. Then, the materials are transported to the sieve by a conveyor system; this sieve eliminates contamination and coarse particles from the material. This step is to prevent handling equipment to be damaged, for instance by iron scrap or a lost glove. Next, the materials are transported to the dryer. Subsequently, the dried materials are sieved to eliminate the particles with a particle size exceeding 2 mm. The result is handled iron ore that can be readily injected into HIsarna. These processing steps are summarised in Table 3-4 and Figure 3-5.

Table 3-4: Process flow – Handling of iron ore

Logistic flow	Handle iron ore, by performing the following activities: 1. Screening on contamination 2. Drying 3. Screening on contamination 4. Transport of materials between activities
Material flow	Input: Raw iron ore Output: Handled iron ore, reverts (see Figure 3-5)
Resource flow	Contamination sieve, tumble dryer, sieve and conveyor system. In addition, buffers between pre-processing steps.

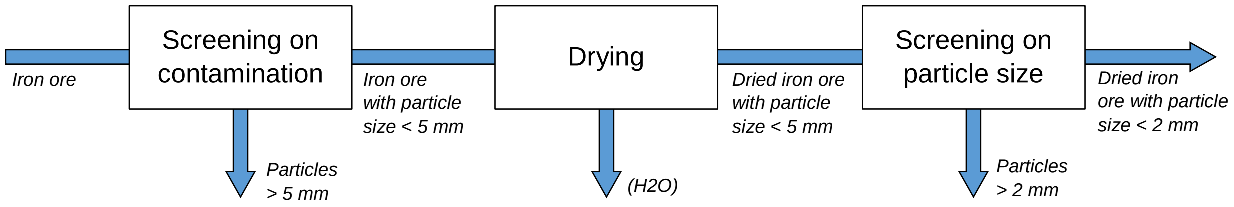

Figure 3-5: Schematic representation of pre-processing line iron-ore

Handling coal

Although there is at present no handling line for coal, the aim is to have this functional soon. To complete the current study, the handling line will be analysed to ascertain which steps are required for processing coal. The processing steps are almost similar to those for iron ore: grinding, sifting, drying and screening. It must be noted that the process steps grinding, sifting and drying all take place in the dryer. An overview of this process is given in Table 3-5 and Figure 3-6

Table 3-5: Process flow – Handling of coal (in future)

Logistic flow	Handle coal, by performing the following activities: 1. Screening on contamination 2. Grinding, sifting and drying 3. Screening on contamination 4. Transport of materials between activities
Material flow	Input: Raw coal Output: Handled coal and reverts
Resource flow	Bunker, contamination sieve, dryer, sieve and conveyor system.

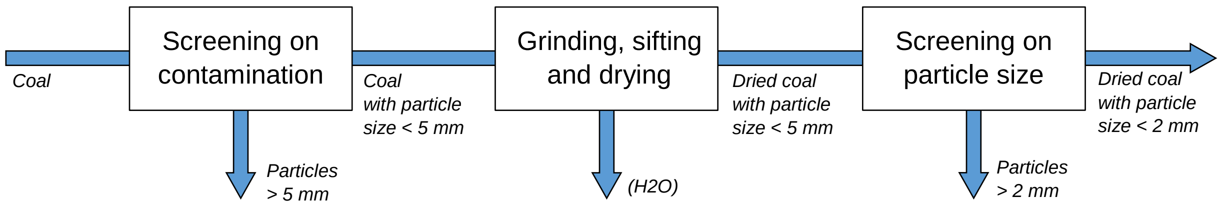

Figure 3-6: Schematic representation of pre-processing line coal

Handled material storage

After pre-processing the raw materials into handled materials, they are transported to the handled material storage. All materials are stored in one or two designated silos. The capacity of this storage covers approximately one day of production. Table 3-6 provides a summary of this process step.

Table 3-6: Process flow – Storage of handled materials

Logistic flow	Storage of handled materials
Material flow	Input: Handled materials Output: Handled materials
Resource flow	Enclosed storage systems; each material has a dedicated silo (or silos)

3-1-2 Characteristics

The main characteristics of the HIsarna pilot plant are listed in Table 3-7. As can be seen in the table, the maximum production capacity of the pilot plant is 60,000 mt of hot metal per year [2]. Comparing this to the blast furnaces of Tata Steel IJmuiden (HO-6 -the smallest furnace- produces 6,000 mt per day, HO-7 -the largest blast furnace- produces 14,000 mt per day) [1], the hot metal output of the HIsarna pilot plant per hour, can be produced, even by the smallest blast furnace, in a minute and a half only! Figure 3-7 shows a top view of the HIsarna pilot plant. Both the main operating parts and the dimensions of the pilot plant are indicated in this figure and listed in Table 3-8.

Table 3-7: Specifications of the HIsarna pilot plant [11]

[redacted]

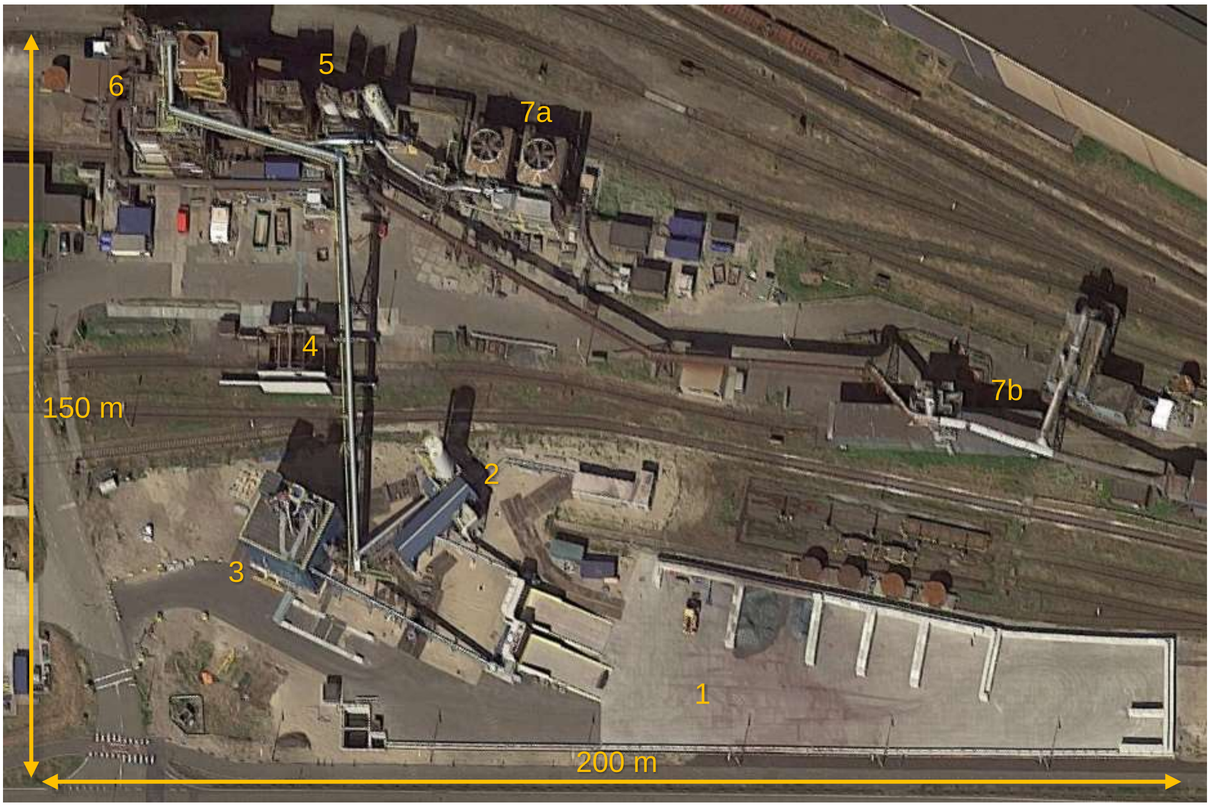

Figure 3-7: Top view of the (storage and handling area of the) HIsarna pilot plant [12]

Table 3-8: Main parts and dimensions of the HIsarna pilot plant [12]

	Part of storage and handling area and HIsarna	**Dimensions**
1	Raw material storage area	100 x 30 m
2	Ore handling line	5 x 20 m
3	Coal handling line	15 x 15 m
4	Transport to silos (before injection into HIsarna)	120 m
5	Silos for handled materials	5 x 15 m
6	HIsarna plant (reactor and cyclone)	20 x 20 m
7	Off-gas treatment; a. dust cyclone, b. secondary treatment	

3-1-3 Bottlenecks

A bottleneck in a system can limit the throughput of a complete system [13]. So, obviously, the reduction of bottlenecks in the storage and handling area will improve the production of hot metal in HIsarna. Bottlenecks are identified by interviewing employees, site viewing and by applying the theory of the seven types of waste established by Lean management. These include transport, inventory, motion, waiting, over-processing, over-production and defects (TIMWOOD) [14]. The main bottlenecks are discussed below.

Arrangement of the storage and handling area
The overall arrangement of the storage and handling area of the HIsarna pilot plant is impractical and inefficient. There are two main reasons for this. First, in order to reduce costs, the initial HIsarna pilot plant was built in an old desulfurization plant for the first campaign in 2000. During the past years, the plant has been extended for consecutive campaigns. This has resulted in an inefficient and illogical layout. The second reason is that the ground on which the pilot plant is located, has some inhibiting elements: for instance, as can be seen in Figure 3-7, the site of HIsarna is inconveniently divided by a train track.

Test phase (inconsistent process and incomplete design)
Another bottleneck is that the HIsarna pilot plant is still in the test phase; in practice, it operates pretty much campaign wise, as discussed in paragraph 3-1. The technique of the storage and handling line is validated by operating it for a day or a week, rather than having a prolonged period of continuous production. In addition, at this moment the handling line for coal is not ready for production. This means that any bottlenecks that may arise during the production at this handling line, cannot be considered for the design of the storage and handling area of the demonstration plant.

Impact on the environment
Several aspects of the storage and handling area have a negative influence on the environment. For instance, the raw materials are transported to the storage and handling line by truck. Transportation by truck leads to high handling losses, high fuel consumption and low efficiency (see paragraph **Error! Reference source not found.**). For shovels, the handling losses are even worse. Furthermore, the raw materials are stored in open stockpiles, which also causes environmental problems, such as dust, water and soil pollution (discussed in paragraph 0).

Storage capacity and redundancy
The storage of handled materials covers only a one-day production of hot metal. Since the technique of the handling lines is not completely proven, this might be a bottleneck for continuous production. Especially, since both handling lines do, at this point, not feature redundancy; the handling lines have no backup components. Consequently, if one system fails, the complete supply of iron ore or coal comes to a halt.

Process stability
During production tests at the HIsarna pilot plant, it has been observed that process stability inside the HIsarna plant is very important. Also, a stable process is required to obtain the desired quality of steel. Furthermore, instability may result in foam formation of materials inside the HIsarna plant, with possible hazardous consequences. Therefore, accuracy must be a leading criterion for the design of the storage and handling area of the demonstration plant.

3-2 Storage and handling area HIsarna demonstration plant

This paragraph investigates the process flow, the characteristics and bottlenecks of the storage and handling area of the HIsarna demonstration plant. This is required to create a feasible design.

3-2-1 Process flow

The process steps required for the storage and handling area of the demonstration plant are largely similar to those for the pilot plant, analysed in paragraph 3-1. Additional steps may be required if the material properties of reverts, as discussed in Chapter 2, are taken into consideration. For example, for materials containing large agglomerated particles, extra milling might be needed. Besides, the layout of the storage and handling area (paragraph 4-4) may also prompt extra required process steps. For instance, when multiple materials are to be processed at one handling line, mixing of materials is necessary. An overview of the required process steps for the storage and handling area of the HIsarna demonstration plant is provided in Table 3-9.

Table 3-9: Process steps storage and handling area HIsarna demonstration plant

Process step	**Explanation**
STANDARD STEPS	*STEPS BASED ON PARAGRAPH 3-1*
Transport	Required to transport materials (both standard materials and reverts) from the supplier to the storage and handling area.
Storage	Storing materials after transport to HIsarna. This is necessary to achieve a continuous input rate of materials and to deal with delays.
Handling materials	Handling of materials is essential to meet the input requirements of HIsarna for pneumatic injection and the production of hot metal. The following steps are required:
▪ *Contamination sieving*	Needed to remove undesired substances from the materials which can damage the handling equipment, for example a lost glove or iron scrap. In addition, this step eliminates large particles (> 5 mm).
▪ *Drying*	Necessary to decrease the moisture content of the materials to meet the required moisture level for pneumatic injection.
▪ *Sieving*	Required to eliminate particles exceeding the maximum allowable size for pneumatic injection.
▪ *Transport*	Needed to transport the materials inside the storage and handling area from one process step to another.
Storage	Storing materials after pre-processing. This is needed to ensure continuous injection into HIsarna. Thus, delays can be prevented, caused by variations in flowrates and shutdowns of handling equipment.
ADDITIONAL STEPS	*ADDITIONAL STEPS BASED ON CHAPTER 2 AND PARAGRAPH 4-4*
Mixing	Mixing of several materials into one blend. This is required if multiple materials are handled on the same processing line.
Milling	Needed in case of significant variations in particle size of the input materials.

3-2-2 Requirements and characteristics

Environmental issues

First of all, as a company, Tata Steel must adhere to environmental regulations. These are defined on different levels by, for instance European, national and local governments. The extent to which these regulations can be met, also depends on the location and process-type of a plant. Moreover, to achieve a competitive position and create a completely clean environment matching HIsarna, Tata Steel has the ambition to limit the following aspects as well: noise, dust, water and soil pollution. This implies that in the design of the storage and handling area of the HIsarna demonstration plant this must be taken into account. For instance, the feasibility of an enclosed storage needs to be investigated.

Reverts

Besides the standard materials that are processed at the blast furnaces and the HIsarna pilot plant, the HIsarna demonstration plant must also be fit to process reverts. As concluded earlier, these materials include BF sludge, currently produced BOF sludge and historic BOF sludge. The material characteristics as well as the chemical and physical properties of these materials were discussed in Chapter 2.

Capacity

As mentioned before, the HIsarna demonstration plant is expected to produce around one million mt hot metal per year. An overview of the characteristics required for the demonstration plant is given in Table 3-10, including the annual operation time and capacities of the plant. These characteristics follow the Basics of Design as defined by Tata Steel Consulting in India [4].

In addition, the amounts of material required to meet the demand of HIsarna, must be determined. The calculations are based on this demand, the chemical and physical properties of materials (Chapter 2) and the Basics of Design by Tata Steel Consulting in India. The calculation of the required amounts of input and output materials is provided in Appendix D, and summarised in Table 3-11. In addition, the assumed pre-processing times are presented in this table, the assumptions are particularly based on the moisture content of the materials.

Table 3-10: Characteristics demonstration plant [4]

[redacted]

Table 3-11: Required quantities and processing time of materials

[redacted]

[1] Losses due to pre-processing (oversize particles and moisture content) and handling losses

3-2-3 Bottlenecks

During the material and system analysis and a brainstorm with employees, the following bottlenecks for the storage and handling area of the demonstration plant emerged.

Reverts
The properties of reverts may lead to problems at HIsarna. This can be caused by the physical properties of these materials: the high moisture level, the stickiness and the inhomogeneity of material. The moisture content of the reverts is significantly higher than that of iron ore and coal. For instance, for BF sludge the difference between the maximum allowed moisture content and that of the revert is immense: 2% versus 47%. Besides, all reverts are sticky, especially BF sludge, which can cause problems during transport, storage and pre-processing. In addition, stickiness may lead to inaccuracy in the process. This might also occur as a consequence of inhomogeneous material. Finally, the combination of inaccurate processing and the difference in chemical compositions of these materials, can result in hazardous situations in the reactor, such as foaming.

Expansion of the demonstration plant
Another bottleneck may result from the wish for expansion of the HIsarna demonstration plant within the next few years. This may imply increasing the number of materials processed at HIsarna and/or an increase in the material flow. There are many more interesting iron rich waste materials available, for instance slag sand (a by-product of the oxy steel plant and Jarosite (a by-product of the zinc plant). A bottleneck could be if the layout and location of the demonstration plant do not allow for expansion.

Material supply
Next, insufficient material supply to both storages decrease the reliability of the HIsarna demonstration plant to the extent that it may result in a shutdown of the HIsarna plant. Insufficient material supply can be for a short or a long period of time. A short shutdown can be caused by, for example, a delayed truck; a long period of inactivity by, for instance, a broken (specific) part of the conveyor belt. Adequate storage capacities as well as redundancy can reduce the effect of such a bottleneck.

All historic BOF sludge is used
Finally, since the processing time of stored historic BOF sludge is estimated at 20 years, all this material will then have been used. This could be a future bottleneck for production of hot metal.

3-3 Conclusion

This chapter has provided an answer to the second sub-question:

How is the storage and handling area of the pilot plant arranged and which bottlenecks can be found? Furthermore, what changes are required for the HIsarna demonstration plant?

An analysis was made of the existing storage and handling area of the HIsarna pilot plant. By using the information thus obtained, the requirements of the HIsarna demonstration plant can be defined, and the necessary processing steps can be determined. In addition, potential future bottlenecks can be identified.

First, the system analysis of the storage and handling area of the HIsarna pilot plant was performed. The main processes are analysed and include: the supply of raw materials, storage of raw materials, pre-processing of raw materials into handled materials and storage of handled materials. The pre-processing area consists of two separated handling lines: one for iron ore and one for coal. Subsequently, the following bottlenecks were found at the current system: an inefficient arrangement of the storage and handling area, the pilot plant still being in its test phase, the plant not being complete, the process instability in the HIsarna plant, an inadequate storage capacity and no features for redundancy.

Second, a system analysis of the storage and handling area of the HIsarna demonstration plant was carried out. Based on the material analysis (performed in Chapter 2) and the system analysis of the pilot plant, the required process steps are defined. These are similar to the main processing steps of the HIsarna pilot plant. In addition, some possible extra processing steps were identified, including mixing and milling of materials. Whether these steps can be implemented, depends on the layout of the storage and handling line in combination with the properties of the reverts.
Next, the requirements and characteristics of the demonstration plant have been established. The storage and handling area must meet the capacity of the HIsarna demonstration plant and must be fit to process reverts. In addition, the storage and handling area must meet environmental regulations. Moreover, in order to achieve a competitive position and create a completely clean environment matching HIsarna, Tata Steel must limit the following aspects as well: noise, dust, water and soil pollution.
Finally, future bottlenecks were identified; these mainly include problems caused by physical and chemical properties of reverts, such as an inaccurate process, but also the future expansion of the plant and an inadequate material supply may create bottlenecks.

Chapter 4

Design of the storage and handling area

This chapter deals with the design of the storage and handling area of the HIsarna demonstration plant. There are four aspects to the design: location, transport, layout and storage.

First, the design methodology is discussed in paragraph 4-1, including among others a description of the multicriteria analysis and sensitivity analysis. Next, the four design aspects are detailed in paragraphs 4-2, 4-3, 4-4 and 0. These paragraphs describe the suitable options and select the best solution for each design aspect. An overview of the design is provided in paragraph 4-6. Finally, the third sub-question is answered in paragraph 4-7.

4-1 Design methodology

As stated above, there are four aspects to the design: location, transport, layout and storage. An overview of the used methodology per aspect is provided in Table 4-1. The design options are based on information and expertise of Tata Steel, literature and information obtained from the material and system analyses performed. As can be seen in Table 4-1, the designs for the location, transport and layout of the storage and handling line are selected using a multicriteria analysis. Additionally, for each of these aspects, a sensitivity analysis is carried out to identify the effect of changing the importance of the criteria. The mechanism of these two analytical methods are described in paragraphs 4-1-1 and 4-1-2 respectively. The selection process of the fourth aspect, storage, is based on information obtained from literature.

Table 4-1: Methodology selection design aspects

Design aspect	Options and criteria	Selection
Location	Tata Steel	Multicriteria analysis
Transport		
▪ To storage and handling area	Literature and Tata Steel	Multicriteria analysis
▪ Within storage and handling area	Literature and Tata Steel	Literature and Tata Steel
Layout	Material and current system analysis (Chapter 2 and 3)	Multicriteria analysis
Storage	Literature	Literature

4-1-1 Multicriteria analysis

A multicriteria analysis (MCA) is a decision-making framework to rank and compare option solutions. MCAs are used to select the best options for the design of the storage and handling area of the HIsarna demonstration plant. The MCA is applied to the following design aspects: the location, transport, and layout of the storage and handling area. Each option is compared to criteria points, which are defined for each design aspect.

First, the weight factors are determined according to Saaty's priority principle; this is done by pairwise comparison [15], [16]. For example, if a design criterion A is more important than design criterion B, the significance factor is assigned as a ratio of k which signifies k times more. The weights express the differences in importance between each design criterion. The weight factors are rated with absolute numbers (between 1-9) [15], the explanation of these numbers is given in Table 4-2. The ranking is based on the requirements of Tata Steel and information gained from the analysis of materials and the current system.

Table 4-2: Explanation of rating numbers [15]

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective.
3	Moderate importance	Experience and judgement slightly favour one criterion over another.
5	Strong importance	Experience and judgement strongly favour one criterion over another.
7	Very strong importance	One element is favoured very strong over another.
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation.
Intensities 2,4,6,8 can be used to express the intermediate values. The reciprocals of above are used to express the inverse comparison, this is a logical assumption.		

Subsequently, a consistency analysis is used to ensure that the ratings are consistent; this is done by using equation 1 and 2 [15]. Where, CI represents the consistency index, λ_{max} represents the consistency measure, n expresses the number of criteria, CR represents the criteria ratio and RI is the random index by Saaty's, as listed in Table 4-3. The ratings are consistent if the consistency ratio is below 0.10 [15].

Afterwards, an MCA is performed to select the best option for each design aspect. The ranking is mainly based on the literature referred to in this chapter and information from employees of Tata Steel.

$$\boldsymbol{CI} = \frac{\boldsymbol{\lambda_{max} - n}}{\boldsymbol{n - 1}} \qquad \textit{Equation 1}$$

$$\boldsymbol{CR} = \frac{\boldsymbol{CI}}{\boldsymbol{RI}} \qquad \textit{Equation 2}$$

Table 4-3: Random consistency index by Saaty [15]

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

4-1-2 Sensitivity analysis

After performing the multicriteria analysis, a sensitivity analysis is carried out to identify the effect of changing the importance of the criteria. The influence of each criterion is investigated by increasing and decreasing the weight factors by a factor of two. The results of the sensitivity analysis are represented in a bar chart, which provides a good overview of the effects.

4-2 Location

First, in paragraph 4-2-1, the options for the location of the HIsarna demonstration plant are described. Subsequently, the criteria considered are detailed in paragraph 4-2-2. Finally, the best option for the location is selected in paragraph 4-2-3.

4-2-1 Options

The management teams of HIsarna and Tata Steel IJmuiden designated four potential locations for the HIsarna demonstration plant, all located at the Tata Steel site and depicted in Figure 4-1. Each option is described below. In addition, for each location the following characteristics are listed: the available area (Table 4-4), the environmental impact (Table 4-5), and the distances to the suppliers of raw materials as well as the distances to the BF and BOF (Table 4-6).

The management team of HIsarna have already appointed location 4 as their preference. This is the only location that does not require an environmental permit and is currently not occupied by another company. Nevertheless, in view of the fact that no detailed research has been performed on these four options, it is interesting to consider all four locations. Furthermore, the fourth location, although the management team's favourite, does not seem to score high when it comes to the environment and the access to the suppliers of materials. A multicriteria and sensitivity analysis are used to investigate the best solution, as outlined in paragraph 4-2-3.

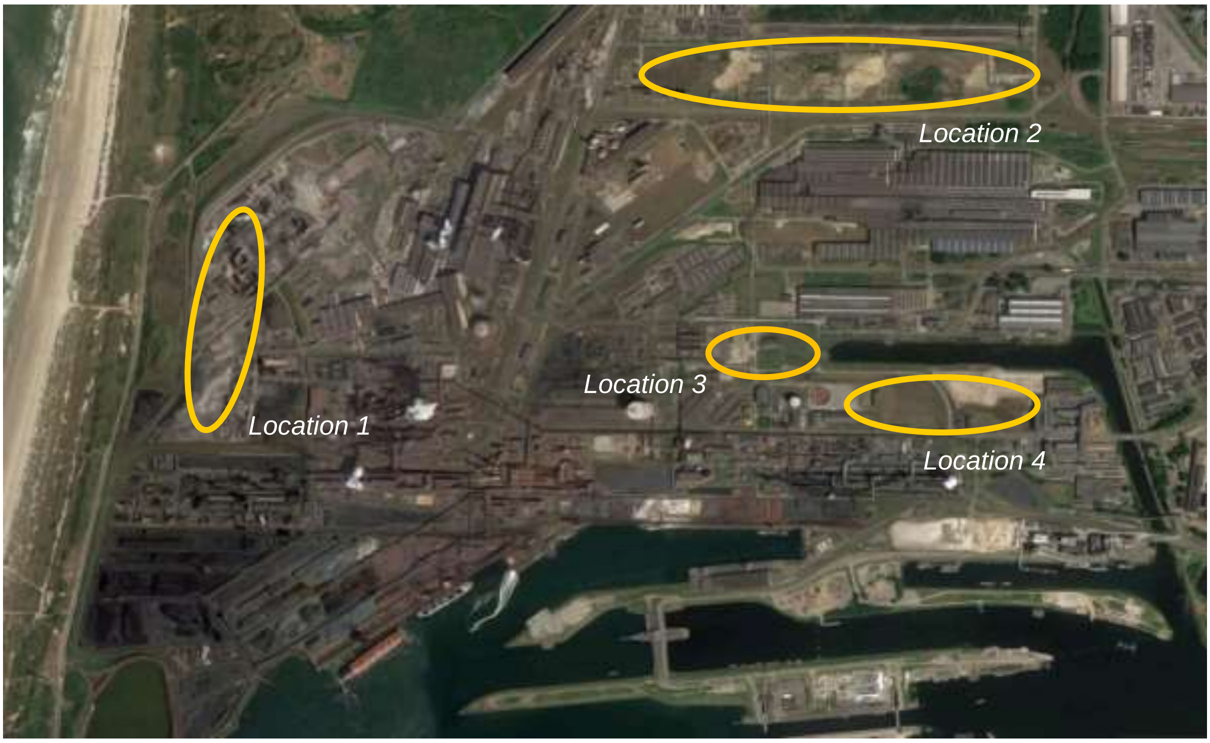

Figure 4-1: Potential locations of the demonstration plant

Location 1

The first option is located near the supply of iron ore, coal and historic BOF sludge. Furthermore, this location is not close to urban areas and, moreover, no environmental regulations apply to this location. In addition, this location has the second largest ground surface. However, this area is currently used by Harsco Metals Holland Velsen Noord, the slag processing company located at the Tata Steel site. Selecting location 1 implies that Harsco must move to another place. A rough estimate of the costs involved is presented in Appendix F.

Location 2

The second location has the largest ground surface of all four options. This could mean a great advantage in case of future expansion. However, this location is far away from the supply of iron ore and coal. Moreover, this option is situated very close to the town of Wijk aan Zee, which may imply strict municipal and environmental regulations.

Location 3

The third option is, on the one hand, located relatively near the storages of currently produced BOF and BF sludge, but on the other hand it is quite far from the supplier of coal and iron ore. In addition, this location is the smallest of all. A positive point is that it is not close to any urban area, which may imply fewer environmental rules.

Location 4

This location is far away from the supplier of iron ore and coal, and from the storage of historic BOF sludge. The main advantage of this location is that no permit is required. Nevertheless, this location is near an urban area. Hence, future environmental issues are quite possible.

Table 4-4: Available area

Location	**Area** [*m*]
Location 1	400 x 700
Location 2	*1200 x 200*
Location 3	300 x 150
Location 4	500 x 200

Table 4-5: Environmental impact

Location	**Close to urbanised area**	**Regulation issues**
Location 1	No	No
Location 2	Wijk aan Zee	Yes, for heavy machinery
Location 3	No	Yes, for high buildings
Location 4	Velsen Noord and Beverwijk	No

Table 4-6: Distances to the locations (in metres)

Distances [m]	**Location 1**	**Location 2**	**Location 3**	**Location 4**
Coal and iron ore	*750*	2500	1800	2200
BF sludge	1200	1000	*500*	1000
Currently produced BOF sludge	1200	1000	*500*	1000
Historic BOF sludge	*200*	1500	1700	2200
BF	*500*	1700	1200	1600
BOF	1000	*700*	*700*	1200
Connection railway [-]	*Yes*	*Yes*	No	No

4-2-2 Criteria

The best location for the HIsarna demonstration plant is selected by using the following criteria: environment, availability, access to materials, processing and production of hot metal and the dimensions. The criteria are detailed below.

Environment ($c_{1,1}$)
The first criterion is determined by, on the one hand, the environmental regulations required for the use of a location for the HIsarna demonstration plant and, on the other hand, the nearness of the location to an urban area. Tata Steel stretches across three different municipalities: Wijk aan Zee, Velsen Noord and Beverwijk. A location close to an urbanised area may raise issues due to noise and dust pollution. A location with a lower environmental impact receives a higher rating.

Availability ($c_{1,2}$)
Availability is the extent to which a location is readily available for the HIsarna demonstration plant. It is preferred that the future location is currently not occupied by another process of Tata Steel, or another company. Higher availability reduces the capital expenditures of the HIsarna demonstration plant, hence an available location is credited with a higher score.

Access to materials ($c_{1,3}$)
Easy access to materials (raw materials and reverts) is crucial and is mainly influenced by the distance between suppliers and the storage area. The shorter the distance, the lower the cost and the higher the reliability of transport.

Processing and production of hot metal ($c_{1,4}$)
Processing and production of hot metal involve transporting hot metal from the blast furnace to HIsarna and from HIsarna to the steelmaking plant. Essential for this is the presence of railway tracks, since hot metal is transported by train. Also, the distance between the plants is an important factor. It should be said that the distance between HIsarna and the steelmaking plant is more crucial than the distance to the blast furnace, since hot metal from the blast furnace is only needed at the start-up of HIsarna.

Dimensions ($c_{1,5}$)
The last criterion is defined by the dimensions of an available location. The larger the dimensions, the higher the rating. As a location of small dimensions means a limitation of the design options, and will reduce the possibilities for future expansion, a larger area is preferred.

4-2-3 Selection

To begin with, a multicriteria analysis is applied to establish the most suitable *location* for the HIsarna demonstration plant. Subsequently, a sensitivity analysis is conducted to investigate the effect of changing the importance of the criteria. The selection is described in more detail below.

Feasible options

First, the suitable options for location are determined; obviously, infeasible options are not to be taken into account for the design. The third location would not be a feasible consideration since the dimensions of the HIsarna demonstration plant exceed the dimensions of this location. Note that the third location can be used in combination with location 4, since these locations are located near each other, functioning as additional area for storages, pre-processing or offices.

Weight factors

The weight factors for the first design aspect *location* are determined by using a pairwise comparison matrix, as depicted in Table 4-7. The ranking is based on the requirements of Tata Steel and information gained from the analysis of materials and the current system. The consistency analysis shows that the ratings are consistent, since the consistency ratio is below 0.10. As can be reasoned from Table 4-7, the order of importance of the criteria is as follows: *environment* / *access to materials* – *dimensions* – *availability* – *processing and production of hot metal*.

Table 4-7: Pairwise comparison matrix for the location

Criteria		$c_{1,1}$	$c_{1,2}$	$c_{1,3}$	$c_{1,4}$	$c_{1,5}$	**Weights**
$c_{1,1}$	*Environment*	1	3	1	6	3	**0.33**
$c_{1,2}$	*Availability*	1/3	1	1/3	4	1/2	**0.12**
$c_{1,3}$	*Access to materials*	1	3	1	6	3	**0.33**
$c_{1,4}$	*Processing and production of hot metal*	1/6	1/4	1/6	1	1/7	**0.04**
$c_{1,5}$	*Dimensions*	1/3	2	1/3	7	1	**0.17**
						Total	**1.00**
$\lambda_{max} = 5.21, CI = 0.05 \text{ and } CR = 0.05 \leq 0.10, \text{OK}$							

Multicriteria analysis

The results of the multicriteria analysis performed for the location of the demonstration plant are represented in Table 4-8. The ratings are based on the advantages and disadvantages as discussed in paragraph 4-2-1. As can be seen in the table, the first option results in the best location. The score is significantly higher than for the other locations.

Table 4-8: Multicriteria analysis location

	Weights	**Location 1**		**Location 2**		**Location 4**	
$c_{1,1}$	0.33	4	1.34	1	0.33	1	0.33
$c_{1,2}$	0.12	1	0.12	4	0.46	3	0.35
$c_{1,3}$	0.33	4	1.34	1	0.33	1	0.33
$c_{1,4}$	0.04	3	0.12	3	0.12	1	0.04
$c_{1,5}$	0.17	3	0.52	4	0.70	2	0.35
Total			**3.44**		**1.95**		**1.40**

Sensitivity analysis

The results of the sensitivity analyses are represented in Figure 4-2. The graph shows that, the preferred location remains the same for all cases of the sensitivity analysis. As can be seen in the figure, the difference becomes slight, by making the criterion *access to materials* ($c_{3,1}$) more important.

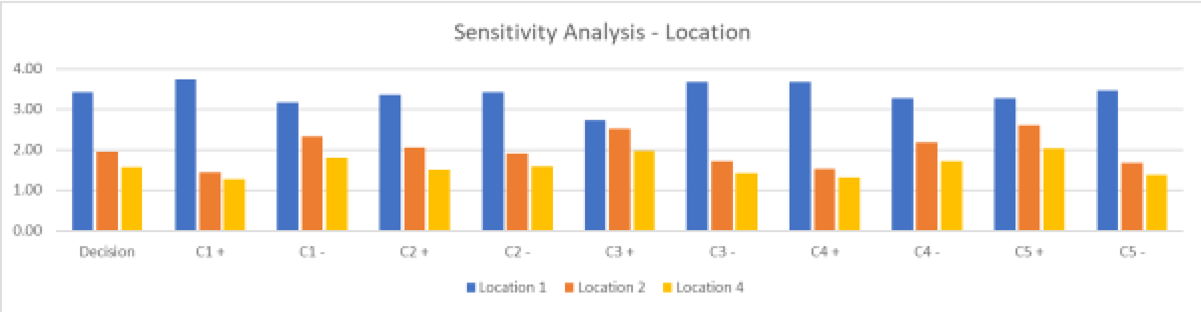

Figure 4-2: Results sensitivity analysis – Location

4-3 Transport

There are two types of transport flows required for the HIsarna demonstration plant: transport from the supplier to the storage area (1) and transport within the area (2), as depicted in Figure 4-3.

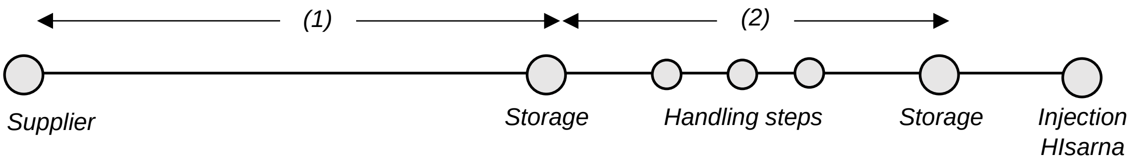

Figure 4-3: Schematic overview of required transport for HIsarna Demo plant.

This paragraph deals with the aspect *transport*. In paragraph 4-3-1 the different modes of transport that can be used for the HIsarna demonstration plant are outlined. For each transport mode the advantages and disadvantages are mentioned. Then, the criteria used to select the best alternative are defined in paragraph 4-3-2. Finally, paragraph 4-3-3 describes the selection process of the best transport mode.

4-3-1 Options

The following four transport systems are described in more detail in this paragraph: truck, train, conveyor belt and pipeline, examples of which are shown in Figure 4-4, A-D. These options are commonly used transport systems in comparable industries, such as dry bulk terminals, the mining industry and powerplants. In addition, these systems are already used transport modes at Tata Steel IJmuiden, as can be seen in Table 4-9. **Note:** in this table a fifth mode of transport is listed, water. Although Tata Steel makes use of maritime transport for supplies, water is not used for transport within the Tata Steel site; hence, for the present research, this option is not taken into consideration.

Figure 4-4: Options for transport, A. Truck, B. Train, C. Conveyor belt and D. Slurry pipeline

Table 4-9: Transport used at Tata Steel

Modality	Transport to and from Tata Steel	Transport used for HIsarna pilot plant
Road	x	x
Water	x[1]	
Rail	x	x
Conveyor belt	x	x
Pipeline	x	

[1] *This transport takes place outside the Tata Steel site*

4-3-1-1 Truck

Currently at Tata Steel, iron ore and coal are transported by truck to the HIsarna pilot plant. In addition, trucks are used at the blast furnace when a conveyor belt breaks down, to provide redundancy.

Road transport is a commonly used mode to move dry bulk materials, such as iron ore and coal. Literature reveals that one of the main reasons to opt for road transport is the high flexibility and the short transit time [17]. It must be mentioned, however, that Tata Steel uses rental trucks, resulting in a decreased flexibility since rental companies operate according to their own, fixed schedule. Nevertheless, road transport makes it possible to react quickly to operational changes. Furthermore, trucks do not require expensive installation in comparison to conveyor systems or pipelines.

Contrastingly, the environmental impact of road transport is significant compared to the other transport systems. The difference in CO_2-emissions between transport modes is illustrated in Table 4-11. Moreover, road transport results in high handling losses, since most of the trucks are not closed, as can be seen in Figure 4-4A. To reduce the impact on the environment, closed, electric trucks should be used. Furthermore, a truck can only be used half the time to transport materials from one point to another.

Table 4-10: (Dis)advantages road transport

Advantages	**Disadvantages**
Flexibility	Environmental impact
Low investment costs	High OPEX
Low transit time	50% efficiency
	Batch process
	Low reliability

Table 4-11: Comparison of the environmental impact of transport modes [18], [19]

Transport mode	**CO_2**	**SO_2**	**NO_X**	**PM2.5**
Truck	124	0.11	1.0	0.022
Train	16	0.022	0.20	0.0078
Conveyor belt	0.023 – 0.055	n/a	n/a	n/a

Table 4-12: Costs of a unit of cargo in rail and road transport

Transport mode	**Investment cost**	**Fuel cost**	**Maintenance and operations**	**External costs**
Road	14%	60%	17%	9%
Rail	22%	46%	30%	2%

4-3-1-2 Train

At present, Tata Steel IJmuiden uses railway to move various products within the IJmuiden site, for example, hot metal from the blast furnace to the steelmaking plant. Trains are also used to transport limestone to the HIsarna pilot plant and finished steel coils to the harbour.

Rail transport is a suitable transport system for dry bulk materials, especially in large volumes; it becomes more profitable when both the distance and the volume of bulk are increased [20]. This implies that rail transport is only suitable for iron ore and coal. Although Table 4-11 shows that a railway is environmentally friendlier than road transport, it cannot compete with the conveyor belt in this respect. A drawback of this transport system may be the fact that railway is already much used by Tata Steel, and adding more might lead to congestion. An overview of the advantages and disadvantages is provided in Table 4-13.

Table 4-13: (Dis)advantages railway transport

Advantages	Disadvantages
High capacity	Rail infrastructure required
Environmental impact is less compared to road transport	Low on-time reliability and flexibility
	50% efficiency
	Batch process
	Primarily suitable for long distances
	Unfavourable transit time

4-3-1-3 Conveyor belt

Currently, conveyor belts are used to transport supplies of iron ore and coal to the blast furnaces. They are also used for the transport within the HIsarna pilot plant. According to employees of Tata Steel, this is mainly because of the high frequency of moves and the reliability of these systems. These advantages can also be found in literature [19], [21]. In addition, as shown in Table 4-11, conveyor belts have a low environmental impact, especially compared to other transport systems. To decrease dust pollution, closed conveyor belts can be used. Conveyors are used when material is frequently moved between fixed points and when there is a sufficient material flow to justify the investment [22] [23].

Table 4-14: (Dis)advantages conveyor transport

Advantages	Disadvantages
Continuous system	Inflexibility
High efficiency	High investment costs
Low in maintenance	
Low environmental impact	
Low handling losses	

4-3-1-4 Slurry pipeline

Slurry pipelines have been used for more than 100 years for the transportation of mineral wastes, for example tailings from the mining industry; almost every mineral-processing installation has a tailings pipeline to transport slurries from the mineral-disposal site [24]. Furthermore, as mentioned in paragraph 2-3, both BF and currently produced BOF slurries are currently transported to the filter press (sludge processing department) by using slurry pipeline. Slurry pipelines are an efficient and reliable way to transport slurries [24].

Note: it could be an interesting option to transport BF and currently produced BOF slurry directly to the storage and handling area of the demonstration plant. In that case the materials will be transported as slurries to HIsarna and processed into sludges at the HIsarna plant itself. This option will provide a benefit to the environment and, interestingly, it will be easier to transport slurries by pipeline than sticky reverts by truck. This option would mean that the sludge processing department should be moved, or additional systems be installed at HIsarna.

Table 4-15: (Dis)advantages slurry pipeline transport [25] [26]

Advantages	**Disadvantages**
Continuous system	Inflexibility
High efficiency	High capex
Low handling losses	High water usage
Low in maintenance	Sludge processing department must be moved to HIsarna
High availability	
Environmental friendly	
Low opex	

4-3-2 Criteria

The following criteria are considered for the aspect transport: environment, reliability, transit time, capital expenditure (capex) and operational expenditure (opex). These are commonly used criteria for transportation of dry bulk materials in literature [17], [19]. They are specified below.

Environment ($c_{2,1}$)
The impact a transport system has on the environment, e.g. handling losses, dust and noise pollution, CO2 emission, has become a crucial criterion and environmental regulations have become more and more strict. Furthermore, one of the requirement for the storage and handling area is an environmental friendly design. Hence, a transport system with a lower impact on the environment receives a higher rating.

Reliability ($c_{2,2}$)
Reliability is measured in the percentage of transfers that arrive on time at the destination [27]. Delays may occur as the result of equipment shutdowns, unavailability of transport systems or external disturbances. A continuous production process at the HIsarna demonstration plant requires on-time delivery, and unreliable transport systems may lead to a shutdown of the HIsarna plant. Moreover, a reliable transport system requires fewer inventory stocks.

Transit time ($c_{2,3}$)
Transit time is defined as the time it takes to transport a specific amount of material from place A to B. This time must be minimised to reduce the processing time of hot metal. A lower transit time will be assessed with a higher rating.

Capex ($c_{2,4}$)
Capital expenditure is described as the investment costs to be made for the transport system; In essence, capex involves the all-in construction and setup expenses for an operational transport system. From a business point of view, Tata Steel obviously wishes to minimise these costs, but it must be understood that criteria like environment and reliability will have a price.

Opex ($c_{2,5}$)
Operational expenditure involves expenses that go with day-to-day operation of a transport system. These include, among others, the maintenance, fuel and labour costs. In view of Tata Steel's wish to maximise profit, it is important to keep Opex in check, as it may significantly influence profit margins.

4-3-3 Selection

As mentioned in paragraph 4-3, there are two types of transport flows: transport from the supplier to the storage and handling area, and transport within the area. First, the selection of the transport to the storage and handling area is elaborated on in paragraph 4-3-3-1. A multicriteria analysis is used to determine the best option. Secondly, the selection of the transport within the storage and handling area is discussed in paragraph 0. Here, selection is based on literature and expertise at Tata Steel. An overview of the selected transport systems is listed in Table 4-16.

Table 4-16: Overview best options for transport

Transport	Materials	Transport options
Transport to storage and handling area	Iron ore and coal	Conveyor belt
	BF and currently produced BOF sludge	Slurry pipeline
	Historic BOF sludge	Truck
Transport within storage and handling area	All materials	Conveyor belt

4-3-3-1 Transport to storage and handling area

Feasible options

First, the suitable design options are determined for each material; obviously, infeasible options are not to be considered for the design. Appropriate transport systems for iron ore and coal are either truck, train or conveyor belt. The properties of these materials exclude the use of a slurry pipeline. Suitable options for BF and currently produced BOF sludge are either slurry pipeline or truck. Here, a conveyor belt would not be a feasible consideration because of the limited flow characteristics of these materials. Finally, for similar reasons, transport by truck is the only feasible option when historic BOF sludge is to be moved. An overview of the suitable design options for transport is provided in Table 4-17.

Table 4-17: Feasible options for the materials

Materials	Transport options
Iron ore and coal	Truck, train and conveyor belt
BF and currently produced BOF sludge	Slurry pipeline and truck
Historic BOF sludge	Truck

MCA and sensitivity analysis

A multi-criteria analysis is used to determine the best solution for the transport of raw materials to the storage and handling area. This analysis is carried out for the standard materials coal and iron ore, and for the reverts BF and currently produced BOF sludge. Historic BOF sludge can be left out of the equation as for this material only transport by truck is feasible, and therefore no selection is necessary. First of all, the weights of the criteria are calculated by using Saaty's Priority Principle. The order of importance of the criteria is as follows: *reliability – opex –environment – transit time – capex*. In addition, the effects of altering the importance of criteria is studied by using sensitivity analyses. A detailed elaboration of these analyses is provided in Appendix E.

The results of the MCA clearly show that iron ore and coal should best be transported by a conveyor belt. Table 4-18 illustrates that this option is rated significantly higher than both truck and train. On the other hand, Table 4-19 reveals that for BF and currently produced BOF sludge, the preferred option is a slurry pipeline.

Table 4-18: MCA results – iron ore and coal

Materials	Score MCA
Truck	1.80
Train	1.45
Conveyor belt	2.75

Table 4-19: MCA results – BF and currently produced BOF sludge

Materials	Score MCA
Truck	1.80
Slurry pipeline	2.75

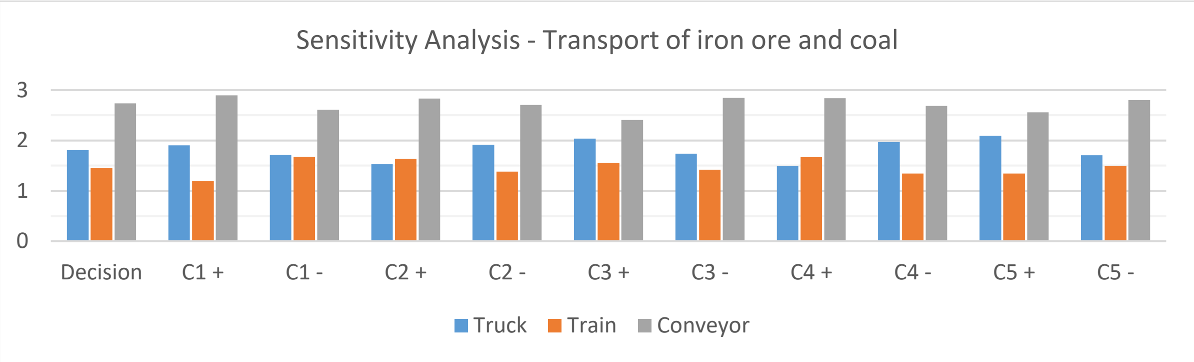

Figure 4-5: Results sensitivity analysis transport – Iron ore and coal

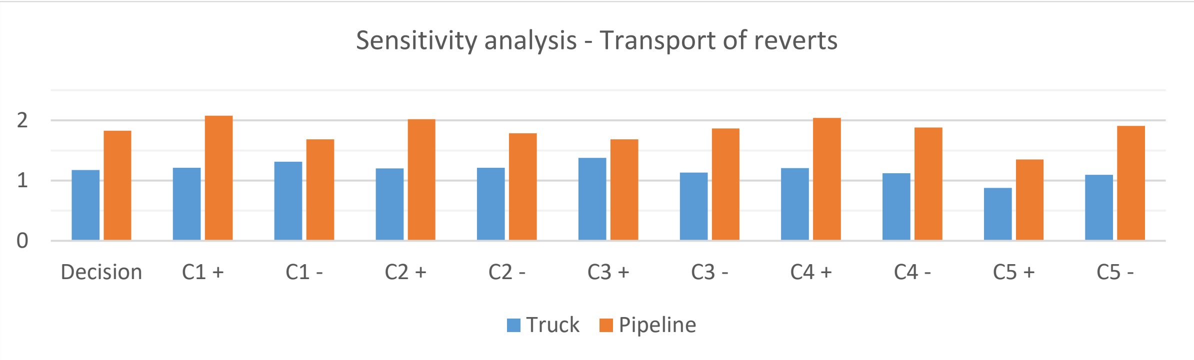

Figure 4-6: Results sensitivity analysis transport – BF and currently produced BOF sludge

4-3-3-2 Transport within storage and handling area

Within the storage and handling area all materials will be transport by conveyor systems. This selection is based on literature and expertise at Tata Steel. The main reasons are the continuity, the large number of movements and the high reliability of a conveyor system. Already, the transport within the storage and handling area of the HIsarna pilot plant, as well as between the general raw material storage and the blast furnaces takes place by using conveyor systems. Generally speaking, conveyor belts are a commonly used transport system at dry bulk terminals and the mining industry.

4-4 Layout

In this paragraph, the design aspect *layout* is elaborated on. Paragraph 4-4-1 describes the potential options for the layout. Paragraph 4-4-2 defines the criteria used to select the best layout. Finally, paragraph 4-4-3 presents the most promising layout for the HIsarna demonstration plant.

During the design of the layout the following obstacles must be reckoned with:

- Low mass flow rate of materials; this can result in a low utilization rate of equipment.
- Properties of some materials, such as a high moisture content in combination with stickiness may present difficulties in drying. Besides, sticky and inhomogeneous materials are hard to mix accurately.
- If two materials with different properties are processed at one handling line, this may cause problems when each material makes different demands on the handling equipment.
- The dimensions of the location of the HIsarna demo plant may limit the design options if not enough ground space is available at the selected location.
- Available funds.

4-4-1 Options layout

Four different options for the layout of the HIsarna demonstration plant can be distinguished, as listed in Table 4-20. A description of each layout is provided in this paragraph.

Table 4-20: Options for layout

Layout	Description	Number of lines	Continuous or batch process	Wet or dry-mixing
1	Each material is processed at a separated handling line.	5	Continuous	Dry mixing
2	One processing line for iron ore, one for coal, and one for reverts, which are processed at the same time.	3	Continuous	Wet mixing
3	One processing line for iron ore, one for coal, and one for reverts, which are not processed at the same time	3	Batch	Dry mixing
4	One processing line for iron ore, one for coal, reverts to be divided between these two lines.	2	Continuous	Wet mixing

Layout 1

The first layout consists of five different lines; each material is processed on a separate processing line, as depicted in Figure 4-7. Hence, this layout can provide a continuous process. Another advantage is that the handling equipment can be perfectly adjusted to the properties of each material, which is beneficial for the quality of the material and the maintenance of equipment. On the other hand, this layout requires high investments and much ground space, since five separated handling lines need to be installed. Furthermore, five different lines can result in a low utilization rate of the handling equipment if only small amounts of materials are handled. An overview of the advantages and disadvantages is given in Table 4-21.

Table 4-21: (Dis)advantages layout 1

Advantage	**Disadvantage**
Perfectly adjusted handling equipment	High investment costs
Dry mixing of the materials	Large area required
Low in maintenance	Low utilization rate of handling equipment
Continuous process	Processing could be difficult, because of the high moisture content of reverts
Flexible process	

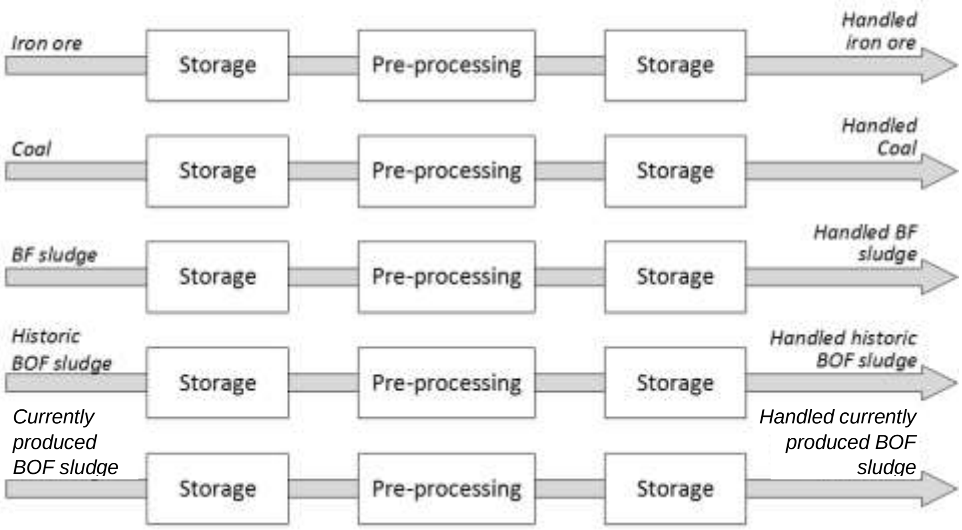

Figure 4-7: Schematic representation of layout 1

Layout 2

The second option for the layout of the storage and handling area has three handling lines; one processing line for iron ore, one for coal and one for all reverts together. Figure 4-8 provides a schematic representation. Fewer processing lines, enhance the overall utilization rate of the handling area. This option is based on a continuous process; therefore, the reverts need to be processed and mixed beforehand (at sludge condition). This could present a problem due to the fact that different physical properties of the reverts make it hard to meet the requirements for accuracy of composition of hot metal. After all, reverts have a high moisture content, are sticky and could be inhomogeneous, as mentioned in Chapter 2. Another problem may be caused by differences in chemical properties; BF sludge, for example, contains a high percentage of carbon, so the chemical properties rather resemble those of coal. This means that the dryer must be adjusted in such a way that it can handle both properties of coal and iron ore. Currently, at the pilot plant, these processes are kept separate because of the physical properties. The main advantages and disadvantages of the second layout are summarised in Table 4-22.

Table 4-22: (Dis)advantages layout 2

Advantage	**Disadvantage**
Lower investment costs	Processing could be difficult, because of the differences in chemical properties of the materials.
Smaller surface required	Processing could be difficult, because of the differences in physical properties of the materials.
Continuous process	Equipment cannot be customised for each material
Higher utilization rate	Mixing before handling is required
	Less flexible

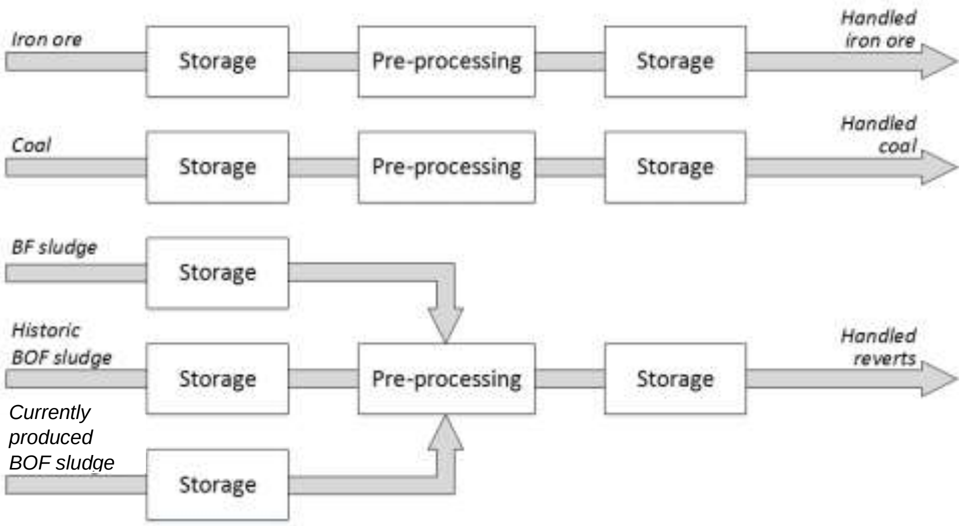

Figure 4-8: Schematic representation of layout 2

Layout 3

This layout is almost similar to the second layout, the difference being that in this option some processes are batch processes rather than continuous; the reverts are processed as a batch system, as indicated in Figure 4-9. A possible batch schedule could be: the first two hours BF sludge is processed, followed by two hours historic BOF sludge and finally two hours BOF sludge. An advantage is that no beforehand mixing is needed. However, all reverts need to be handled using only one processing line. Table 4-23 provides an overview of the main advantages and disadvantages of the third option.

Table 4-23: (Dis)advantages layout 3

Advantage	**Disadvantage**
Lower investment costs	Equipment cannot be customised for each material
Smaller area required	Processing could be difficult, because of the differences in chemical properties of the materials.
No extra mixing required	Processing could be difficult, because of the differences in chemical properties of the materials.
Higher utilization rate	Partly a batch process
	Less flexible

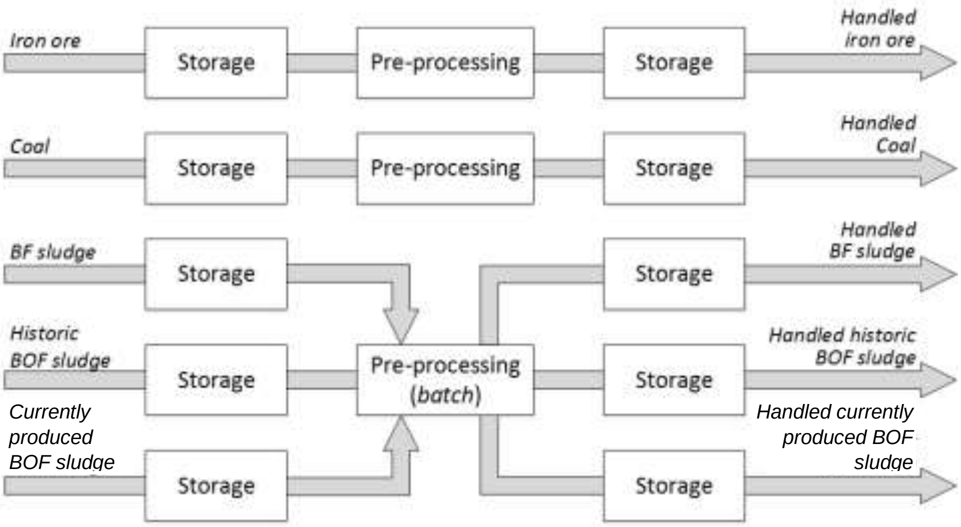

Figure 4-9: Schematic representation of layout 3

Layout 4

The fourth option consists of two different handling lines processing continuously. The first line is set up for processing iron ore, historic BOF sludge and currently produced BOF sludge. These three materials are combinable because of the similarity in physical properties; all three contain a high percentage of iron. In addition, these materials need to be injected at the same place in HIsarna. On the second line two materials are processed; coal in combination with BF sludge, both containing a high percentage of carbon. The schematic representation of this layout is presented in Figure 4-10.

As for the second layout, this option requires mixing before the materials are processed, which may result in problems since the reverts are moisterous, sticky and possibly inhomogeneous. Positive in comparison to the second layout is the fact that this layout produces a mix with either a high moisture content (like BF sludge) and a low moisture content (like coal). This will make it easier to process the materials. In addition, this layout requires a lower investment, less ground surface and provides the highest utilization rate. An overview of the pros and cons of this layout is given in Table 4-24.

Table 4-24: (Dis)advantages layout 4

Advantage	**Disadvantage**
Lower investment costs	Mixing before handling is required
Materials are classified on physical properties	Processing could be difficult, because of the differences in physical properties of the materials.
Higher utilization rate	Equipment cannot be customised for each material
Requires less surface	Less flexible
Continuous process	

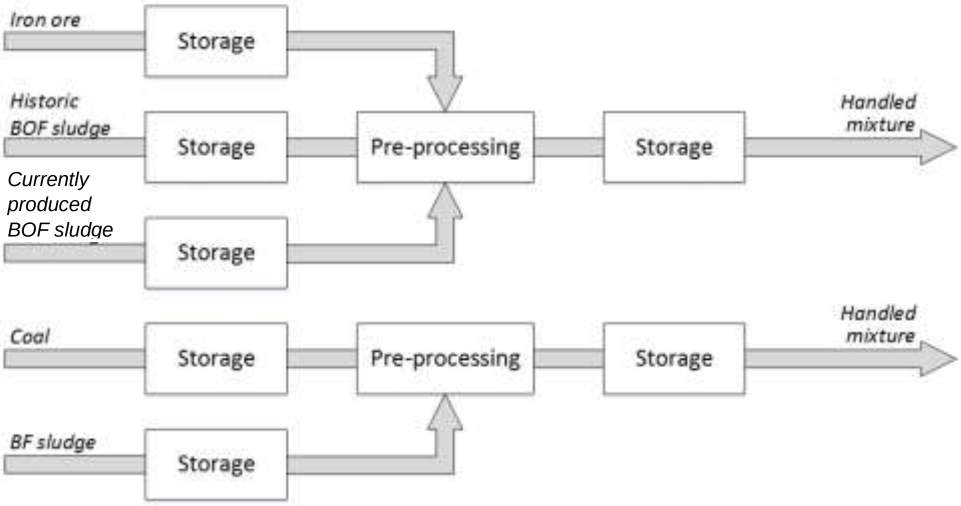

Figure 4-10: Schematic representation of layout 4

4-4-2 Criteria

The design criteria for the *layout* include the following: process flexibility, precision, capex, opex, equipment utilization, required area and expandability. These are used to compare the four different layout options. Each criterion is described below.
Note: criteria like reliability and processing time have not been taken into account here, even though they might in general be important for the design of the storage and handling area. However, since they are mainly dependent on the processing equipment, they should not be considered as a criterion for the aspect *layout*.

Process flexibility ($c_{3,1}$)
Process flexibility can be defined as the extent to which a system is adaptable to changing demands during the process. Adaptability may be crucial, for example, when the composite of materials that is required to produce hot metal, should be altered. Such adjustment must be made smoothly and swiftly, which is best guaranteed when handled materials are stored in separate silos, and the necessary modifications can be carried out as closely as possible to the HIsarna injection site. A higher flexibility of the layout results in a higher rating.

Precision ($c_{3,2}$)
Precision is defined as the accuracy by which materials can be handled at a layout. This is a crucial criterion since HIsarna must be able to produce hot metal of constant high quality. For example, dry mixing of materials provides a higher precision than wet mixing of materials. Consequently, a layout that ensures a higher precision, will receive a higher score.

Capex ($c_{3,3}$)
Capex (capital expenditure) is defined as the costs to be made to acquire systems and their components. It includes also the costs for predevelopment and construction. In view of Tata Steel's wish to maximise profit, capex is to be kept as low as possible; the lower the capex of the layout, the higher the option will be rated.

Opex ($c_{3,4}$)
Opex (operational expenditure) is defined as the expenses related to the operation and maintenance of a system or process. Opex has a significant influence on the profit margin of Tata Steel, thus a layout with lower operational costs will receive a higher rating.

Equipment utilization ($c_{3,5}$)
Utilization is expressed as the percentage of the handling area that is used. A high utilization is an indication for an efficient layout, and logically, a low utilization rate indicates an inefficient layout; the higher the utilization, the higher the ranking. For instance, a handling area where material is processed for only three hours daily is not efficient. It should be noted, however that the equipment itself has a significant influence on the utilization rate.

Required area ($c_{3,6}$)
The required area can be defined as the ground surface required for a layout design. A smaller required area will receive a higher rating, since this results in a more efficient land use at the Tata Steel site.

Expandability ($c_{3,7}$)
Expandability is a criterion to ascertain the capability of the system to adapt to an increase in both quantities of materials and processes on the site. Since the demonstration plant will be installed to be operative for the coming 20 years, it is likely that processed materials will be added. Hence, the design of the demonstration plant requires sufficient flexibility to expand.

4-4-3 Selection

A multicriteria analysis (MCA) is used to determine the best option for the layout of the HIsarna demonstration plant. As explained in Appendix E, the most suitable solution is the first layout with a rating of 2.78, compared to respectively 1.85, 2.32 and 2.48 for the other three (see Table 4-25). Layouts 4 and 3 come not far behind the winning layout.

Table 4-25: MCA results – iron ore and coal

	Layout 1	Layout 2	Layout 3	Layout 4
Rating MCA	2.78	1.85	2.32	2.48

The results of the sensitivity analysis for the layouts are provided in Figure 4-11. As can be seen in the figure, increasing and decreasing the weights have a significant effect on which option results as the preferred layout. The fourth option emerges as the best when the weight of the *precision criterion* ($c_{3,2}$) is reduced, the importance of *capex* and *opex* ($c_{3,3}$ and $c_{3,4}$) are increased, as well as *equipment utilization* ($c_{3,5}$). When the weight of the *required area* ($c_{3,6}$) is increased, the first and fourth option are rated equally. The third layout comes out a winner when the criterion *environment* ($c_{3,1}$) is made less important, although it must be said that the difference is slight. The second layout never turns out to be the preferred layout. Figure 4-12 provides an overview of the number of times a specific layout is considered the best option after sensitivity analysis.
Within Tata steel, process technology shows a strong preference for the first layout, with its focus on precision and flexibility. The management team of HIsarna, gives preference to the layout ensuring the highest profit.

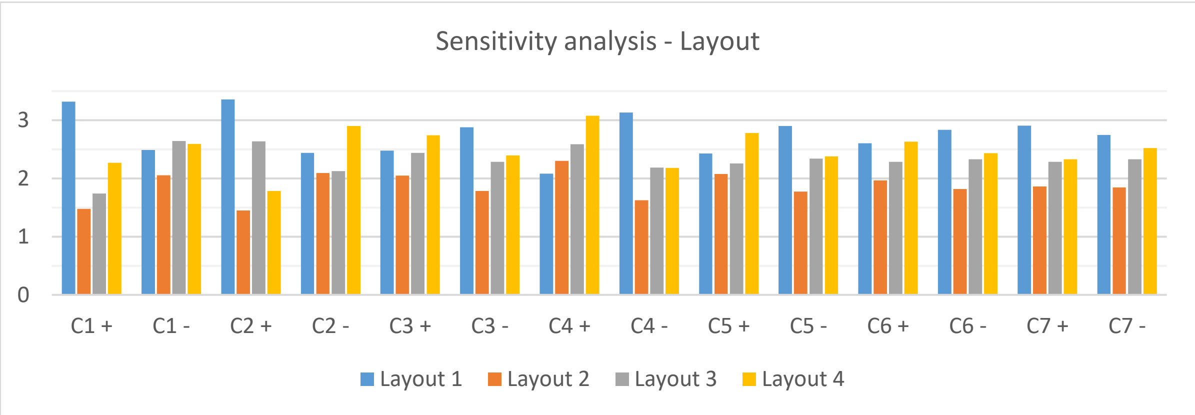

Figure 4-11: Results sensitivity analysis – Layout

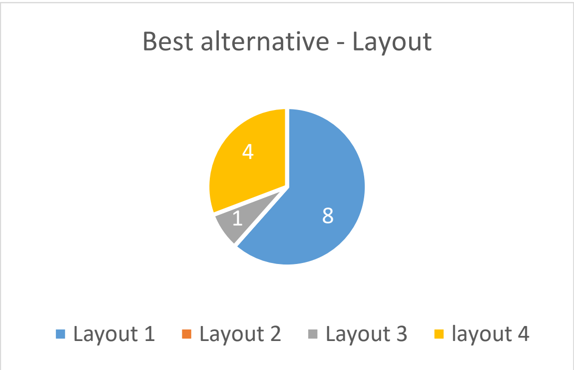

Figure 4-12: Number of times resulting in best option – Layout

4-5 Storage

All materials required for HIsarna have to be stored at the storage and handling area of the demonstration plant. Similar to the HIsarna pilot plant, two storage areas are essential for the demonstration plant (see Table 4-26): a storage for raw materials after entering the HIsarna demonstration plant and a storage for handled materials after pre-processing at the storage and handling area. The storages are required to provide a buffer and thus ensure a continuous production of hot metal at HIsarna.

This paragraph deals with the aspect *storage*. First, the advantages and disadvantages of open and closed storage systems are weighed in paragraph 4-5-1. Next, paragraph 4-5-2 discusses the feasibility of closed storage systems for HIsarna. Finally, in paragraph 4-5-3, the required storage capacities are determined.

Table 4-26: Storage systems of HIsarna demonstration plant

Tata Steel	**HIsarna**	
Storage raw materials	Storage raw materials	Storage handled materials

4-5-1 Open versus closed storage systems

Open storage systems

As a rule, large dry bulk terminals use open storage fields for their materials, such as iron ore and coal [28]. The main reasons for open storage facilities are the high flexibility and low investment costs. Flexibility is especially important for terminals with a large variety of materials. [28]. In addition, open storage systems are inexpensive compared to closed storage systems, since no (or lower) investments for buildings and foundations are required. However, open storage systems come with pollution and noise. This causes additional costs for measures to be taken to protect the environment, for example spraying stockpiles to eliminate dust [29]. This is especially an issue when terminals are located close to urban areas [28]. Currently, Tata Steel IJmuiden is using open stockpiles to store the raw materials as shown in Figure 4-13, even though they are located near the urban areas of Wijk aan Zee, Beverwijk and Velsen-Noord. The incoming materials at the HIsarna pilot plant are also stored at open storage areas, as mentioned in paragraph 3-1. Furthermore, these type of storage systems require large ground surface. An overview of the pros and cons of open storage systems is given in Table 4-27.

Table 4-27: (Dis)advantages open storage systems

Advantages	**Disadvantages**
Flexibility	Substantial environmental footprint
High capacity	Large ground surface
Unloading and loading at the same time	
Low investment costs	

Figure 4-13: Open storage piles at Tata Steel IJmuiden [12]

Closed storage systems

As mentioned before, environmental regulation becomes more and more strict. Compared to open storage systems, closed storage facilities have a less negative effect on the environment, since dust, pollution and noise can be minimised [28]. This improves the quality of water, air and soil. It is also beneficial for the health of employees and will reduce the wear and tear of equipment, resulting in lower maintenance costs. Apart from that, closed storage requires less ground surface than open storage. Therefore, when the availability of ground is limited, closed storage is a feasible option [28]. On the other hand, closed storage facilities are significant less flexible than open storage systems. This may prove to be problematic when a variety of materials is processed [28]. In addition, enclosed storage requires relatively high investments: the capex ratio between closed and open storage is 1/0.55 [29]. Partly, these investments can be compensated by lower investments in protective environmental measures, such as a dust-spraying system [29]. Closed storage systems require a more advanced logistic planning, because they are less flexible, and loading and unloading cannot always take place at the same time. A summary of the advantages and disadvantages of closed storage systems is given in Table 4-28.

Table 4-28: (Dis)advantage closed storage systems

Advantages	**Disadvantages**
Less impact on the environment	High investment costs (buildings and foundation structures)
Fewer handling losses	Inflexibility (capacity, number of materials)
Less surface area required	Simultaneous loading and unloading not always possible
No pollution treatment required	Chemical reactions: coal burn
Lower labour costs	
No weather influences	

Examples of generally used enclosed storage facilities are [28]:

- Covered stockpile
- Mammoth silo: cylindrical silo with flat bottom
- Dome silo: part of a sphere with an installed reclaim mechanism
- Dome silo (cover): used to cover a stockpile

The demand for covered storages increases due to stricter environmental regulations. This can be seen, for example, at power plants and the cement industry. In Germany, USA and Finland several mammoth silos have been installed for the storage of coal. The port of Mai Liao in Taiwan has installed domes for the storage of coal, as shown in Figure 4-14 [28]. Until now, no large scale covered storage systems are used on import and export dry bulk terminals [28]. Closed storage systems are difficult to implement in large scale bulk terminals with a large variety of products: variety of products requires a flexible storage system [30].

Figure 4-14: Closed storage for coal at Mai Liao in Taiwan [31]

4-5-2 Selection

At present, closed storage systems are not commonly used for the storage of dry bulk materials at industries such as large dry bulk terminals. This is mainly because of the inflexibility of storing a large variety of products and capacities. But since environmental regulations have become stricter and stricter, the demand for enclosed storage systems increases. This can be seen in power plants or the cement industry, as mentioned in paragraph 4-5-1. The management team of HIsarna also prefers closed storage systems, in order be able to create an environmental friendly steel industry, like HIsarna. Whether it is feasible to use closed storage systems for HIsarna must be the subject of further study. Important points to take into consideration are: flexibility, environment, required area, capex.

Literature shows that terminals with a limited variety of materials or producing for a limited number of end users, may be suitable for enclosed storage systems [28]. HIsarna complies to both conditions: the number of bulk materials processed at the HIsarna demonstration plant is limited; traditional blends of raw materials are no longer needed during the new way of ironmaking, only one type of iron ore and coal is required. Moreover, HIsarna can be considered its own end user, just like, for example, the cement manufacturing industry. This implies that the number of processed materials and the demand for hot iron are constant during the year. It must be noted that different types of materials can be used, so it is recommended to consider the redundancy required for closed storage systems. Closed storage facilities are more than feasible, because the benefits (fewer costs to adhere to environmental regulations, less pressure on the environment in general, a more efficient utilization of ground surface) amply outweigh the higher capex and restriction in flexibility.

4-5-3 Storage capacities

The capacity of a storage is a trade-off between the costs and the reliability of HIsarna. A higher storage capacity will result in a more reliable system, but on the other hand, the costs will increase as well. The opposite is true for a storage with a small capacity. According to Lean Manufacturing, a storage with a capacity that is too large should be considered a form of waste.

According to literature, a commonly used storage capacity for dry bulk terminals can be determined by taking 10% of the yearly throughput [32]. However, for HIsarna this may be different, since HIsarna is rather like a powerplant. Schott indicates that the storage capacity for a powerplant is mainly related to the safety margin that is required for a certain number of days of operation, and mentions two weeks as a typical number for safety stocks [29]. Drbal distinguishes two types of storages: active and reserve storage, with a normal capacity of respectively three days at full operation and 60 to 90 days of operation at a flow rate of 65% to 80%. He mentions the following factors affecting these figures: the transport mode, sources, plant availability requirements, transportation distance and climate [33]. The factors affecting the storage capacity of HIsarna are represented in Table 4-29.

Table 4-29: Factors affecting storage capacity

Factors
Source of materials (available capacity at Tata Steel)
Transport mode (interarrival time, availability)
Availability of storage and handling area
Capacity of HIsarna
Availability requirements of HIsarna
Costs of shutdown HIsarna
Costs of storage materials

As shown in Table 4-29, one of the factors affecting the required capacity is the available capacity of materials at Tata Steel IJmuiden. An overview of these capacities is given in

Table 4-30. These available capacities can be considered as the safety stocks of the materials. Because of this, a smaller storage capacity is required at the storage and handling area itself. Consequently, a storage capacity for two days is selected for the raw materials storage and three days for the handled material storage. An exception is made for the raw material storage of BF sludge and currently produced BOF sludge, since these materials are directly supplied to the storage and handling area. For these materials a larger storage capacity is required; a storage capacity of seven days is to be considered. Whether these capacities are feasible, is investigated in Chapter 6 by using a simulation model (created in Chapter 5).

Table 4-30: Available storage capacities at Tata Steel IJmuiden

[redacted]

4-6 Design overview

The best options for the four aspects of the design (location, transport, layout and storage) have been selected in previous paragraphs and an overview of the preferred options is shown in Table 4-31. In addition, iron ore and coal will be transported to the storage and handling area by one conveyor belt, to reduce capital expenditures and to increase the utilization rate. Furthermore, pipelines are selected for the transport of BF and currently produced BOF sludge to the storage and handling area. These materials are transported as slurries and will be processed into sludges at the HIsarna plant itself.

Table 4-31: Selected design of the storage and handling area

Subsystem	**Selected option**
Location	Location 1
Transport to HIsarna	
▪ *Iron ore and coal*	One conveyor belt
▪ *Historic BOF sludge*	Truck
▪ *BF and currently produced BOF sludge*	Pipelines
Transport within HIsarna	Conveyor system
Layout	Layout 1: Five separated lines
Storage	Closed storage systems

4-7 Conclusion

The following sub-question has been answered by this chapter:

> How can each of the aspects (location, transport, layout and storage) of the storage and handling area be designed to meet the criteria?

This chapter has determined the best design for the storage and handling area of the HIsarna demonstration plant. The design of the storage and handling area is divided into four design aspects: location, transport, layout and storage. The possible options have been identified for each design aspect, these are listed in Table 4-32.

Table 4-32: Morphological overview

Subsystem	Option 1	Option 2	Option 3	Option 4
Location	Location 1	Location 2	Location 3	Location 4
Transport	Truck	Train	Conveyor belt	Pipeline
Layout	Layout 1: Five lines – continuous processing	Layout 2: Three lines – continuous processing	Layout 3: Three lines – batch processing	Layout 4: Two lines – continuous processing
Storage	Open storage	Closed storage		

The best options for location, transport and layout of the storage and handling area, have been selected by using multi-criteria analyses. Each design option is compared to a set of decision criteria. The selection of the best option for storage is based on information obtained from literature. The following design of the storage and handling area has been created: iron ore and coal will be transported by conveyor belt to the storage and handling area, historic BOF sludge by truck, and BF and currently produced BOF sludge by pipeline. Both the raw and handled materials will be stored in enclosed storage systems. Each material will be pre-processed at a dedicated handling line. Within the storage and handling area, all materials will be transported by conveyor belt. The raw material storage of iron ore, coal and BOF sludge has a capacity for two days; and that of BF and currently produced BOF sludge for seven days. In addition, all handled material storages have a capacity for three days.

Chapter 5

Modelling

The design of the storage and handling area of the HIsarna demonstration plant has been defined in Chapter 4. The selection process of the overall design has been made using multicriteria analyses and information gained from literature and Tata Steel. Next, the performance of the design needs to be tested by using a simulation model. This model is also used to examine how the parameters affect their response variables, in order to fine-tune the parameter settings of the design as accurately as possible. Such a model will be dealt with in this chapter.

A description of the conceptual model is given in paragraph 5-1, including the objective of the model, the model content, and the assumptions and simplifications made for the model. Subsequently, the implementation of the model is presented in paragraph 5-2, giving a description of the software package and simulation model. The verification of the model is discussed in this paragraph as well, to ensure the model works correctly.

5-1 Conceptual model

Before the simulation model of the storage and handling area is built, a conceptual model is created in order to reduce the risk of errors in the real model. Robinson believes that no model can exist without a conceptual model [2]. According to Robinson, a conceptual model is defined by a description of the simulation model in a non-software specific language, and it has to study the following elements: objective of the model, model content, and the assumptions and limitations of the model [34], [35].

5-1-1 Objective of the model

The purpose of this simulation model is to study the performance of the design of the storage and handling area. In addition, the input parameters affecting the defined response variables are investigated by using the simulation model, with the aim to optimise the parameter settings of the design of the storage and handling area. The model is particularly focused on the performance of the storage facilities of HIsarna demonstration plant.

5-1-2 Model content

This paragraph describes the required content of the conceptual model. A schematic representation of the model is depicted in Figure 5-3 and the corresponding processes are described in Table 5-1. The input parameters are divided into the following sections and are discussed in more detail in Appendix G:

- Characteristics of HIsarna
- Material characteristics
- Characteristics of supplying
- Characteristics of storing
- Characteristics of transporting
- Characteristics of processing
- Failure distributions

Note that the input and response variables for the design evaluation and optimisation are defined in Chapter 6 (paragraph 6-1). The input variables are the parameters that will be varied to investigate the effects the simulation model has on the response variables. The response variables are the outputs of the simulation model, commonly called key performance indicators, but in this research the term *response variables* will be used.

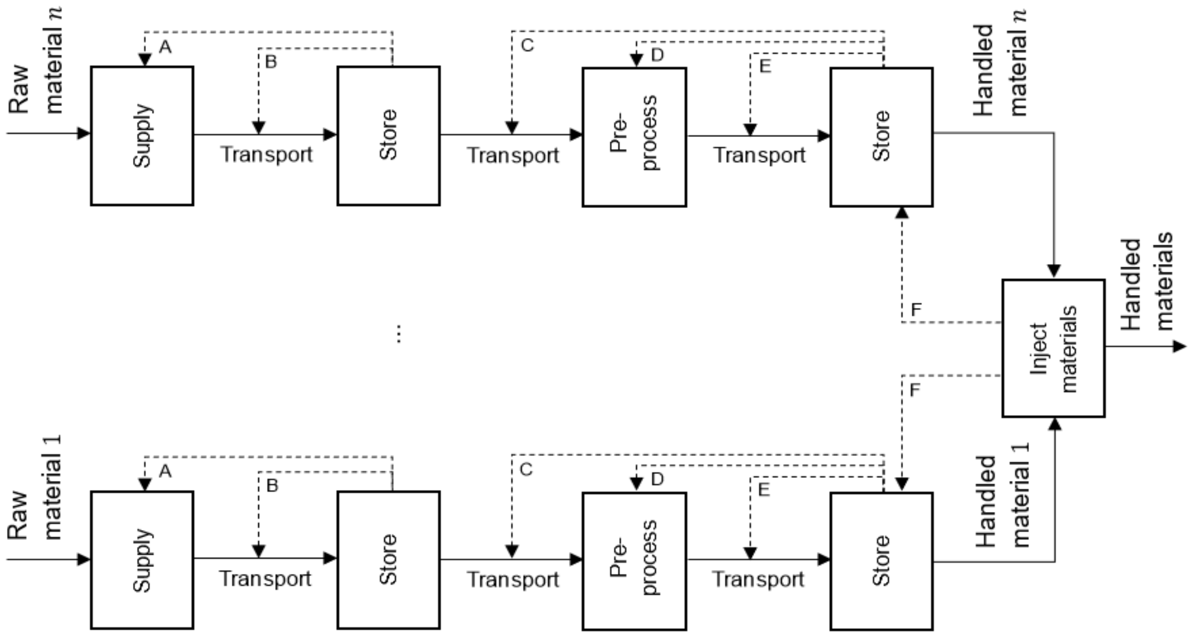

Figure 5-1: Representation of the conceptual model

Table 5-1: Processes of the conceptual model

Process	Process step	Description
Supply and transportation of raw materials	Supply raw materials	If a *reorder* is made, supply raw materials
	Transport raw materials	If materials are supplied, transport materials to the raw material storage at required flow rate.
	Set transport capacity	Set transport capacity factor to nominal or maximal capacity.
Storage of raw materials	Store raw materials	If materials entering the raw materials storage, store in the buffer.
	Supply raw materials	If there is free space, supply raw materials to the processing line at the required flow rate.
	Check storage level and make reorder	If the storage capacity is below the reorder point, *reorder* raw materials.
Pre-processing of raw materials	Transport raw materials	If there is free space available at the conveyor, transport materials at the required flow rate.
	Pre-process raw materials into handled materials	If there is free space available at the processing server, process raw materials at the required flow rate.
	Transport handled materials	If there is free space available at the conveyor, transport materials.
Storage of handled materials	Store handled materials	If materials entering the handled materials storage, store in the buffer
	Supply handled materials	Supply handled materials to the HIsarna plant at the required flow rate. Materials will only be injected when all materials are available.
Injection	Check storage level and inject handled materials	If the storage levels of all storages for handled materials exceed zero, supply materials to HIsarna at required flow rate. If one or more storages are empty, do not supply materials to HIsarna.

5-1-3 Assumptions and simplifications of the model

Since the model cannot represent all details of the storage and handling area completely, some assumptions and simplifications have been made, as listed below.

- The material flow in the storage and handling area is assumed to be a discrete flow of materials.
- The storage and handling area is working on a FIFO (First-In-First-Out) stock-handling system.
- The model must run the processing steps as defined in paragraph 3-2, detailed processing steps are neglected. This means that certain equipment, such as transition and controlling equipment, is not considered in the simulation. Furthermore, the pre-processing lines of the materials are assumed to be a blackbox, each with a dedicated capacity and estimated processing time.
- Delays and failures in the supply of materials are neglected. These may be delays of vessels with coal and iron ore, or failures of pipelines transporting BF and currently produced BOF sludge.
- Historic BOF sludge is transported by trucks with a fixed capacity of 30 mt each.
- The available quantity of materials, material properties and composition of hot metal are as defined in Chapter 2 and assumed constant.
- The demand of HIsarna is taken as constant.
- The handled materials are not checked and meet the input requirements of HIsarna.
- The failures of equipment are modelled using statistic distributed functions, as described in Appendix G. The same applies to the interarrival, loading and unloading time of the trucks and the interarrival time of BF and currently produced BOF sludge is distributed triangularly.
- Preventive maintenance of both the storage and handling line and HIsarna is not considered. Likewise, failures in the storage of handled materials and HIsarna are neglected and a continuous injection rate is assumed.
- Maximum downtime of equipment is not considered for this model. The same applies to the minimum processing time of systems.
- Redundancy of storage, transport and processing equipment is not considered in the model. For instance, the possibility to switch over to trucks for the transport of iron ore and coal in the event of a conveyor belt breaking down, or a temporary replacement of one storage system by another.
- Hot metal is produced only when all materials are available at the handled material storage.

5-2 Implementation

5-2-1 Discrete simulation

In simulation modelling, a distinction can be made between continuous and discrete modelling. In a continuous model, state variables change continuously over time, in other words, they do not change abruptly from one state into another, whereas by using a discrete simulation the state variables change only at discrete points in time [36]. These points are the specific moments an event occurs. Modelling may either be discrete, continuous, or a combination of both.

The materials at the storage and handling area of the HIsarna demonstration plant behave like a continuous flow. Therefore, continuous modelling seems a logical choice. On the other hand, discrete modelling is desired to investigate the performance and feasibility of the design of the storage and handling area, since discrete modelling supports the simulation of events, such as failures of equipment. As found in literature, it is possible to model continuous behaviour in a discrete modelling paradigm [37]. A continuous flow consists of an infinite number of small sized packages of materials; this can be accessed by modelling the material flow as small portions that are each treated discretely, as depicted in Figure 5-2 [37]. The smaller the size of the portions, the more the modelling resembles a continuous process. Increasing the number of entities, however, means an increase in computing time. In this research discrete event simulation is used.

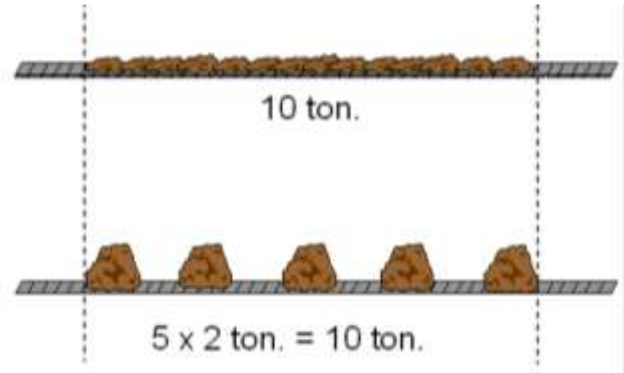

Figure 5-2: Example of discrete coal flow [37]

5-2-2 Simio®

The simulation model is built using the software program Simio®, an object-based modelling framework supporting discrete event simulation [38]. Simio® is used for a wide range of applications, such as transportation, manufacturing, healthcare, supply chain and mining field. A model is built by using several intelligent objects representing the components of the real system, such as conveyors, storages and processing systems. This makes it easier to build a model and there is no need to use a complicated programming language. Simio® provides several standard objects and processes can be added to define the underlying logic of an object. Furthermore, Simio® provides graphic animations of the behaviour of the modelled system, which improves the verification and validation process of the simulation model and at the same time provides a good view of the model [38]. An overview of the advantages and disadvantages is shown in Table 5-2.

In Simio®, a portion of materials is called an entity. The number of entities per hour can be modified to control the accuracy of the output measures and, at the same time, to adjust the computing time of a simulation run. In other words, it can be compared to the resolution of the simulation model. A few test runs have been performed to ascertain an adequate resolution. Eventually, a resolution of 50 entities was selected.

Table 5-2: (Dis)advantages of Simio®

Advantages	**Disadvantages**
Discrete event and object-based modelling framework	No optimization method
User friendly and easy to build; no complicated programming language	Less information and fewer tutorials available
Easy to adjust and expand the model	

5-2-3 Simulation model

A representation of the simulation model is given in Figure 5-3. As can be seen, the simulation model has five separated handling lines for the materials. Each handling line contains the following objects: material source and supply, transportation to the raw material storage, raw material storage, transport to the handling process, pre-processing equipment, transport to the handled material storage, handled material storage, and, finally, injection into HIsarna. In addition, after these steps the entities are destroyed at the sink. The objects are modified by entering the required input parameters, such as processing time and capacity. Furthermore, various processes are added to define the underlying logic of the objects, such as operational events (like failures), time delays and assigning a new state.
The coloured triangles (orange, green, blue, pink and yellow) are the entities in the simulation model; each colour represent a different type of material. Further, the red lines represent road transport (only for transport of historic BOF sludge to storage and handling area) and conveyor belts. The vehicle pictogram represents the truck for transport of historic BOF sludge and the green lines visualise the queues in an object.

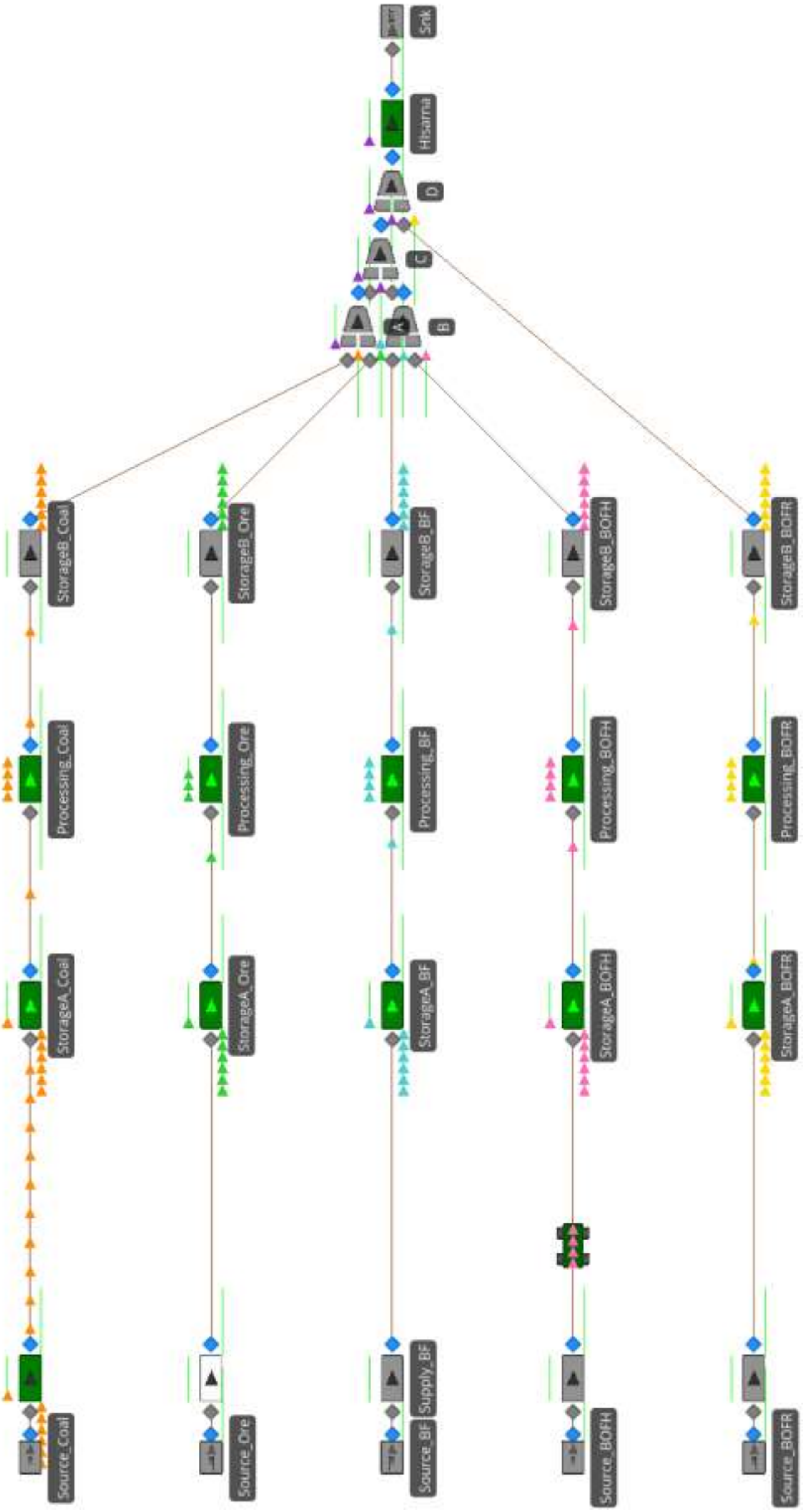

Figure 5-3: Representation of the simulation model

5-2-4 Verification

After modelling the storage and handling area of the HIsarna demonstration plant, the model must be verified. This is required to ensure that modelling and implementation of the conceptual model is done correctly [37]. In other words, the model must be checked on the presence of any programming errors ('bugs'). The following approaches are found in literature and used to verify the model: model description verification, structured walk-through, animation verification, tracing, seed (in)dependence, extreme condition testing and sensitivity analysis [39], [40]. In addition, the simulation model is verified by analytical results. As mentioned in paragraph 1-4, the validation of the simulation model is not considered for this research, since the HIsarna demonstration plant has not been realised yet.

Model description verification

The simulation model needs to complete all process steps as defined in the conceptual model. This is checked by comparing all process steps from the conceptual model (as listed in Table 5-1) to the steps that are conducted in the simulation model. No irregularities were observed during the model description verification; therefore, based on this method the model has been verified.

Structured walk-through

A structured walk-through is a static verification method, where the simulation model is explained to a third person, helping the modeller to focus on different aspects and thus detect possible flaws in the model. First, the model is explained to an employee of Tata Steel; preferably this would be someone who is knowledgeable about the storage and handling area, but with no knowledge of the model. Then, the model is explained to someone who is familiar with the simulation model, but has no knowledge of the storage and handling area. Finally, the model is explained to someone with no knowledge of either. No flaws were observed during the structured walk-through. Hence it is justified to conclude that the model functions correctly.

Animation and operational graphics

The simulation software Simio® offers a dynamic display of the behaviour of the model whilst the simulation is running. This provides information about several output parameters and can help to discover problems in the model. Examples of dynamic displays are status labels and plots, the status of equipment and the entities moving through the system. Figure 5-4 shows a part of the simulation model, where the orange triangles represent the materials moving through the system, the green boxes represent, respectively, the supply, storage and pre-processing steps of the materials, the red lines represent the conveyor belts and the green lines the queues. In addition, a green box indicates that material is being processed. If a box is coloured red, this means that a process is faulty, for instance because of a failure or error in the model. No faults were observed using animation and operational graphics. Therefore, it is safe to say that, also from the perspective, the model is verified.

Figure 5-4: Example of dynamic display provided by Simio®

Tracing

Tracing is a useful verification method to detect incorrect behaviour in the model. Several entities are run through the model to determine if the logic and implementation of the model is correct. Simio provides its own trace function for this. No irregularities were found during this test; consequently, based on tracing, it can be it can be said that the model works correctly.

Testing seed (in)dependence

Several forms of probability distributions were used to characterise parameters in the simulation model, for instance, a triangular distribution to simulate the interarrival time of materials, an exponential distribution to model the mean time to repair (MTTR) a failure, and a weibull distribution to simulate the mean time between a failure (MTBF). These distributions result in varying output variables and these must be kept limited in order to obtain accurate results. The seed (in)dependence is determined by conducting two experimental runs with a different simulation time. The first run has a simulation time of one year, the second of three years, and both runs are repeated 15 times. The effects are studied on the following output variables: the minimum, maximum and mean value of the availability of HIsarna, MTBF and MTTR. The results are shown in Table 5-3, making clear that all results show a certain amount of seed independence, but no significant fluctuations are observed. Note that the outcomes of the one-year simulation run result in a greater variability compared to the three-year run. This makes sense, since an increase in simulation time leads to more accurate results. But, since this research is related to the first stage of the design of the storage and handling area, experiments with a run length of one-year are adequately accurate.

Table 5-3: Results seed (in)dependence

Run	**Availability of HIsarna** [*%*]			**MTBF** [*d*]			**MTTR** [*h*]		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1 years	98.19	99.98	**99.34**	12.74	16.15	**14.19**	7.48	14.79	**11.26**
3 years	99.89	99.40	**99.21**	13.52	14.48	**13.96**	9.23	12.78	**11.13**

Extreme condition tests

The model should work correctly with any combination of input parameters, no matter how extreme or unlikely. This is verified using the extreme condition tests. First, several experimental runs are performed with low and high parameter values. The model output must correspond to the expected output of the simulation runs. The effects are studied on the throughput of HIsarna, in other words, the hot metal production. The expected values are categorised into low, medium, (initial) and high values compared to the initial production rate of HIsarna. An overview of the tests and expected effects on the throughput of HIsarna is provided in Table 5-4. In addition, the initial throughput is equal to the initial throughput of HIsarna. All simulation outputs appear to verify the expected values. For instance, the results of the run with a low storage capacity of handled materials is represented in Figure 5-5. The upper graph shows the storage level of the handled material storage, and the lower graph represents the material injection into HIsarna. As can be seen in both graphs, from a qualitative point of view, the graphs match each other's behaviour; if the storage contains no materials, none are injected into HIsarna. From a quantitative perspective, this test leads to a match factor of 95% (based on material being unavailable both at HIsarna and the handled material storage). This similarity is sufficient proof that the model can be verified.

Secondly, several tests are performed with parameter values set to zero. The effects of these tests are also studied on the throughput of HIsarna. The experimental runs are listed in Table 5-5. The model appears to work correctly for these parameters. For instance, the results of the parameter *supply amount of one raw material* is represented in Figure 5-6. The graphs give the same outcome as in the previous test: if one of the materials is not supplied to the storage and handling area, none of the materials are injected into HIsarna. This test results in a match factor of 100%; therefore, it is safe to conclude that this part can be verified quantitatively. Note that all tests are conducted with a random seed of one.

Table 5-4: Extreme condition test - Low and high parameter values

Parameter		**Value**	**Expected output**
Interarrival time of materials	[s]	1	Initial throughput
	[h]	1,000	Low throughput
Amount of material supply	[ent]	1	Low throughput
		1,000	Initial throughput
Storage capacity raw materials	[h]	1	Medium throughput
		10,000	Initial throughput
Storage capacity handled materials *(Figure 5-5)*	[h]	1	Low throughput
		10,000	Initial throughput
Processing times	[s]	1	Initial throughput
	[h]	100	Initial throughput
Availability of equipment	[%]	1	Low throughput
		100	Initial throughput
Capacity HIsarna	[mt/y]	1	Low throughput
		2 million	High throughput

Table 5-5: Extreme condition test - Parameter values of zero

Parameter		**Value**	**Expected output**
Amount of supply (one material) (*Figure 5-6*)	[ent]	0	Zero throughput
Amount of supply (all materials)	[ent]	0	Zero throughput
Storage capacity raw materials	[h]	0	Medium throughput
Storage capacity handled materials	[h]	0	Low throughput
Processing times	[s]	0	Initial throughput
Availability of equipment	[%]	0	Zero throughput
Capacity HIsarna	[mt/y]	0	Zero throughput

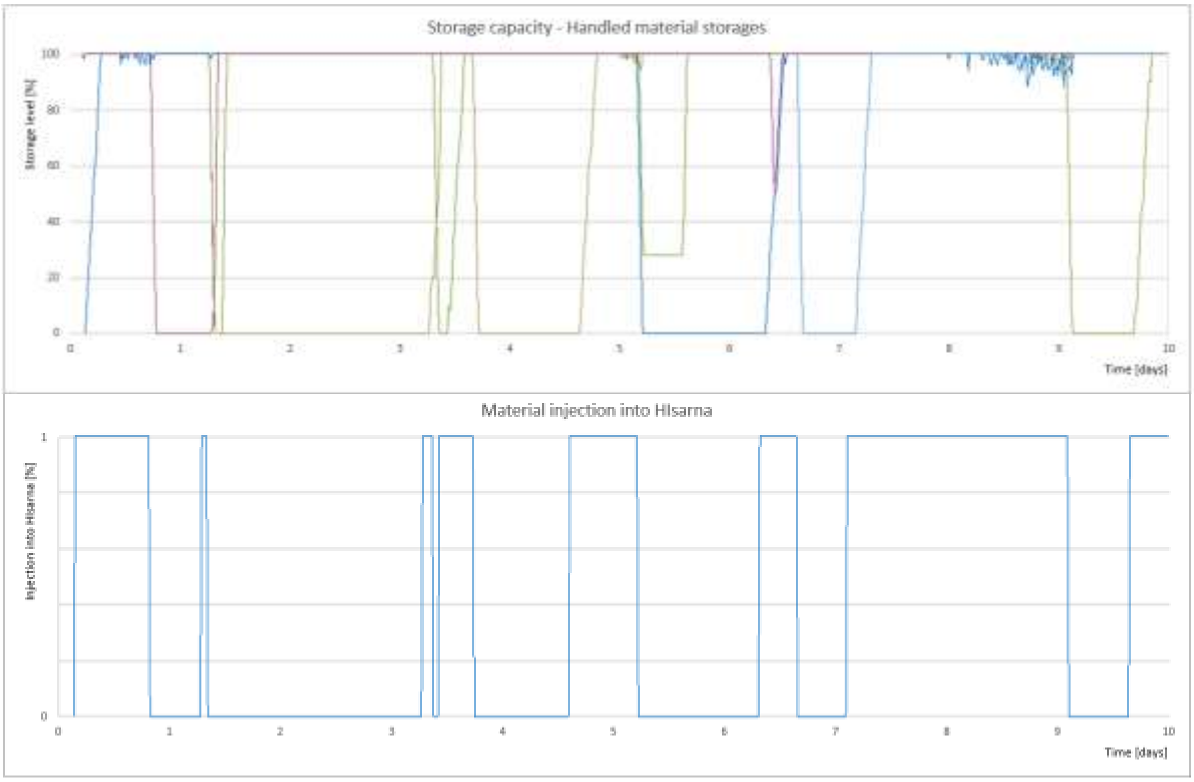

Figure 5-5: Extreme condition tests - Condition 1

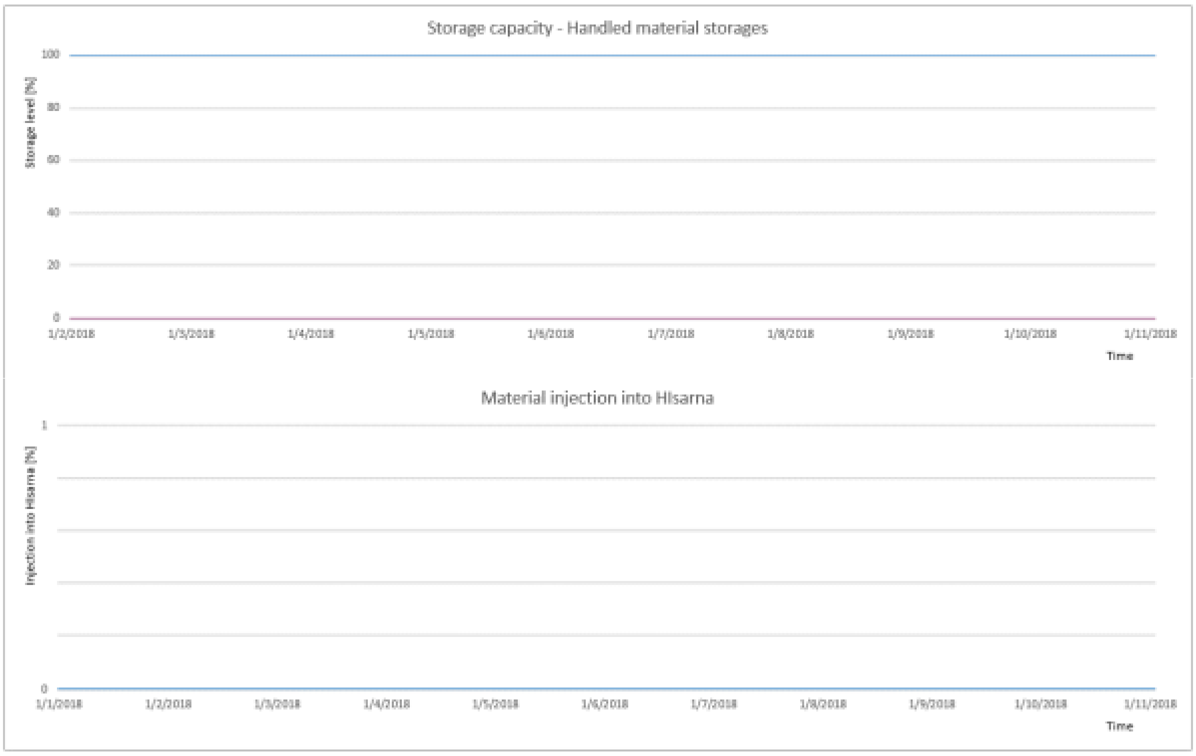

Figure 5-6: Extreme condition tests - Condition 2

Sensitivity analysis

For the sensitivity analysis, several input parameters of the model are varied to determine the effect on the model's behaviour and output of the system. The same behaviour should occur in the model as expected in the real system. The sensitivity analysis is performed for the following input parameters: the required capacity of HIsarna, processing times of materials, and storage capacity of materials. The parameter levels are considered at +/- 20% and +/- 10% of the initial design values. As can be seen in Table 5-6, no difference in throughput is obtained by altering the capacity of raw material storage, the capacity of the handled material storage, and the processing times. However, a difference in throughput is found by varying the parameter *capacity of HIsarna*, but these results correspond to the expected results. In summary, no significant deviations have been observed during the sensitivity analysis; therefore, it is safe to say that the model works correctly.

Table 5-6: Sensitivity analysis – Throughput HIsarna [mt/y]

Parameter	**In/Output**	**- 20%**	**- 10%**	**+/- 0%**	**+ 10%**	**+ 20%**
Capacity raw material storage [*h*]	Input	38.4	43.2	48.0	52.8	57.6
	Output	*1.200*	*1.200*	*1.200*	*1.200*	*1.200*
Capacity handled material storage [*h*]	Input	57.6	64.8	72.0	79.2	86.4
	Output	*1.200*	*1.200*	*1.200*	*1.200*	*1.200*
Processing time [*min*]	Input	16	18	20	22	24
	Output	*1.200*	*1.200*	*1.200*	*1.200*	*1.200*
Capacity HIsarna [million mt]	Input	0.96	1.08	1.20	1.32	1.44
	Output	*0.960*	*1.080*	*1.200*	*1.320*	*1.440*

Randomness is disabled during these tests; this means that during a simulation run the sampling of any random distribution will return the expected value (the mean) of the distribution, instead of a random variate. This is often useful to facilitate verification and debugging. This is a function within Simio®.

Analytical results

All calculations within the simulation model are checked with analytical results to verify if the model works correctly. The calculations include the mass flow of materials and processing times of the storage and handling area. The material flow comprises the material input at the storage and handling area, the losses due to pre-processing of materials, and the material output of the storage and handling area (this is the input into HIsarna). As stated by Kleijnen, verifying simulation responses that are influenced by ‘rare events’ such as failures, is practically impossible to do by hand [41]. In these situations, modellers may verify the simulation response by running a simplified version of the simulation program with a known analytical solution [41]. Therefore, each distribution in the simulation model is made constant, and besides, the failures are not considered during these tests. The results of the calculations of the material flow and processing times are listed in respectively Table 5-7 and Table 5-8. As can be seen in the tables, the model outputs correspond to the results of the calculations made by hand. Based on these calculations, it can be said that the model works correctly.

Table 5-7: Hand calculations versus model outputs – Material flows (for design parameters)

[redacted]

Table 5-8: Hand calculations versus model outputs – Process times coal (for design parameters)

Process step	**Time** [min]	
	Hand calculations	Model output
Transport to storage and handling area	10.0	10.0
Raw material storage	≤ 48.0 · 60	*(max.)* 47.6 · 60
Transport to handling area	2.0	2.0
Processing time	20.0	20.0
Transport to handled material storage	2.0	2.0
Handled material storage	≤ 72.0 · 60	*(max.)* 71.5 · 60

5-3 Conclusion

The following sub-question has been answered by this chapter:

How can the storage and handling area of the HIsarna demonstration plant be modelled and verified?

The model of the storage and handling area of the HIsarna demonstration plant has been discussed in this chapter. This model can be used to investigate the feasibility of the design. First a conceptual model is created and afterwards the simulation is built using Simio®, a widely used object-oriented software package. In addition, the storage and handling area is discretely simulated.

To make sure that the modelling and implementation of the conceptual model is done correctly, the model is verified. This was done by using the following approaches: model description verification, structured walk-through, animation verification, tracing, seed (in)dependence, extreme condition testing, sensitivity tests. In addition, the simulation results are compared to analytical results. No noticeable discrepancies were observed during these tests, which sufficiently proves that the modelling and implementation of the conceptional model was done correctly.

Chapter 6

Design optimization and feasibility study

This chapter evaluates the performance of the initial design of the storage and handling area of the demonstration plant, as defined in Chapter 4. In addition, this chapter investigates which input parameters affect the response variables considered for this design, in order to arrive at the optimal parameter settings, resulting in the best design of the storage and handling area for Tata Steel IJmuiden. The performance of the designs is verified by using the simulation model described in Chapter 5. Finally, the feasibility of the selected location will be studied.

First, the methodology used for the design optimization will be discussed in paragraph 6-1; this consists of the considered response and input variables, the experimental design, and the number of replications. Subsequently, the design analysis will be provided in paragraph 6-2, including the performance of the initial design and the determination of the significant input parameters. Next, the optimal design parameter settings will be found in paragraph 6-3. The options for redundancy to improve the reliability of the storage and handling area will be given in paragraph 6-4. Further, the feasibility of the location is elaborated on in paragraph 6-5. Finally, the fifth sub-question will be answered in paragraph 6-6.

6-1 Methodology

Two experiments are performed, investigating the performance of the initial design and to identify the significant parameters. Both experiments are carried out using the simulation model.

This paragraph discusses the methodology used for the design optimization. First, the response variables, used to express the performance of the design of the storage and handling area, will be defined in 6-1-1. The considered input variables will be provided in paragraph 6-1-2. The experimental design is detailed in paragraph 6-1-3, the focus will be on the fractional factorial design, which is used to investigate the factor effects. Finally, the simulation time-length and required number of replications will be discussed in 6-1-4.

6-1-1 Response variables

The performance of the design of the storage and handling area is expressed using the following four response variables: the storage turnover ratio, the availability of materials, the refilling time and the storage costs. These are described in Table 6-1. In addition, the expressions for each response variable are provided in Table 6-2.

Table 6-1: Response variables

Response variables		Description
y_1	Storage turnover [-]	Expresses the efficiency of a storage and is given by Equation 3. It represents the number of times the storage must be replaced during a year. A low turnover causes overstocking and non-moving inventory. Therefore, the storage turnover ratio needs to be maximised. A high storage turnover can also result in unreliable stocks.
y_2	Availability of materials [%]	Represents the proportion of time that all materials are available and injected into HIsarna. In addition, the availability of materials in the storage systems is considered. A high availability of materials is required to obtain reliable and continuous production of hot metal. This response variable is given by Equation 4.
y_3	Refilling time [*h*]	Expresses the required time to increase the storage level of the handled material storage by one day of production of HIsarna; this is given by Equation 5. This response variable focuses on the handled material storage, since this storage may yield the most serious consequences. A shorter time needed to refill a storage contributes to a more reliable system.
y_4	Storage costs [€]	Denotes the costs for storing materials and it covers the interest on the value of stored materials and the capital expenditures for storage systems, as given by Equation 6. This response variable must be minimised.

Table 6-2: Expressions response variables

Expression response variable	*Reference*
$\boldsymbol{y_1} = \frac{C_{HIsarna}}{C_{storage}}$	*Equation 3*
$\boldsymbol{y_2} = \frac{\sum t_{available}}{t_{total}}$	*Equation 4*
$\boldsymbol{y_3} = \frac{C_{storage} \cdot \eta_R}{\dot{m}_{in} - \dot{m}_{out}}$	*Equation 5*
$\boldsymbol{y_4} = \boldsymbol{c_m} \cdot \boldsymbol{c_s}$	*Equation 6*

Where:

$C_{HIsarna}$	Annual capacity of HIsarna [mt]
$C_{storage}$	Capacity of storage [mt]
$t_{available}$	Time a material is available at the storage [h]
t_{total}	Total time of the simulation run [h]
$\dot{m}_{\mathrm{in}}$	Incoming mass flow into the handled material storage [mt/h]
$\dot{m}_{\mathrm{out}}$	Outcoming mass flow to HIsarna [mt/h]
η_R	Required refill capacity of raw material storage [%]
c_m	Interest calculated over stored material [€]
c_s	Yearly costs of capital expenditures storage systems [€]

6-1-2 Input variables

As described before, the analysis of the design covers both the performance of the initial design and the investigation of input parameters affecting the defined response variables. The significant parameters are studied by altering the four input variables of the storage and handling area, as listed in Table 6-3. These input variables include the capacity of raw material storage (A), capacity of handled material storage (B), supply capacity ratio (C) and the processing capacity ratio (D). Each factor is characterised by two levels, which are also given in Table 6-3. Two levels are recommended in the early stages of a design when linear behaviour is expected. The selection of a level takes place by taking a lower (1) and higher (2) parameter value and compare these to the parameters of the initial design. The parameter levels of the initial design are also shown in this table. A complete overview of the input parameters is provided in Appendix G.

Table 6-3: Input variables

Input parameters		**Description**	**Initial level**	**Levels fractional factorial design**	
				Low (1)	High (2)
A	Capacity of raw material storage	The capacity of the raw material storage [*d*].	2	1	3
B	Capacity of handled material storage	The capacity of the handled material storage [*d*].	3	2	4
C	Capacity ratio of materials supplied	The relation between the supply capacity of raw materials, and the required capacity of HIsarna [-].	1.3[1]	1.2	1.4
D	Capacity ratio of material handling	The relation between the capacity of the handling area and the required capacity of HIsarna [-].	1.3[1]	1.2	1.4

[1] *Based on pre-processing of raw material in literature* [42]

6-1-3 Experimental design

Two experiments are performed by using the simulation model. The first experiment is carried out with the initial design parameter settings. The second experiment is aimed at identifying the significant parameters effects; this is done by using a method called *design of experiments,* or *experimental design*.

Design of experiments, or experimental design, is used to investigate the significant parameter effects on the response variables. Experimental design is a statistical approach where multiple input variables are varied simultaneously, instead of the One-Factor-At-a-Time method where only one factor is changed in each experimental run [43]. Experimental design significantly reduces the number of experimental runs needed. In addition, the quality and information gained from an experiment will improve by using experimental design [44]. Furthermore, the relations between the factors, also called interaction effects, can be investigated by this approach [43].

There are several experimental designs, such as full factorial design, fractional factorial, orthogonal arrays by Taguchi and response surface method. Fractional Factorial design is the most appropriate design for this experiment, because of the number of considered factors and levels [43], [45], [46]. In addition, this design is a popular tool for industrial research and process improvement [44]. Fractional factorial design is a subset of a full factorial design and investigates only the most important main and interaction effects [43]. This method requires significantly fewer experimental runs compared to full factorial design; in this case, eight instead of 16 experimental runs are required [43]. The experimental matrix is listed in provided in Table 6-4.

Table 6-4: 2^{4-1}fractional factorial design (I) and filled in with considered levels (II) [43]

#	A	B	C	D
1	1	1	1	1
2	2	1	1	2
3	1	2	1	2
4	2	2	1	1
5	1	1	2	2
6	2	1	2	1
7	1	2	2	1
8	2	2	2	2

#	A	B	C	D
1	1	2	1.2	1.2
2	3	2	1.2	1.4
3	1	4	1.2	1.4
4	3	4	1.2	1.2
5	1	2	1.4	1.4
6	3	2	1.4	1.2
7	1	4	1.4	1.2
8	3	4	1.4	1.4

6-1-4 Simulation time and replications

Each simulation run is given a simulation time of one year and replicated 15 times. The replications are performed to increase the accuracy of the results. The Simple Graphical Method by Robinson is used to determine the required number of replications. This method compares the cumulative mean of an output variable to the number of replications [47]. The distributions of the failures are examined, since these show the greatest variety in values. The method is discussed in more detail in Appendix H. The verification of the simulation length is provided in paragraph 5-2-4.

6-2 Design analysis

The experimental plan has been carried out to give an analysis of the performance of the design of the storage and handling area of the HIsarna demonstration plant. Initially, the performance of the initial design of the storage and handling area is examined, then, the input parameters which have an effect on the response viariables are identified. Both are discussed for each response variable. First, the storage turnover ratio is elaborated on in 6-2-1. Next, the availability of materials is discussed in paragraph 0. Subsequently, the refilling time of handled material storage is evaluated in paragraph 6-2-3. And finally, details of the storage costs of the storage and handling area are given in paragraph 6-2-4.

6-2-1 Storage turnover ratio

As described in paragraph 6-1-1, the storage turnover expresses the efficiency of a storage system; a high turnover represents a fast-moving storage and in contrast, a low turnover represents a slow-moving storage. A high storage turnover is preferred because it leads to an efficient and fast-moving storage. Moreover, a high storage turnover improves the flexibility of the storage and handling area. On the other hand, a high storage turnover ratio may decrease the reliability of the system.

Initial design parameters

First, the storage turnover ratio is determined for the storages of the initial design of the storage and handling area. The results are shown in the second column of Table 6-5. For instance, the storage turnover ratio of the handled material storages is 122, meaning that these storages must be replaced 183 times per year. As seen in the table, the storage turnovers of the raw material storages of coal, iron ore and historic BOF sludge are more efficient compared to those of the handled material storage. This is because the handled material storages require a higher capacity, which is caused by the lower reliability of the handling lines and the need for a continuous injection of materials into HIsarna. In addition, the lower storage turnover ratio of the raw material storages of BF and currently produced BOF sludge results from the fact that these materials do not have a general storage facility separate from the storage and handling area of HIsarna, as discussed in paragraph 0.

Comparison of these values to storage turnover ratios of other storages will give a decent impression of the feasibility of the design. As mentioned in paragraph 3-1, the storages of the HIsarna pilot plant provide a storage capacity for one day, in other words, this means a storage turnover ratio of 365. Consequently, the storages of the pilot plant are more efficient compared to the designed storages of the demonstration plant. However, the storages of the demonstration plant have a higher reliability. This might be a crucial advantage, since, as can be seen in paragraph 3-1, one of the bottlenecks identified during the system analysis of the pilot plant is the low storage capacity, possibly resulting in unavailability of materials. In addition, the results are compared to the storage turnovers of the interim material stocks at the blast furnaces. These storages have a storage capacity for one or two days, resulting in a storage turnover ratio of respectively 365 and 183. However, it must be noted that these storages provide several options for redundancy.

Table 6-5: Results of the storage turnover rate [-]

Storage	*Initial design*	Fractional factorial design							
		1	2	3	4	5	6	7	8
Raw material storages for coal, iron ore and historic BOF sludge	*183*	365	122	365	122	365	122	365	122
Raw material storages for BF and currently produced BOF sludge	*52*	46	61	46	61	46	61	46	61
Handled material storages	*122*	183	183	91	91	183	183	91	91

Parameter effects

Table 6-5 also gives the results of the fractional factorial design for the *storage turnover ratio*. The storage turnover ratios of raw material storages vary between 122 and 365. The high storage turnovers (365) are achieved at runs in which the storage capacity is at low level. The opposite is true for the low storage turnover ratios. The high storage turnovers correspond to the turnover ratios of the HIsarna pilot plant. The storage turnover ratios of the handled material storages vary between 91 and 183 replenishments per year.

The parameters affecting the storage turnover ratio of the raw material and handled material storage are identified using Pareto charts, which are shown in Figure 6-1. On the Pareto chart, bars that cross the reference line (the red dotted line at 0.0) are marked as significant [48]. As can be seen in these charts, the storage turnover ratios are only influenced by the storage capacity (parameters A and B). The parameters *capacity ratio of supply material* (parameter C) and *capacity ratio of handling material* (parameter D) do not affect the storage turnover ratios.

Figure 6-2 shows the main effects plots of the storage turnover ratios of the raw material and the handled material storages. A main effect plot shows how the mean response reacts on the different levels of a parameter. When the line is horizontal (parallel to the x-axis) means that there is no main effect present. When the line is not horizontal, the main parameter effect is significant. The steeper the slope of the line, the greater the significance of the effect. The dotted line represents the overall mean of the response.

As depicted, the storage turnover ratios increase by decreasing the storage capacity. For instance, by reducing the storage capacity of the raw material storage to one day, the storage turnover ratio rises to 365.

The best storage turnover ratio of the raw material storage is obtained with the following parameter set: **A1 – B1/2 – C1/2 – D1/2**. Here, A1 means that the *capacity of raw material storage* affects the storage turnover ratio and results in the best performance with low parameter level. In addition, B1/2 means that the capacity of handled materials has no significant effect on this response variable.

Besides, the highest storage turnover ratio for handled materials is arrived at with the parameter setting **A1/2 – B1 – C1/2 – D1/2**.

In summary, by combining these results, the optimal storage turnover ratios of the storage and handling area are achieved with the following parameter settings: **A1 – B1 – C1/2 – D1/2**.

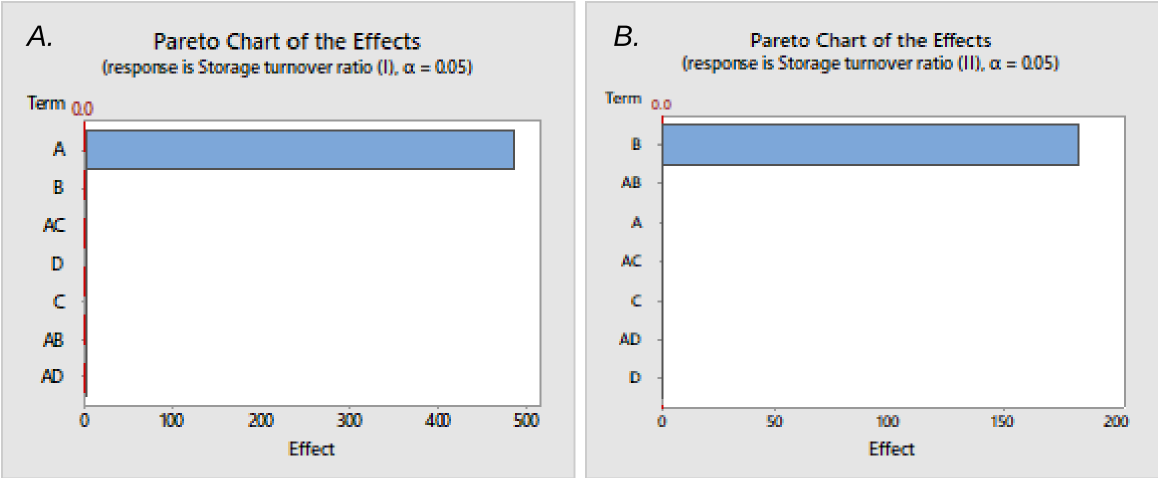

Figure 6-1: Pareto charts storage turnover ratio: A. Raw material storage, B. Handled material storage. Where, the letters A-D represents the parameters, note that AB represents the interaction affect between parameter A and B.

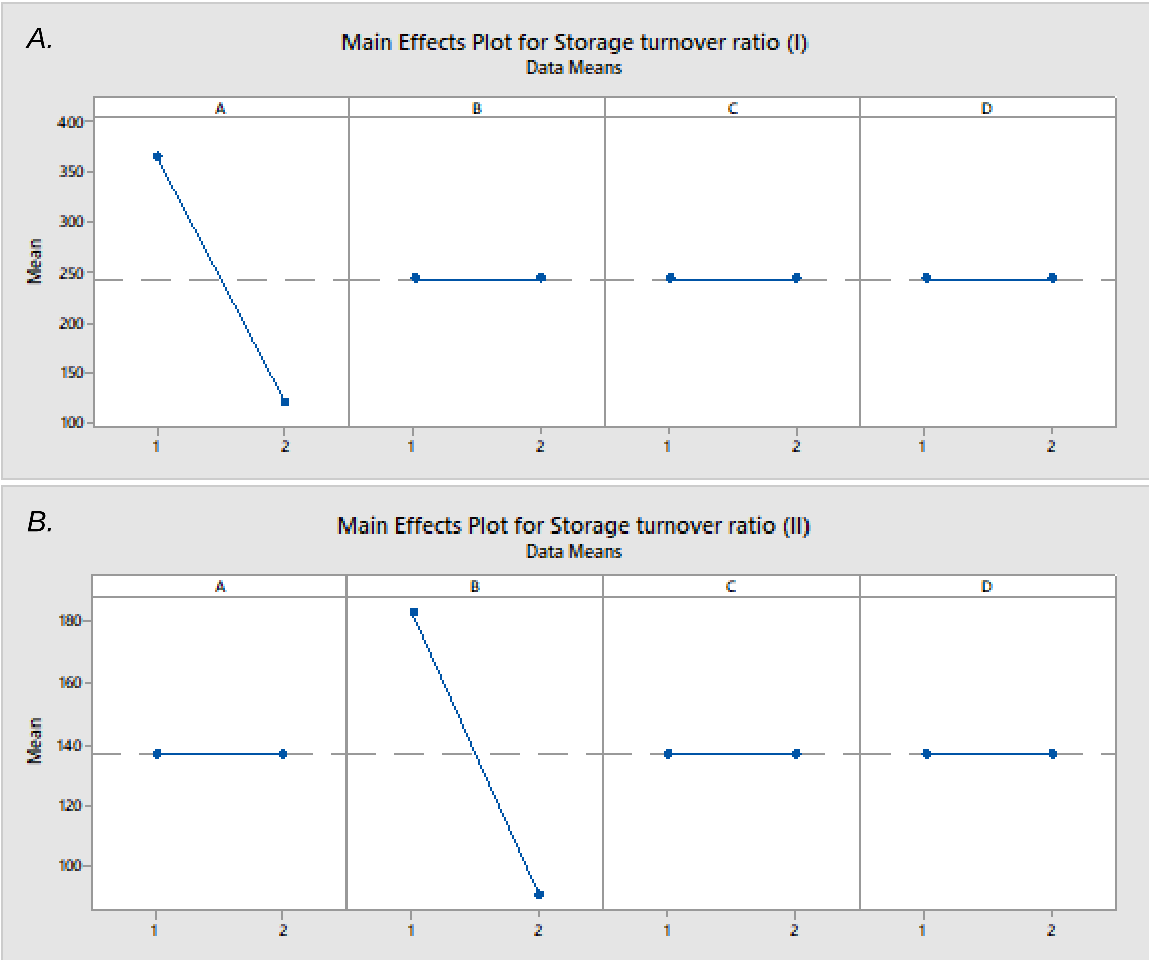

Figure 6-2: Main effects plots storage turnover ratio: A. Raw material storage, B. Handled material storage. Where, the letters A-D represents the parameters, the numbers 1 and 2 represents the considered levels.

6-2-2 Availability of materials

The second response variable is the availability of materials; a high availability of materials is required to ensure a continuous injection into HIsarna, and thus to achieve a reliable production of hot metal. A higher availability of materials will also result in a more reliable system but, on the other hand, in higher storage costs. This response variable focuses on the availability of materials at HIsarna; additionally, the availability of materials at both storages is discussed.

Initial design parameters

Availability of materials at HIsarna

The initial design of the storage and handling area results in an availability of material at HIsarna of **99.34%**, as is shown in the second column of Table 6-6. In addition, to provide a better impression, the number of hours lost as a result of unavailability of materials is also shown in this table. It seems the outcome is workable; on a yearly basis, it appears that in total for approximately two and half days no handled materials will be injected into HIsarna.
Obviously, the impact of the unavailability of materials depends on the duration of each unavailability. For instance, the unavailability caused by one large failure will have a more significant effect than several small failures. In other words, long-time unavailability of materials at HIsarna can result in a shutdown, at huge costs. Since the detailed characteristics of HIsarna have as yet not been established, additional research is recommended to investigate these effects in more detail. A possible solution might be found by designing the HIsarna plant in such a manner that, for a limited time, the production of hot metal can continue without injecting new materials.

Table 6-6: Availability of materials – Injection into HIsarna

		Initial design	Fractional factorial design							
			1	2	3	4	5	6	7	8
Availability of materials	[%]	99.34	93.09	97.82	99.71	96.33	97.63	93.80	95.94	99.89
	[*h*]	58	605	191	25	321	208	543	356	10

In addition, the shutdown costs of HIsarna are stated in Table 6-7, providing an idea of the financial consequences of such a shutdown. According to Tata Steel, the shutdown costs of HIsarna should be estimated at €1,500 per hour; these are the costs to keep HIsarna manned during a shutdown. Note, this does not include profit loss and other costs. A rough estimate of the profit loss during a shutdown is also listed in Table 6-7, based on an assumed profit of €250.- per mt of produced hot metal. As can be seen in the table, these costs are quite substantial.

Table 6-7: Costs due to material unavailability

Run	**Shutdown costs** [€]	**Profit loss** [€]
Initial	86,724	2,168,100
1	*907,974*	*22,699,350*
2	286,452	7,161,300
3	38,106	952,650
4	482,238	12,055,950
5	311,418	7,785,450
6	814,680	20,367,000
7	533,484	13,337,100
8	*14,454*	*361,350*

Availability of materials – Raw and handled material storages

The available materials of the storages are listed in Table 6-9, including the availabilities of material calculated over 100%, 10-100% and 20-100% of the storage capacity. The colours indicate the range of the availability, where red represents an availability below 95% and yellow an availability between 95% and 98%. As can be seen in the table, the availabilities of the raw material storages vary between 99.87% and 100%. The availability of storage for handled materials lies between 99.73% and 99.97% and for 99.30% of the time, the raw material storages are filled to at least 20% of storage capacity. The handled material storages use more than 10% of its storage capacity for at least 98,96 of the time, and over 20% for 97,60% of the time.

Parameter effects

Availability of materials - Injection HIsarna

The results of the fractional factorial design for the *availability of materials* at HIsarna are listed in Table 6-6 as well. As can be seen in the table, the availability of materials varies between 93.09 and 99.89 percent. The first run, with the parameter settings A1 – B1 – C1 – D1 (all parameters set at low level), results in the lowest availability of materials. An availability of 93 percent means 25 days without material injection into HIsarna but an availability of materials of 99.89 percent results in only a half day without material injection. It makes sense that small storage capacities (A and B) in combination with a low *handling capacity ratio* (D) result in a low availability of materials. The highest availability of materials is achieved in run eight, with the parameter settings A2 – B2 – C2 –D2 (all parameters set at high level). The third run results in the second best availability of materials (99.71%); this run has the following parameter settings: A1 – B2 – C1 – D2. By comparing these results, it can be concluded, that the parameters A and C do not have a significant effect on this response variable.

The parameter effects are also identified using a Pareto chart, shown in Figure 6-3. As can be seen in the figure, the availability of materials is influenced by the capacity ratio of the handling area (D) and the storage capacity of handled materials (B), since these parameters cross the red dotted reference line. These parameter effects are depicted in the main effects plot, represented in Figure 6-4 As can be clearly seen, the availability of materials of injection into HIsarna is enhanced by increasing both the capacity of handled materials storage (B) and the capacity ratio of the handling area (D). It can be concluded that the highest availability of materials is achieved with the following parameter set: **A1/2** – **B2** – **C1/2** – **D2**. Note that in the Pareto chart none of the interaction effects are marked as significant.

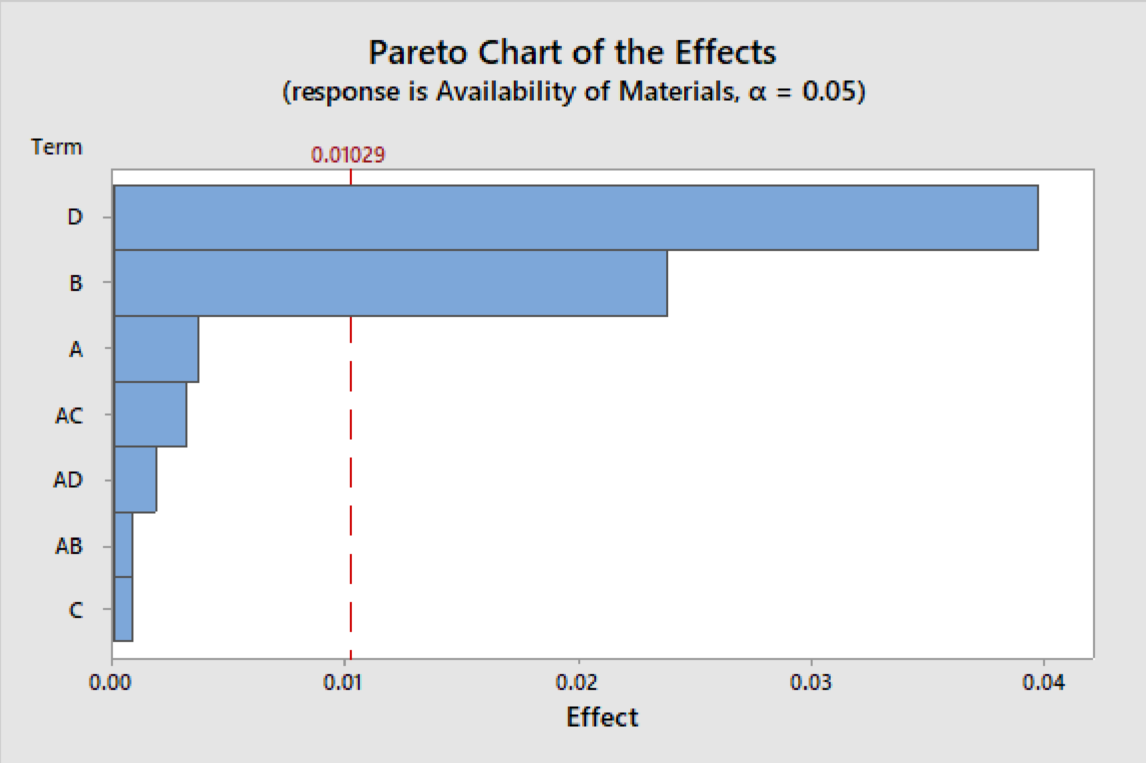

Figure 6-3: Pareto chart – Availability of materials at HIsarna

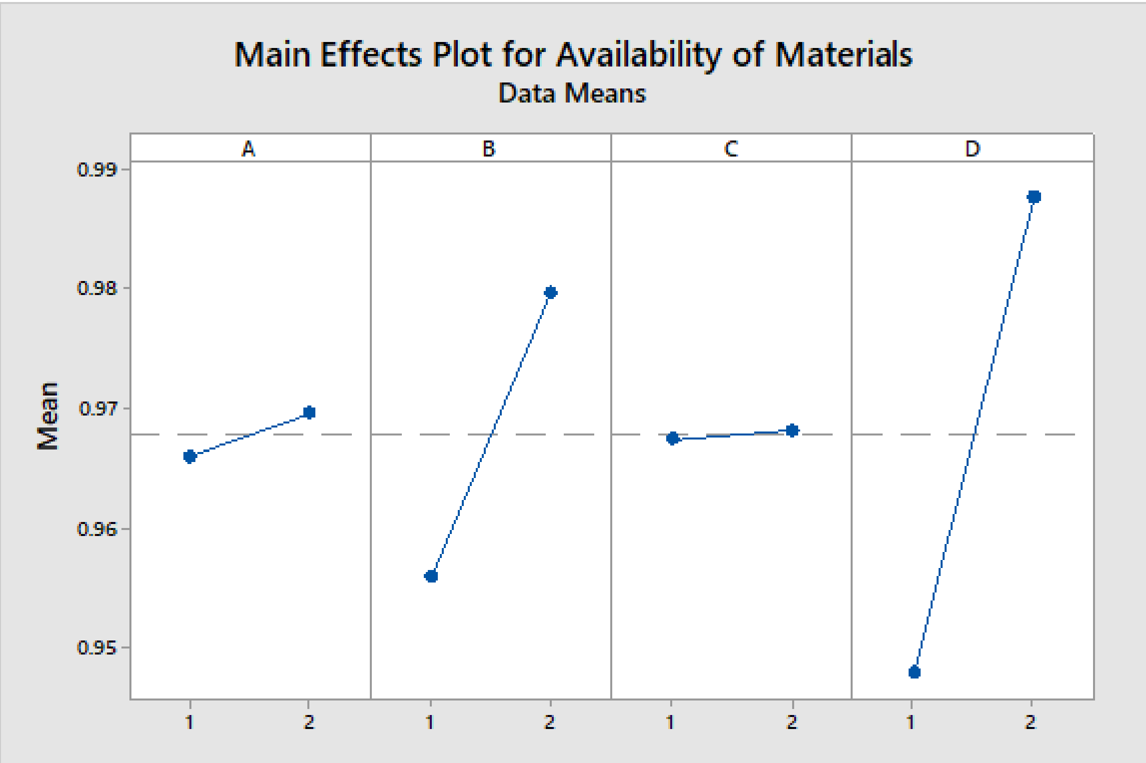

Figure 6-4: Main effects plot - Availability of materials at HIsarna

Availability of materials – Raw and handled material storages

Secondly, the material availabilities of the storages, obtained during the fractional factorial design, are listed in Table 6-9. In general, the material availabilities for the handled material storage show a lower result than for the raw material storage. This can be explained by the fact that the reliability of the supply and transport of raw materials to the storage and handling area is higher than that of the storage and handling area itself. In addition, it must be noted that for the simulation model it is assumed that the availability of the raw materials supply is 100 percent (for example, the materials at the general storages of Tata Steel).

As can be seen in the table, the highest availabilities at the raw material storages are achieved in runs four, six and eight, with respectively the parameter settings A2 – B2 – C1 – D1, A2 – B1 – C2 – D1 and A2 – B2 – C2 – D2; these setting all yield an availability of (nearly) 100 percent. The common factor for these runs is the high capacity of the raw material storage. On the other hand, the lowest availabilities of materials are obtained in run three, with the parameter settings A1 – B2 – C1 – D2.

For the handled material storages, the highest and lowest availabilities are achieved in the same runs as for the availabilities for injection into HIsarna. As can be seen in the table, the availability of materials in run 1, 4, 6 and 7 varies between 76 and 97% (calculated over 10-100% of the storage capacity), and between 60% and 93% when calculated over 20-100% of the storage capacity.

Conclusion

In summary, the optimal parameter settings for the total availability of materials is **A2** – **B2** – **C2** – **D2**, as presented in Table 6-8. In other words, a higher capacity of all parameters results in a higher availability of materials.

Table 6-8: Optimal parameter settings availability of materials

Availability of materials	**A**	**B**	**C**	**D**
Injection HIsarna	1/2	2	1/2	2
Raw material storage	2	1/2	2	1/2
Handled material storage	1/2	2	1/2	2
Total	**2**	**2**	**2**	**2**

Table 6-9: Availability of materials – Raw and handled material storages

Run	Material	Storage A [%]			Storage B [%]		
		> 0%[1]	≥ 10%[2]	≥ 20%[3]	> 0%[1]	≥ 10%[2]	≥ 20%[3]
Initial	Coal	99.92	99.83	99.50	99.86	98.96	97.60
	Iron ore	99.87	99.71	99.30	99.92	99.23	98.28
	BF sludge	100.00	100.00	99.93	99.73	98.91	97.48
	Historic BOF sludge	100.00	99.97	99.94	99.97	99.57	98.68
	Currently produced BOF sludge	100.00	99.98	99.83	99.84	99.22	98.19
1	Coal	98.75	98.55	97.39	97.28	87.89	78.00
	Iron ore	98.69	98.43	97.07	98.11	90.15	82.78
	BF sludge	100.00	100.00	99.98	98.52	94.60	89.81
	Historic BOF sludge	99.87	99.56	99.41	98.11	94.25	89.12
	Currently produced BOF sludge	100.00	100.00	99.96	99.64	95.28	90.34
2	Coal	99.97	99.82	99.58	99.52	98.29	96.83
	Iron ore	99.94	99.88	99.53	99.61	98.65	97.32
	BF sludge	99.86	99.75	99.73	99.84	98.60	97.32
	Historic BOF sludge	100.00	100.00	99.98	99.36	98.80	97.61
	Currently produced BOF sludge	100.00	100.00	100.00	99.47	98.72	97.41
3	Coal	97.36	93.69	88.48	99.97	99.82	99.35
	Iron ore	97.69	93.74	88.64	99.89	99.12	98.19
	BF sludge	99.95	99.73	98.52	99.94	99.77	99.50
	Historic BOF sludge	99.84	99.59	99.45	99.98	99.81	99.53
	Currently produced BOF sludge	99.98	99.90	99.50	99.95	99.78	99.41
4	Coal	100.00	99.96	99.82	98.63	82.97	70.35
	Iron ore	99.98	99.86	99.58	98.96	92.02	84.40
	BF sludge	100.00	100.00	99.99	99.32	97.17	93.53
	Historic BOF sludge	100.00	99.97	99.95	99.02	93.83	87.96
	Currently produced BOF sludge	100.00	100.00	100.00	99.54	94.75	88.08
5	Coal	98.74	98.38	97.36	99.36	98.43	96.97
	Iron ore	98.90	98.60	97.65	99.32	98.44	96.93
	BF sludge	100.00	100.00	99.91	99.74	98.56	97.22
	Historic BOF sludge	99.73	99.57	99.42	99.58	98.49	97.19
	Currently produced BOF sludge	99.99	99.94	99.87	99.51	98.74	97.57
6	Coal	100.00	99.96	99.85	97.65	89.66	81.10
	Iron ore	100.00	99.99	99.92	98.42	92.64	85.90
	BF sludge	100.00	100.00	100.00	98.76	94.28	89.21
	Historic BOF sludge	100.00	100.00	99.99	98.93	95.04	90.65
	Currently produced BOF sludge	100.00	100.00	100.00	99.89	93.99	88.70
7	Coal	99.46	98.93	98.15	97.83	76.18	60.05
	Iron ore	99.36	98.78	97.95	98.92	91.28	84.18
	BF sludge	100.00	100.00	99.96	99.76	97.01	93.06
	Historic BOF sludge	99.81	99.64	99.52	99.87	95.23	89.31
	Currently produced BOF sludge	100.00	99.97	99.89	99.51	95.41	90.57
8	Coal	100.00	99.92	99.84	99.97	99.88	99.72
	Iron ore	100.00	99.92	99.75	99.98	99.85	99.66
	BF sludge	100.00	100.00	99.97	100.00	99.97	99.85
	Historic BOF sludge	100.00	99.96	99.94	100.00	99.95	99.80
	Currently produced BOF sludge	100.00	100.00	99.98	99.93	99.69	99.43

[1] The material availability calculated over 100% of the storage capacity
[2] The material availability calculated over 10-100% of the storage capacity
[3] The material availability calculated over 20-100% of the storage capacity

6-2-3 Refilling time

This paragraph discusses the results of the third response variable, the *required refilling time*. This response variable needs to be curtailed as much as possible, since a shorted refilling time will result in a higher reliability of the storage and handling area. Moreover, a shorter time will reduce the required storage capacity. This response variable focuses on the handled material storage, since the consequences of unavailability of materials at this storage are more serious than those at the raw material storage.

Initial design parameters

The results of the *refilling time* are listed in Table 6-10. As the table shows, it takes around four days to increase the storage level by one day production of HIsarna, in other words, the handling area can deliver 125% of the nominal material usage of HIsarna. According to employees of Tata Steel this is workable.

Table 6-10: Required refilling time handled material storage for 24-hours production

	Initial design	**Fractional factorial design**							
		1	2	3	4	5	6	7	8
Refilling time [*d*]	4.3	6	3.5	3.5	6	3.5	6	6	3.5

In addition, the probability of a failure occurring during refilling time requiring a repair time of more than 24 hours, must be calculated, since this can lead to an empty storage. It must be mentioned, that this will only happen if the storage capacity is already at low level. The probable duration of the MTBF and MTTR are listed in Table 6-11, in accordance with the used Weibull and Exponential distributions (as described in Appendix G). As can be seen in the table, the probability a failure occurs within 4.3 days and a MTTR of more than 24 hours results in 0.59 percent (this is around two days), as shown in Table 6-12.

Table 6-11: Probabilities MTBF and MTTR

MTBF		**MTTR**	
Days	Probability	Hours	Probability
1	9.995E-4 %	20	13.53 %
2	0.79 %	24	9.07 %
3	2.66 %	30	4.98 %
4	6.20 %	40	1.83 %
5	11.75 %	50	0.67 %
6	19.43 %		

Table 6-12: Probability failure occurred within the refilling time, with repair time of more than 24 hours.

	Initial design	**Fractional factorial design**							
		1	2	3	4	5	6	7	8
Probabilities [%]	0.59	1.76%	0.38%	0.38%	1.76%	0.38%	1.76%	1.76%	0.38%

Parameter effects

The results for the refilling time of the fractional factorial design can also be found in Table 6-10. As shown in the table, varying the parameters results in either an increase or a decrease in the required refilling time. The lowest required refilling times are achieved in runs 2, 3, 5 and 6; this is a logical result, since the parameter *handling capacity ratio* (D) is at high level during these runs. In addition, the probabilities of a failure occurring during the refilling time are listed in Table 6-12. These are calculated in the same way as for the initial design.

The significant factors affecting the required refilling time are shown in the main effects plot, which is represented in Figure 6-5. As can be seen in the graph, only the handling capacity ratio (D) is significant; by increasing the *handling capacity ratio*, the refilling time decreases. The shortest time is achieved with the parameter settings: **A1/2 – B1/2 – C1/2 – D2**.

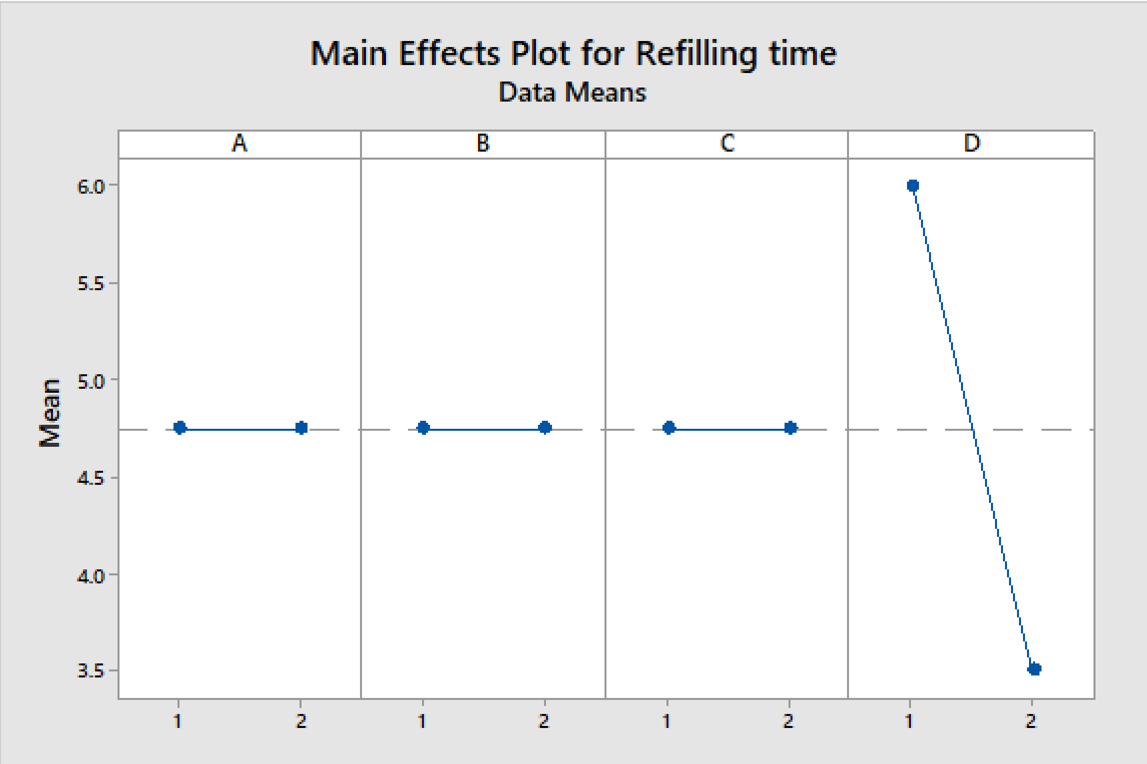

Figure 6-5: Refilling time – Handled material storage

6-2-4 Storage costs

This paragraph deals with the results of the final response variable, the *storage costs*. As mentioned in paragraph 6-1-1, the storage costs the interest on the value of stored materials during a period of time and the capital expenditures for the storage systems. It should be noted that the other capital and operational expenditures of the storage and handling area are not taken into account. This response variable should be minimised, because lower storage costs result in a higher profit of HIsarna.

Initial design parameters

The storage costs for the initial design are presented in Table 6-14 (shaded row). The costs of stored materials are based on the annual interest which is calculated over the average yearly storage level. The price of coal and iron ore is assumed at €100.- per mt and the price of the reverts at €30.- per mt. This (substantial) difference can be explained by the fact that the standard materials must be purchased, whereas the reverts are by-products of Tata Steel itself. The interest rate for the storage costs is set at 5%. All these figures were provided by Tata Steel, and an overview is presented in Table 6-13. Next, the capital expenditures of enclosed storage systems are estimated at €80.- per mt for each material; these costs are based on literature [49]. Tata Steel amortises yearly 15% of the total capex. The storage costs are shown in Table 6-14. It must be noted that this calculation is only a rough estimate; in reality, capital expenditures for example, depend on the type and the number of the storage systems used

Table 6-13: Material costs

Material	**Material costs** [€]	**Interest rate** [%]
Coal and iron ore	100	5
Reverts	30	5

Table 6-14: Storage costs (materials)

Run	**Material costs** [€]	**Capex storage** [€]	**Total storage costs** [€]
Initial	201,715	516,120	717,835
1	121,130	315,240	436,370
2	206,160	527,880	734,040
3	197,270	504,360	701,630
4	282,300	717,000	999,300
5	121,130	315,240	436,370
6	206,160	527,880	734,040
7	197,270	504,360	701,630
8	282,300	717,000	999,300

Design considerations

The storage costs for the different parameter settings of the fractional factorial design are presented in Table 6-14 as well. As can be seen in the table, the first and fifth runs result in the lowest storage costs, based on the parameter settings A1 – B1 – C1 – D1 and A1 – B1 – C2 – D2. This is plausible since these parameters include the lowest storage capacity. The highest costs result from the parameter settings of runs four and eight.

The same results have been found using the Pareto chart and the main effects plot, as presented in Figure 6-6 and Figure 6-7. Only the capacities of both storages (*B* and *D*) have a significant effect on the storage costs. By reducing the storage of both raw and handled materials, the storage costs will become less. In conclusion, the lowest storage costs are achieved with the following parameter settings: **A1 – B1 – C1/2 – D1/2**.

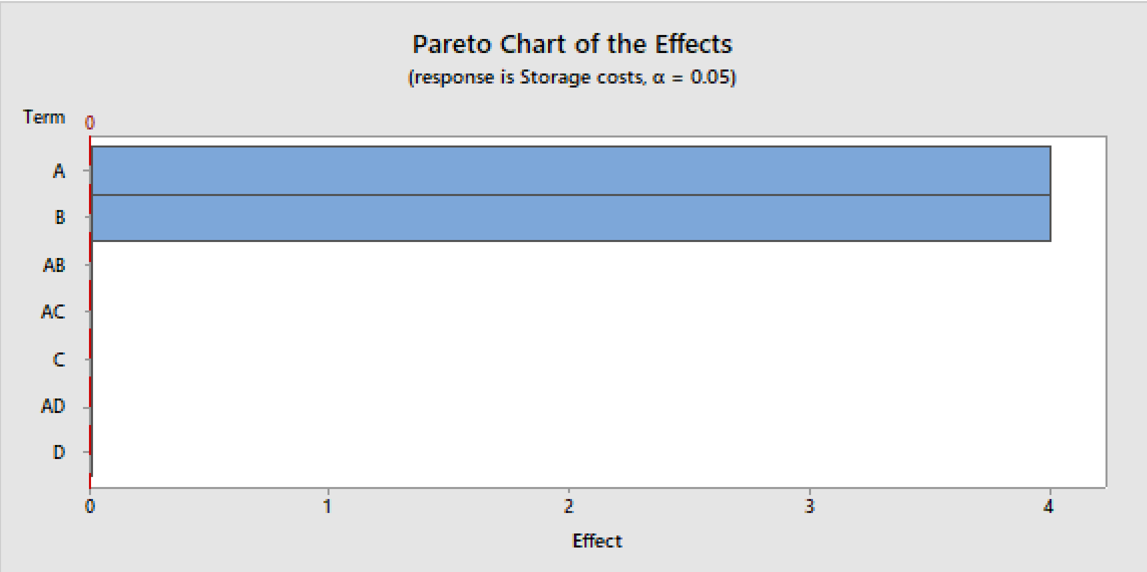

Figure 6-6: Pareto Chart storage costs

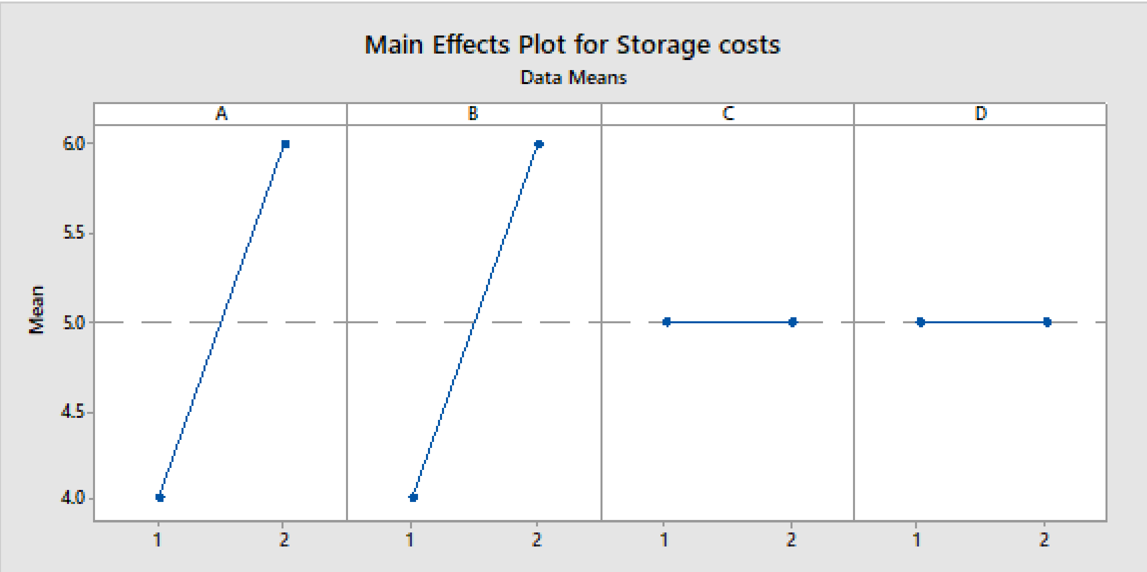

Figure 6-7: Main effects plot storage costs

In addition, the relation between the storage costs of the storage and handling area and the shutdown costs of the HIsarna demonstration plant are investigated and displayed in Figure 6-8. The optimum storage capacity could be found at the break-even point of the storage costs and shutdown costs. Viewed with a critical eye, it would be preferable have higher storage costs rather than higher shutdown costs, in order to ensure a continuous production of hot metal. At the same time, the sum of both costs must be kept as small as possible.
As can be seen in the graph, none of the parameter settings of the fractional factorial results in an optimum. But the third and fifth runs come closest, with the parameter settings **A1 – B2 – C1 – D2** and **A1 – B1 – C2 – D2** respectively. Interestingly, the parameter setting of the fifth run has the smallest storage capacities (A and B). The initial design parameters are the next best parameters. The first, fourth and sixth runs result in the highest costs.

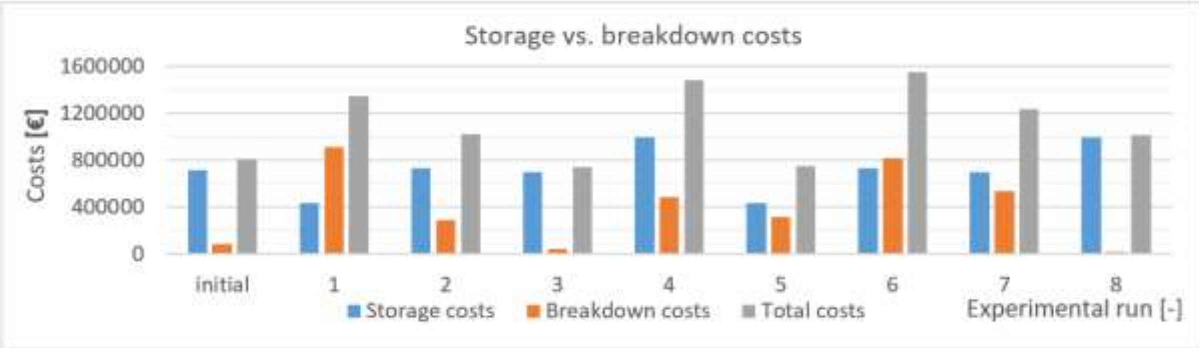

Figure 6-8: Storage vs. shutdown costs

6-3 Optimization of the design

This paragraph provides an overview of the results obtained from the evaluations discussed in paragraph 6-2. In addition, these results will be examined to select the parameter settings resulting in the best design for the storage and handling area. It is noteworthy that the optimal settings are to be found for a limited design space, since the parameter effects are determined for two levels only. This means that a linear behaviour of the storage and handling area is assumed, and no conclusions can be drawn outside this scope.

Table 6-15 shows the best parameter settings for each response variable, as analysed in paragraph 6-2. It is clear that not all response variables lead to the same optimal parameter settings. This makes sense because, for example, a high availability of materials requires a high storage capacity. The opposite is true to achieve a high storage turnover ratio.

Table 6-15: Optimal parameter settings of the storage and handling area

Response variable		**Parameter**			
		A	*B*	*C*	*D*
Storage turnover ratio	y_1	1	1	1/2	1/2
Availability of materials	y_2	2	2	2	2
Refilling time	y_3	1/2	1/2	1/2	2
Storage costs	y_4	1	1	1/2	1/2

Where parameter *A* represents the storage capacity of raw materials, *B* represents the storage capacity of handled materials, *C* lists the capacity ratio of materials supplied and *D* gives the capacity ratio of material handling (a detailed description can be found in paragraph 6-1-2). The numbers *1* and *2* indicate the parameter-level that leads to the best result of a response variable. **Note:** 1/2 means that a parameter has no significant effect on a response variable.

Based on the results described in paragraph 6-2, three design options emerge, each emphasizing a different starting point. An overview can be found in Table 6-16. The first design option "*High reliability*" is based on the response variables *availability of materials* and *refilling time*; it has the parameter settings: **A2** – **B2** – **C2** – **D2**. The second design option "*Customised*" is formed by selecting the most important response variable for each parameter and is set as follows: **A1** – **B2** – **C1** – **D2**. Finally, the third design option, *Minimised costs,* focuses on cost-effectiveness and has the following parameter settings: **A1** – **B1** – **C1** – **D1**.

Table 6-16: Design options for the storage and handling area

Design option	**Parameter setting**
1. High reliability	A2 – B2 – C2 – D2
2. Customised'	A1 – B2 – C1 – D2
3. Minimised costs	A1 – B1 – C1 – D1

The results of the three design options are presented in Table 6-17, together with the results of the initial design parameters. The first design provides a high availability of materials and short refilling time. Nevertheless, it also results in high storage costs: more than double compared to the third design option. The second design also provides promising results: it offers a high turnover ratio for the raw material storages and a short refilling time as well. Furthermore, the availability of materials is only slightly lower than the high availability reached in the first option (99.71% versus 99.89%). Yet, the storage costs are significant lower. The second option also results in a better overall rating compared to the initial design. The third design results in the lowest storage costs and provides high storage turnover ratios, but it also leads to a relatively low availability of materials (93.09%). The table demonstrates that the initial design parameters do not return in the best design once. This makes sense, since the fractional factorial design is based on the initial design, but with higher and lower levels.

In addition, the design of the storage and handling area can be improved by adding redundancy. Redundancy will increase the reliability of the system and decrease the storage capacity required. The use of redundancy will cause the storage and handling area to have more possibilities to transport, handle and/or store materials. The options for redundancy are elaborated on in paragraph 6-4.

Table 6-17: Proposed designs for the storage and handling area

Response variable		***Initial design***	**Design option 1**	**Design option 2**	**Design option 3**
Storage turnover ratio	[-]	*183*[1] *122*[2]	122 91	*365* 91	*365* *183*
Availability of materials	[%]	*99.34*	*99.89*	99.71	93.09
Refilling time	[d]	*4.3*	*3.5*	*3.5*	6
Storage costs	[€]	*718,000*	999,000	701,630	*436,000*

[1] *Storage turnover ratio of raw material storages*

[2] *Storage turnover ratio of handled material storages*

Conclusion

In summary, the first design option may be recommended if financial resources are not a restrictive factor, since this design leads to an excessive reliability. The second design might be interesting when fewer financial resources are available but still an adequate reliability is aimed at. Finally, the third design option would be best when funds are limited. It must be said that this design results in a low availability of materials. In all cases, redundancy can be added to the storage and handling area, increasing the reliability and decreasing the required storage capacity. This will be further discussed in paragraph 6-4.

6-4 Redundancy

Redundancy can be used to improve the reliability of HIsarna and to reduce the required storage capacity at the storage and handling area. It must be mentioned that the HIsarna demonstration plant can produce hot metal without the use of reverts, as is currently done at the pilot plant. In other words, it is more important to afford redundancy for iron ore and coal than for reverts. This can save costs and ground space. The options for applying redundancy are discussed below and summarised in Table 6-18.

First, the materials iron ore and coal are currently transported to the raw material storage by conveyor belt. In case of failure of the conveyor system, the materials can be transported by trucks, as is currently done at the blast furnaces. Therefore, no second conveyor belt is required for the transport of iron ore and coal to the storage and handling area. As mentioned above, a redundant for the supply of reverts is less important, since hot metal can still be produced without such materials. Historic BOF sludge is transported by truck and more than enough trucks are available at the Tata Steel site. BF and currently produced BOF sludge are transported by pipelines to the storage and handling area of the HIsarna demonstration plant. Since these materials are not crucial for the production of HIsarna and moreover, it would be extremely costly to construct another pipeline system providing for redundancy for these materials is not recommended.

Secondly, in order to increase the reliability of HIsarna, the required storage capacity can be divided over multiple silos. This is also necessary when different types of iron ore and coal will be processed at HIsarna. In addition, as mentioned in Section 0, multiple silos provide a more flexible storage system, since closed storage systems not always allow for the possibility to unload and load at the same time.
Similarly, the required capacity for processing can be divided over multiple systems, for instance using two dryers instead of one. This increases the reliability of the storage and handling line, for the simple reason that when a failure occurs at one system, the other system can still be used for processing the materials. Even with a limited capacity, this is better than having complete shutdown of HIsarna. As mentioned before, it is more important to apply redundancy for the processing line of iron ore and coal rather than for the reverts. Finally, redundancy for transport of materials within the storage and handling area can be achieved by dividing the required transport capacity over two or more conveyors.

Table 6-18: Redundancy

Processing step	**Current system**	**Redundancy options**
Supply of coal and iron ore	Conveyor	Trucks
Supply of historic BOF sludge	Trucks	Trucks
Supply of BF and currently produced BOF sludge	Pipeline	-
Storage	Silos	Dividing required capacity over multiple silos
Process materials	Processing equipment	Dividing required capacity over two processing systems
Transport within the storage and handling area	Conveyor	Dividing required capacity over two conveyors

6-5 Feasiblity study

The feasibility of the location must be investigated; it needs to be checked if the required area of the designed storage and handling area fits the available surface of the location selected. The feasibility study is performed for the design requiring the largest area, the second proposed design from paragraph 6-3, focusing on a high reliability. The surfaces are estimated by using the Basic of Design (BOD) by Tata Steel Consulting India, literature and the HIsarna pilot plant. For instance, the required surface for the HIsarna plant is stated in the BOD, the required surface for storages is calculated using literature. Besides, as described in paragraph 4-2, the projected location of the HIsarna demonstration plant measures approximately 400 by 700 meters.

An aerial view of the selected location is depicted in Figure 6-9, including the estimated surfaces required for the demonstration plant. Nos. 1-3 indicate the storage and handling lines of the reverts, nos. 4 and 5 represent the storage and handling lines of coal and ore, no. 6 represents the surface required for the demonstration plant and the offices and off-gas treatment department, and finally, nos. 7 and 8 stand for the sludge processing departments for BF and currently produced BOF sludge. As can be concluded from the figure, the design of the storage and handling area fits the selected location. In addition, more ground is available for applying redundancy whenever this may be needed. It must be noted that the ground surface needed for conveyor systems is not included in this figure. An overview of the Tata Steel site in its entirety, including the new HIsarna demonstration plant is shown in Figure 6-10.

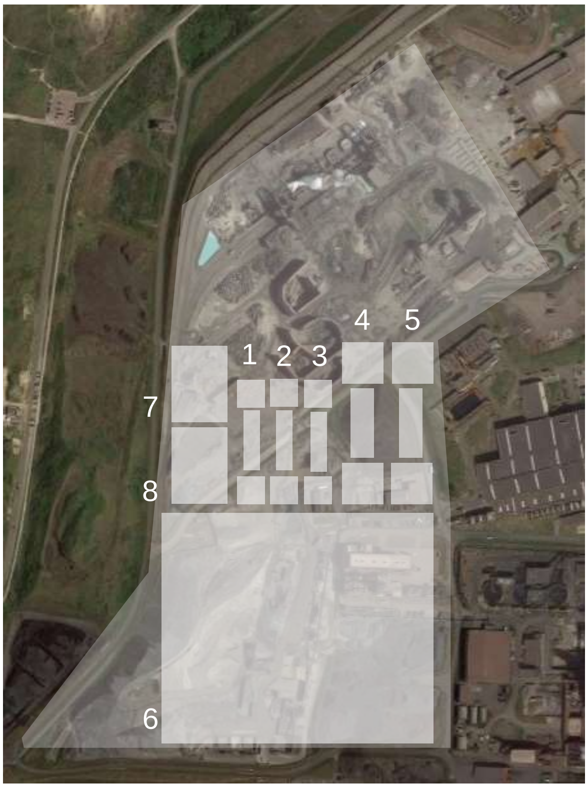

Figure 6-9: Feasibility – Design option 2

Figure 6-10: The site of Tata Steel IJmuiden with the HIsarna demonstration plant highlighted

6-6 Conclusion

The following sub-question has been answered by this chapter:

> Which input parameters of the storage and handling area affect the response variables and what combination of parameters results in the best design for the storage and handling area?

The performance and feasibility of the design of the storage and handling area has been analysed in this chapter, by performing and analysing two experiments. An experiment is conducted with the original parameter settings (as designed in Chapter 4) and a fractional factorial design is applied to analyse the important factors affecting the response variables. An overview of the considered input parameters and response variables is shown in Table 6-19.

Table 6-19: Overview input parameters and response variables

Input parameters				**Response variables**		
A	Capacity raw material storage	[*d*]		y_1	Storage turnover	[-]
B	Capacity handled material storage	[*d*]		y_2	Material availability	[-]
C	Capacity ratio of material supply	[-]		y_3	Refilling time	[*h*]
D	Capacity ratio of material handling	[-]		y_4	Storage costs	[€]

The optimal parameter settings for each response variable are presented in Table 6-20. As shown in the table, the storage capacities of both storages have a significant effect on the storage turnover ratios. Secondly, the material availability is affected by all input parameters, but it must be noted that the capacity of handled material storage and the capacity ratio of material handling are marked as the most significant parameters. Next, the refilling time is only influenced by the capacity ratio of material handling. Finally, all input parameters have a significant effect on the storage costs.

Table 6-20: Optimal parameter settings of the storage and handling area

Response variable	**Parameter**			
	A	*B*	*C*	*D*
Storage turnover ratio	1	1	*1/2*	*1/2*
Material availability	2	2	2	2
Replenishment time	*1/2*	*1/2*	*1/2*	2
Storage costs	1	1	*1/2*	*1/2*

Based on these results, the following three design options for the storage and handling area have been defined, each from a different perspective:

- Design option 1 “High reliability”: A2 – B2 – C2 – D2
- Design option 2 “Customised”: A1 – B2 – C1 – D2
- Design option 3 “Minimised costs”: A1 – B1 – C1 – D1

The performances of these designs are shown in Table 6-21, together with those of the initial design. The suitable conditions for each design are also included in this table. The reliability of the designs can be improved by adding redundancy. Options have been described in Paragraph 6-4, for instance multiple conveyor belts, silos or handling equipment. Finally, an additional check was performed to further investigate the feasibility of the designs. It was observed that the required ground surface for the storage and handling are fits the surface available at the selected location.

Table 6-21: Proposed designs for the storage and handling area

Response variable	**Initial design**	**Design option 1** High reliability	**Design option 2** Customised	**Design option 3** Minimised costs
Storage turnover ratio	●●●○○ [1] ●●●○○ [2]	●○○○○ ●○○○○	●●●●● ●○○○○	●●●●● ●●●●●
Material availability	●●●○○	●●●●●	●●●●○	●○○○○
Replenishment time	●●●○○	●●●●●	●●●●●	●○○○○
Storage costs	●●●○○	●○○○○	●●●○○	●●●●●
Recommended for:		- Reliable system - Capex are not limited	- Partially high storage turnover - Adequate reliability - Medium capex	- Limited capex - High storage turnover required

[1] *Storage turnover ratio of raw material storages*
[2] *Storage turnover ratio of handled material storages*

Chapter 7

Conclusion and recommendations

7-1 Conclusion

This master thesis provides the answer to the following main research question:

> How can the storage and handling area of the upscaled HIsarna plant be designed, in order to meet the increased capacity, environmental requirements and to be suitable for iron-rich waste materials?

First, analysis of materials was performed to establish which materials are suitable for processing at the HIsarna demonstration plant. This analysis has been essential to identify the properties of the materials, and how these properties affect the design of the storage and handling area. The following reverts have been selected for processing at HIsarna: currently produced BOF sludge, historic BOF sludge and BF sludge, all by-products of Tata Steel IJmuiden. These materials are particularly interesting because of the high levels of iron, carbon, calcium and/or zinc. In addition, the environment will benefit, since these reverts will no longer have to be part of the landfilling process. Less positive are the high moisture level, the stickiness and the inhomogeneity of composition. These might result in problems during processing.

Second, the existing storage and handling area of the HIsarna pilot plant was analysed. The main processes of this area are: the storage of raw materials, pre-processing these into handled materials (by means of contamination screening, drying (and grinding) and particle screening) and storage of handled materials. The processes for the storage and handling area of the HIsarna demonstration plant are almost similar to those of the pilot plant, be it that some additional steps for material handling may be needed, such as grinding and milling. The storage and handling area must meet HIsarna's annual capacity requirements, be able to process reverts, and comply with HIsarna's green ambitions. The potential bottlenecks have been identified. Constrictions may be caused by physical and chemical properties of reverts, instability of the ironmaking-process due to inaccurate injection, and inadequate storage capacity.

Subsequently, based on multi-criteria analyses and literature, the design of the storage and handling area has been created: iron ore and coal will be transported by conveyor belt to the storage and handling area, historic BOF sludge by truck, and BF and currently produced BOF sludge by pipeline. Both the raw and handled materials will be stored in enclosed storage systems. Each material will be pre-processed at a dedicated handling line. Within the storage and handling area, all materials will be transported by conveyor belt. The raw material storage of iron ore, coal and BOF sludge has a capacity for two days; and that of BF and currently produced BOF sludge for seven days. In addition, all handled material storages have a capacity for three days.

Next, a simulation model of the storage and handling area was built. It was modelled in Simio®, a software focused on an object-based modelling paradigm, but also supporting the use of discrete event simulation. The model has been verified by using several methods, such as structured walk-through, seed (in)dependence, extreme condition testing and sensitivity analysis. No flaws were observed during these tests; therefore, it is safe to conclude that the model works correctly.

The input parameters affecting the design of the storage and handling area were investigated by performing a fractional factorial design. The following variables were taken into consideration: the capacity of the raw material storage (*A*), the capacity of handled material (*B*), the capacity ratio of materials supplied (*C*), and the capacity ratio of materials handled (*D*). Each of these variables is characterised by a low (*1*) and high level (*2*) compared to the initial design. The parameter effects were examined in their comparison to the following response variables: storage turnover ratio (affected by *A* and *B*), availability of materials (influenced by all parameters), refilling time (only affected by *D*) and storage costs (influenced by *A* and *B*). Based on these results, three designs for the storage and handling area have emerged, each emphasizing a different starting point. The three designs are listed in Table 7-1. In addition, motivations are given for each design. In all cases, redundancy can be added to the storage and handling area, increasing the reliability and decreasing the required storage capacity.

In conclusion, this research thesis proposes three designs for the storage and handling area of the HIsarna demonstration plant, meeting HIsarna's three main requirements: the annual capacity of around one million mt, the facilitation of processing reverts and the compliance with HIsarna's green ambitions. The designs cover four aspects: location, transport, layout and storage. Each of the designs has a different starting point. The first design option provides the highest reliability and is recommended if financial resources are not a restrictive factor. The second design is an interesting choice when fewer financial resources are available but still an adequate reliability is aimed at. Finally, the third design results in the lowest reliability. This option may only be suggested when funds are limited. In all cases, redundancy can be added to the storage and handling area, increasing the reliability and decreasing the required storage capacity. All designs fit the selected location at the Tata Steel site, IJmuiden.

Table 7-1: Optimal parameter settings of the storage and handling area

Initial design	**Design 1** High reliability A2 – B2 – C2 – D2	**Design 2** Customised A1 – B2 – C1 – D2	**Design 3** Minimised costs A1 – B1 – C1 – D1
Average performance	Reliable system	Adequate reliability	Limited funds
	Unlimited capex	Medium capex	High storage turnover
	Low storage turnover ratio is acceptable	High turnover ratio raw material storage	High reliability is not essential

7-2 Recommendations

This paragraph provides recommendations for further research to the design of the storage and handling area, based on the findings during this research.

- For further research it is recommended to widen the scope of the simulation model of the storage and handling area by adding more specific tasks. For instance, the pre-processing can be modelled in more detail and redundancy of equipment can be added.

- Second, to get a better insight into the performance of the design of the storage and handling area, more input parameters can be varied, and more response variables can be investigated. For instance, it could be interesting to investigate the consequences of the reliability of equipment, by altering the MTBF and MTTR of failures. In addition, response variables like the *total costs* and the *utilization of equipment* may be an interesting object of further research extend the feasibility study of the design.

- Next, it could be interesting to vary some alternatives for the considered design aspects (location, transport, layout and storage), since the sensitivity analyses (in Chapter 4) have resulted in different best solution by altering the weights of criteria. For instance, the layout consisting of only two handling lines might be an interesting option when the capital expenditures are a restrictive factor.

- It is recommended to broaden the scope of the analysis of materials as well. For example, additional material tests could be carried out to investigate the technical feasibility of the design; such tests should be mainly focused on the ability of processing reverts. Besides, the maximum content of calcium in hot metal is not taken into consideration for this research. It may be necessary to verify if this level is not exceeded by the selected amount of materials (especially considering the high calcium content of historic BOF sludge).

- Furthermore, it is recommended to examine the optimal configuration of the storage and handling area. For instance, an optimization model could be used to determine the optimal capacity and amount of equipment (redundancy). In addition, to make a carefully considered choice for the design of the storage and handling area, Tata Steel must weigh Capex (and Opex) against the desired reliability of the storage and handling area. The funds Tata Steel is willing to make available for the project, will have a significant influence on the viability of the design of the storage and handling area.

- Finally, widening the scope by further studying the opportunities of processing reverts that can be found outside the Tata Steel site, could be interesting for HIsarna. Increasing the amount of reverts may result in decreasing the required amount of iron ore and coal. Also, more zinc could be processed. For instance, jarosite from the zinc plant is an interesting revert because of the high content of zinc.

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Appendix A

Paper

This appendix introduces a research paper that summarises the thesis. The paper will start on the next page.

Design of the Storage and Handling area of the HIsarna demonstration plant

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1. ABSTRACT

This paper aims to design the storage and handling area for the future HIsarna demonstration plant at Tata Steel, IJmuiden. HIsarna is a new ironmaking technique, which will result in a significant reduction of carbon emissions, allow for more flexible input requirements for materials, and lead to a reduction of processing costs as well. Based on material and system analyses, an initial design is created by using multicriteria analysis and literature. The performance of this design is evaluated using a discrete simulation model. In addition, a fractional factorial design is performed in order to investigate the affecting parameters and find the optimal parameter settings for the storage and handling area. Resulting in three different design options, each with emphasizing a different starting point.

KEYWORDS

Dry-bulk; material properties; multi-criteria analysis; design; enclosed storage; design of experiments; fractional factorial design; discrete simulation; design optimization.

Figure 1: 3D overview of the HIsarna pilot plant [1]

2. INTRODUCTION

Tata Steel IJmuiden, formerly Corus BV and Koninklijke Hoogovens, is an integrated steelmaking site and produce high-quality strip steel for various customers, such as the packaging, automotive and construction industries. Currently, Tata Steel IJmuiden is using traditional blast furnaces to produce hot metal. For this manner of ironmaking, raw materials (mainly iron ore and coal) need to be pre-processed, the preparatory steps are the agglomeration of iron ore and carbonization of coal, as shown in Figure 2. The carbon emissions from these processes are significant [1]. The aim of Tata Steel is to reduce its carbon footprint by at least 50% in 2050, in order to comply with the latest climate agreements, [2]. HIsarna (the name derives from "Isarna", the ancient Celtic word for iron, and "HIsmelt", the name of the melting vessel) is one of the technologies to achieve this significant reduction. HIsarna is a process where fine iron ore and non-coking coal can (almost) be directly used to produce hot metal. Besides the environmental benefits, HIsarna will allow for more flexible input requirements for materials, be able to recycle iron-rich waste materials (also called reverts), and lead to a reduction of processing costs as well. In 2010, Tata Steel IJmuiden built a pilot plant to test and develop the technology of HIsarna, a schematic representation of this plant is shown in Figure 1. The plant includes a storage and handling area where the materials are stored and pre-processed before they will be injected into HIsarna (indicated by nos. 12, 13 and 14 in Figure 1). If the HIsarna plant validates successful, the next step is to build an industrial scale installation: the HIsarna demonstration plant. The design of the storage and handling area of this new plant is the subject of this research.

Thus far, Tata Steel has been working on the first design phase of the demonstration plant. Nevertheless, the design of the storage and handling area is missing. Furthermore, Tata Steel has not entirely established which reverts will be processed at the demonstration plant. Consequently, the required quantities and necessary pre-processing steps of materials are unknown. Moreover, the existing storage and handling area at the HIsarna pilot plant cannot directly be used for the demonstration plant, because the new plant must meet the increased capacity requirements of around one million mt, be able to process iron-rich waste materials, and comply with HIsarna's green ambitions.

The objective of this paper is to create a design of the storage and handling area for the HIsarna demonstration plant, which meet the three main requirements, HIsarna's capacity requirements, recycle iron-rich waste materials, and comply with HIsarna's green ambitions.

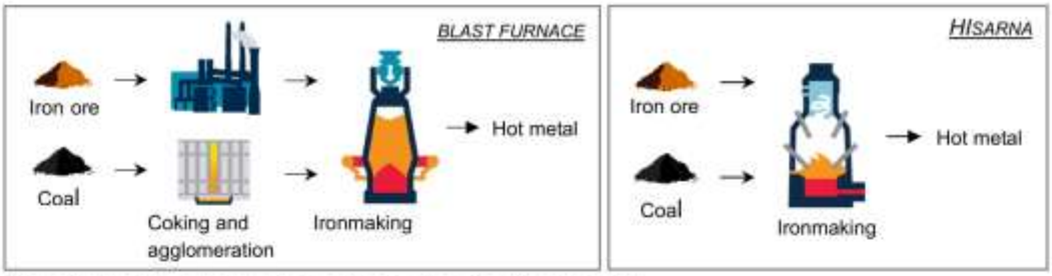

Figure 2: Traditional ironmaking process using blast furnaces [1]

2

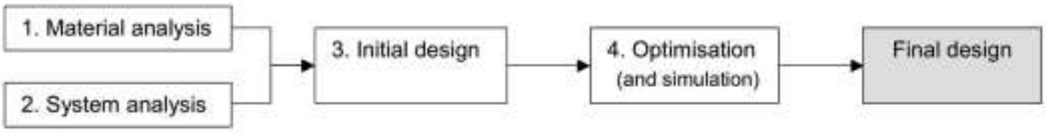

Figure 3: Methodology

3. METHOD

The methodology used for this study is listed in Figure 3. As can be seen, four stages are performed to create a feasible design of the storage and handling area of the HIsarna demonstration plant. These are elaborated on below.

(1) MATERIAL ANALYSIS

Besides the standard materials such as iron ore and coal, the HIsarna demonstration plant will be used to process and recycle iron-rich waste materials (also called reverts). To date, Tata Steel has not established which materials these will be. Therefore, an analysis of materials is performed to establish which materials are suitable for processing at the HIsarna demonstration plant. This analysis has been essential to identify the properties of the materials, and how these properties affect the design of the storage and handling area.

First, the requirements for the materials have been defined, both chemical and physical. Chemically, materials that are high in iron, coal, calcium and/or zinc contents are particularly interesting. Physically, it must be possible to process them by pneumatic injection at the end of the storage and handling area. This implies that the moisture content of the materials must be below 2% and particle size must be smaller than 2 mm. In addition to these requirements, it is preferred to focus on zinc-rich by-products of Tata Steel IJmuiden itself. This is beneficial for enclosing the zinc cycle, the satisfaction of customers, the environment and, last but not least, profit.

Second, the selected reverts are by-products of the blast furnaces and the oxy steel plant: currently produced BOF sludge, historic BOF sludge and BF sludge. Both the chemical and the physical properties of these materials are analysed, an overview is presented in Table 1. The materials are mainly interesting because of the high levels of iron, carbon, calcium and/or zinc. On the other hand, these materials have some disadvantages, e.g. the high moisture level, sticky properties and inhomogeneity of composition, which might result in problems during processing. Moreover, the components of each revert may result in unforeseen chemical reactions when more than one reverts are used simultaneously.

Table 1: Material properties

Material	**Chemical properties**			**Physical properties**	
	Fe [%]	C [%]	Zn [%]	Moisture level [%]	Others
Iron ore	62	0	-	8	-
Coal	6	82	-	12	-
Historic BOF sludge	44	0	0.15 – 6	24	Sticky and inhomogeneous
Currently produced BOF sludge	65	0	0.4	12	Sticky
BF sludge	22	37	6.9	46	Sticky

(2) System analysis

An analysis is made of the existing storage and handling area of the HIsarna pilot plant, including the process flow, characteristics and bottlenecks found at this area. By using the information thus obtained, the requirements of the HIsarna demonstration plant can be defined, and the necessary processing steps can be determined. In addition, potential future bottlenecks can be identified.

First, the system analysis of the storage and handling area of the HIsarna pilot plant is performed. The main processes of this storage and handling area include the supply of raw materials, storage of raw materials, pre-processing of raw materials into handled materials and storage of handled materials. The pre-processing area consists of two separated handling lines: one for iron ore and one for coal. Subsequently, the following bottlenecks were found at the current system:

- an inefficient arrangement of the storage and handling area;
- the pilot plant still being in its test phase;
- the plant not being complete;
- the process instability in the HIsarna plant;
- inadequate storage capacity and no options for redundancy.

Second, a system analysis of the storage and handling area of the HIsarna demonstration plant is carried out. Based on the material analysis and the system analysis of the pilot plant, the required process steps are defined. These are similar to the main processing steps of the HIsarna pilot plant. In addition, some possible extra processing steps are identified, including mixing and milling of materials. Whether these steps can be implemented, depends on the layout of the storage and handling line in combination with the properties of the reverts.

Next, the requirements and characteristics of the demonstration plant are established. The storage and handling area must meet the capacity of the HIsarna demonstration plant (around one million mt hot metal per year) and must be fit to process reverts. In addition, the storage and handling area must meet environmental regulations. Moreover, in order to achieve a competitive position and create a completely clean environment matching HIsarna, Tata Steel must limit the following aspects as well: noise, dust, water and soil pollution.

Finally, future bottlenecks are identified; these mainly include problems caused by physical and chemical properties of reverts, such as an inaccurate process, but also the future expansion of the plant and an inadequate material supply may create bottlenecks.

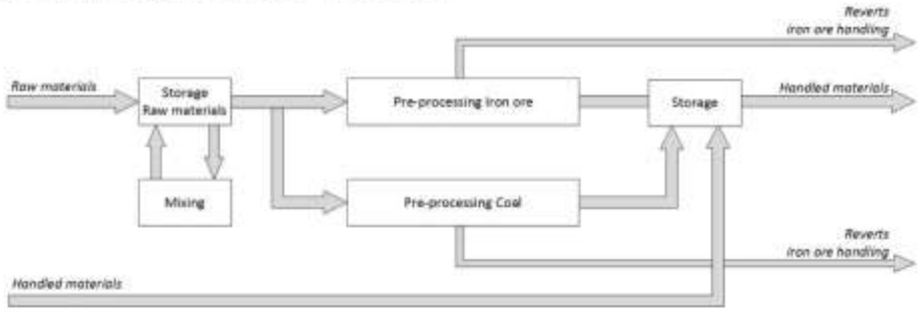

Figure 4: Process flow of the storage and handling area of the HIsarna pilot plant

4

(3) Initial design

A design for the storage and handling area of the demonstration plant is created by using the information of both analyses. The design of this area is divided into the following four design aspects: *location*, *layout*, *transport* and *storage*. For each of these aspects, the best possible solutions are identified by using information obtained from literature and expertise of Tata Steel. The best options for *location*, *transport* and *layout* of the storage and handling area, have been selected by using multi-criteria analyses. Each design option is compared to a set of decision criteria. The weights of the decision criteria are determined according to Saaty's priority principle and the consistency is checked to ensure that the ratings are consistent [3]. In addition, after performing the multicriteria analysis, a sensitivity analysis is carried out to identify the effect of changing the importance of the criteria. The selection of the best alternative for storage is based on information obtained from literature.

The following design is created: iron ore and coal will be transported by one conveyor belt to the storage and handling area, historic BOF sludge by truck, and BF and currently produced BOF sludge by pipeline. Both the raw and handled materials will be stored in enclosed storage systems. Closed storage facilities seem more than feasible, because the benefits (fewer costs to adhere to environmental regulations, less pressure on the environment in general, a more efficient utilization of ground surface) amply outweigh the higher capex and restriction in flexibility. Each material will be pre-processed at a dedicated handling line; all materials within the storage and handling area are transported by conveyor belt. The raw material storage of iron ore, coal and BOF sludge has a capacity for two days; and that of BF and currently produced BOF sludge for seven days. In addition, all handled material storages have a capacity of three days.

(4) Optimization

A discrete event simulation model of the storage and handling area is used to study both, the performance of the design thus created and the affecting parameters by varying some of the input parameters; resulting in optimal parameter settings for the design of the storage and handling area. The second part is planned using design of experiments, or experimental design, this is a statistical approach where multiple input variables are varied simultaneously, instead of the One-Factor-At-a-Time method where only one factor is changed in each experimental run [4]. Experimental design significantly reduces the number of experimental runs needed.

The effects of the following four input parameters are studied: the capacity of raw material storage (A), the capacity of handled material storage (B), the capacity ratio of materials supplied (C) and, the capacity ratio of material handling (D). Each factor is characterized by two levels, an overview is shown in Table 2. Two levels are recommended in the early stages of a design when linear behaviour is expected [4]. The performance of the storage and handling area is expressed by the following response variables: the storage turnover ratio, the availability of materials, the refilling time, and the storage costs.

A fractional factorial design has been selected for this experiment, this is the most appropriate design for of the number of considered factors and levels [references]. Resulting in eight simulation runs. This method results in significantly less experimental runs compared to full factorial design; in this case, eight instead of 16 experimental runs are required [5]. The experimental matrix is listed in provided in Table 3.

The discrete simulation is built using the software Simio®, an object-oriented simulation software. Discrete modelling is preferred to investigate the performance and feasibility of the design of the storage and handling area, since discrete modelling supports the simulation of events, such as failures of equipment. Each simulation run is simulated for one year and replicated 15 times. The model is verified by using the following approaches: model description verification, structured walk-through, animation verification, tracing, seed (in)dependence, extreme condition testing, sensitivity tests. In addition, the simulation results are compared to analytical results

4. RESULTS

The performance of the initial design of the storage and handling area is analysed. In addition, the input parameters affecting the design of the storage and handling area are investigated by examining the fractional factorial design, to select the parameter settings resulting in the best design for the storage and handling area.

The affecting parameters are identified using Pareto charts and main effects plots from the statistical software Minitab®. As an example, the graphics for the response variable *storage turnover ratio* are represented in Figure 6 and Figure 7. As can be seen in these figures, the storage turnover ratio of the raw material storage is only affected by the *capacity of raw material storage*, while the *storage turnover ratio* of the handled material storage is only influenced by the *capacity of the handled material storage*. Thus, it can be concluded, that the optimal parameter settings for the storage turnover ratio are A1 – B1 – C1/2 – D1/2. Where *A* represents the parameter *storage capacity of raw materials*, *B* represents the *storage capacity of handled materials*, C lists the *capacity ratio of materials supplied* and *D* gives the *capacity ratio of material handling*. The numbers *1* and *2* indicate the parameter-level that leads to the best result of a response variable, *1/2* means that a parameter has no significant effect on a response variable.

The optimal parameter settings for each response variable are presented in Table 2, together with the performance of the initial design. As shown in the table, the storage capacities of both storages have a significant effect on the *storage turnover ratios*.

Table 2: Input parameters and response variables

Input parameters		Level 1	Level 2
A	Capacity of raw material storage	1	3
B	Capacity of handled material storage	2	4
C	Capacity ratio of materials supplied	1.2	1.4
D	Capacity ratio of material handling	1.2	1.4

Table 3: Fractional factorial design

#	A	B	C	D
1	1	1	1	1
2	2	1	1	2
3	1	2	1	2
4	2	2	1	1
5	1	1	2	2
6	2	1	2	1
7	1	2	2	1
8	2	2	2	2

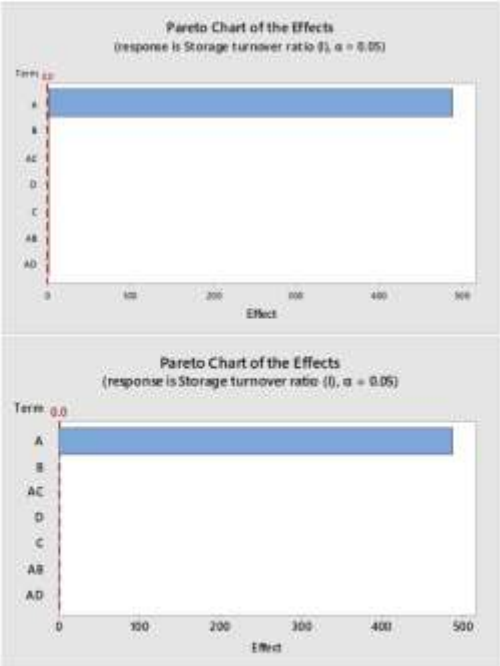

Figure 5: Pareto chart storage turnover ratios: A. Raw material storage, B. Handled material storage

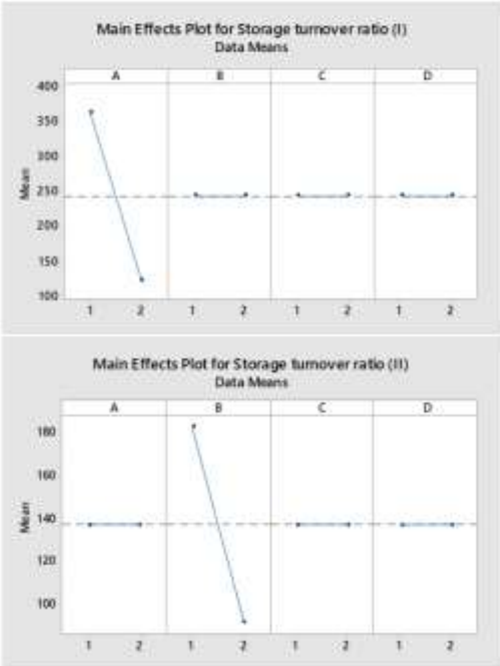

Figure 6: Main effects plot storage turnover ratios: A. Raw material storage, B. Handled material storage

Secondly, the *availability of materials* is affected by all input parameters, but it must be noted that the capacity of handled material storage and the capacity ratio of material handling are marked as the most significant parameters. Next, the *refiling time* is only influenced by the capacity ratio of material handling. Finally, the storage capacities of both storages have a significant effect on the *storage costs*.

Based on these results, the following three design options for the storage and handling area emerge, each emphasizing a different starting point. An overview can be found in

Table 3. The first design option, High reliability, *is based on the response variables* availability of materials *and* refilling time. *The second design option,* Customized, *is formed by selecting the most important response variable for each parameter. Finally, the third design option,* Minimized costs, *focuses on cost-effectiveness. The performances of these designs are shown in*

Table 4 and Table 5. The first design provides a high availability of materials and short refilling time. Nevertheless, it also results in high storage costs: more than double compared to the third design option. The second design also provides promising results: it offers a high turnover ratio for the raw material storages and a short refilling time as well. Furthermore, the availability of materials is only slightly lower than the high availability reached in the second option (99.71% versus 99.89%). Yet, the storage costs are significant lower. The second option also results in a better overall rating compared to the initial design. The third design results in the lowest storage costs and provides high storage turnover ratios, but it also leads to a relatively low availability of materials (93.09%). The table demonstrates that the initial design parameters do not return in the best design once. This makes sense, since the fractional factorial design is based on the initial design, but with higher and lower levels. In addition, the design of the storage and handling area can be improved by adding redundancy. Redundancy will increase the reliability of the system and decrease the storage capacity required. The use of redundancy will cause the storage and handling area to have more possibilities to transport, handle and/or store materials.

Table 2: Results of the initial design and fractional factorial design

Response variable		**Initial design**	**Affecting parameters**			
			A	B	C	D
Storage turnover ratio	[-]	183[1] 122[2]	1	1	1/2	1/2
Availability of materials	[%]	99.34	2	2	2	2
Refilling time	[d]	4.3	1/2	1/2	1/2	2
Storage costs	[€]	718,000	1	1	1/2	1/2
1. Storage *turnover ratio of the raw material storage; 2. Storage turnover ratio of the handled material storage*						

Table 3: Design options for the storage and handling area

Design option	**Parameter setting**
1. High reliability	A2 – B2 – C2 – D2
2. Customized	A1 – B2 – C1 – D2
3. Minimized costs	A1 – B1 – C1 – D1

Table 4: Performance design options storage and handling area (I)

Response variable		**Design option 1**	**Design option 2**	**Design option 3**
Storage turnover ratio	[-]	122[1] 91[2]	365 91	365 183
Availability of materials	[%]	99.89	99.71	93.09
Refilling time	[*d*]	3.5	3.5	6
Storage costs	[€]	999,000	701,630	436,000
1. Storage turnover ratio of the raw material storage; 2. Storage turnover ratio of the handled material storage				

Table 5: Performance design options storage and handling area (II)

Response variable	**Design option 1**	**Design option 2**	**Design option 3**
Storage turnover ratio	●●●●● ●○○○○	●●●●● ●●●●●	●○○○○ ●○○○○
Availability of materials	●●●●○	●○○○○	●●●●●
Replenishment time	●●●●●	●○○○○	●●●●●
Storage costs	●●●○○	●●●●●	●○○○○
Recommended for:	- Limited capex - High storage turnover required	- Partially high storage turnover - Adequate reliability - Medium capex	- Reliable system - Capex are not limited

5. CONCLUSIONS

In conclusion, the aim of this study was to design the storage and handling area for the HIsarna demonstration plant at Tata Steel IJmuiden, meeting HIsarna's three main requirements: the annual capacity of around one million mt, the facilitation of processing reverts and the compliance with HIsarna's green ambitions. Three designs are proposed, each with a different starting point. The designs cover four aspects: location, transport, layout and storage. The first design option provides the highest reliability and is recommended if financial resources are not a restrictive factor. The second design is an interesting choice when fewer financial resources are available but still an adequate reliability is aimed at. Finally, the third design results in the lowest reliability. This option may only be suggested when funds are limited. In all cases, redundancy can be added to the storage and handling area, increasing the reliability and decreasing the required storage capacity.

6. RECOMMENDATIONS

To get a better insight into the performance of the design of the storage and handling area, more input parameters can be varied, and more response variables can be investigated. In addition, response variables like the *total costs* and the *utilization of equipment* may be an interesting object of further research extend the feasibility study of the design.

It is recommended to broaden the scope of the analysis of materials as well. For example, additional material tests could be carried out to investigate the technical feasibility of the design; such tests should be mainly focused on the ability of processing reverts. Besides, the maximum content of calcium in hot metal is not taken into consideration for this research. It may be necessary to verify if this level is not exceeded by the selected amount of materials.

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Appendix B

HIsarna plant

HIsarna is a new ironmaking process as an alternative for the conventional blast furnaces. It is developed to produce steel with lower CO_2 emissions. The main difference with the blast furnaces is that fine iron ore and coal could (almost) be directly used to produce hot metal, thus without the use of agglomeration and coking steps of ore and coke, as shown before in Figure 1-4 (paragraph 1-1-2). The HIsarna furnace, illustrated in Figure B-1, uses two different technologies: The Cyclone Converter Furnace (CCF), developed by Tata Steel and shown in the upper part of the figure, and the Smelting Reduction Vessel (SRV) created by Rio Tinto in Australia and depicted in the lower part of the figure.

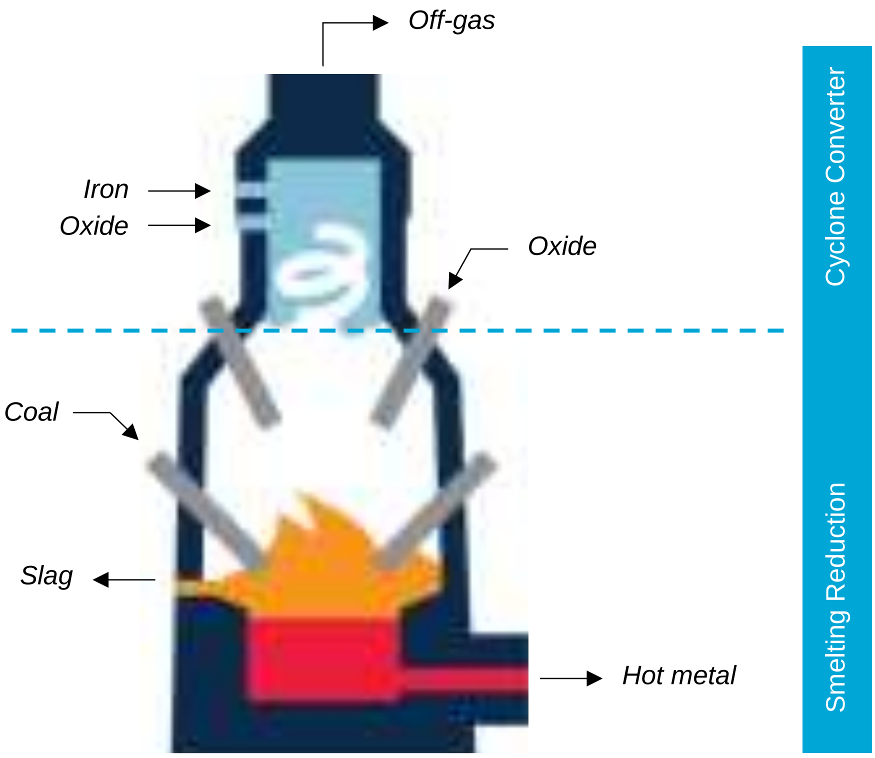


Figure B-1: Alternative ironmaking process using HIsarna [2]

The technology of HIsarna has several advantages over the traditional blast furnaces, the most important being:

- Significant reduction of CO_2.
- Flexibility in the processing of raw materials: on the one hand HIsarna uses low grade iron but on the other hand iron rich waste materials can be processed as well.
- Recycling of metallurgical materials, such as zinc.
- Direct use of fine iron ore and coal, thus dropping preparation technologies like sintering, pelletizing of iron ore.
- Reduction of the number of process steps.
- Easy to operate, i.e. quick starting and stopping without (serious) damage.

B.1. General ironmaking process

Iron is found on the surface of the earth and is mainly present as oxides, for instance: hematite (Fe_2O_3) and magnetite (Fe_3O_4), since iron tends to oxidize [1]. To extract iron from the oxides the HIsarna process or a conventional blast furnace can be used. The general ironmaking process consists of the following two reactions:

1) Coal reacts with oxygen to produce carbon monoxide:

$$2C + O_2 \rightarrow CO$$

2) Carbon monoxide reduces the iron ore to hot metal:

$$FeO + C \rightarrow Fe + CO$$

B.2. HIsarna process

Before the raw materials can be used for the production of hot metal, the materials should be pre-processed to meet the input requirements of the HIsarna furnace. The preparation steps consist of drying, sieving and grinding and take place at the raw material storage and handling area of HIsarna.
After these steps, the raw materials are injected into HIsarna. This process is illustrated in Figure B-2. First the handled materials are injected pneumatically into HIsarna; fine ore is inserted via the CCF (2) and coal is injected into the slag layer inside the SRV (1). Besides, additional materials such as limestone and dolomite are added to control the slag composition. Furthermore, oxygen is injected in both the CCF and the SRV to balance the heat between the two compartments.

The off-gas coming from the reactor is treated in several steps. First, the dust particles are captured as much as possible in the flux chamber (3). Next, the off-gas is quenched by recycling some of the (already) cooled off-gas in the gas quench section (4). The gas is further cooled in the gas cooler (5). Note that this will be different in the HIsarna demonstration plant, where excess heat will be recovered to generate steam. The residual dust in the off-gas is removed using the dust cyclone (6) and bag filter (7). It must be mentioned that the SO_x scrubber (8) will be installed together with the off-gas recycling duct (9) during campaign F.

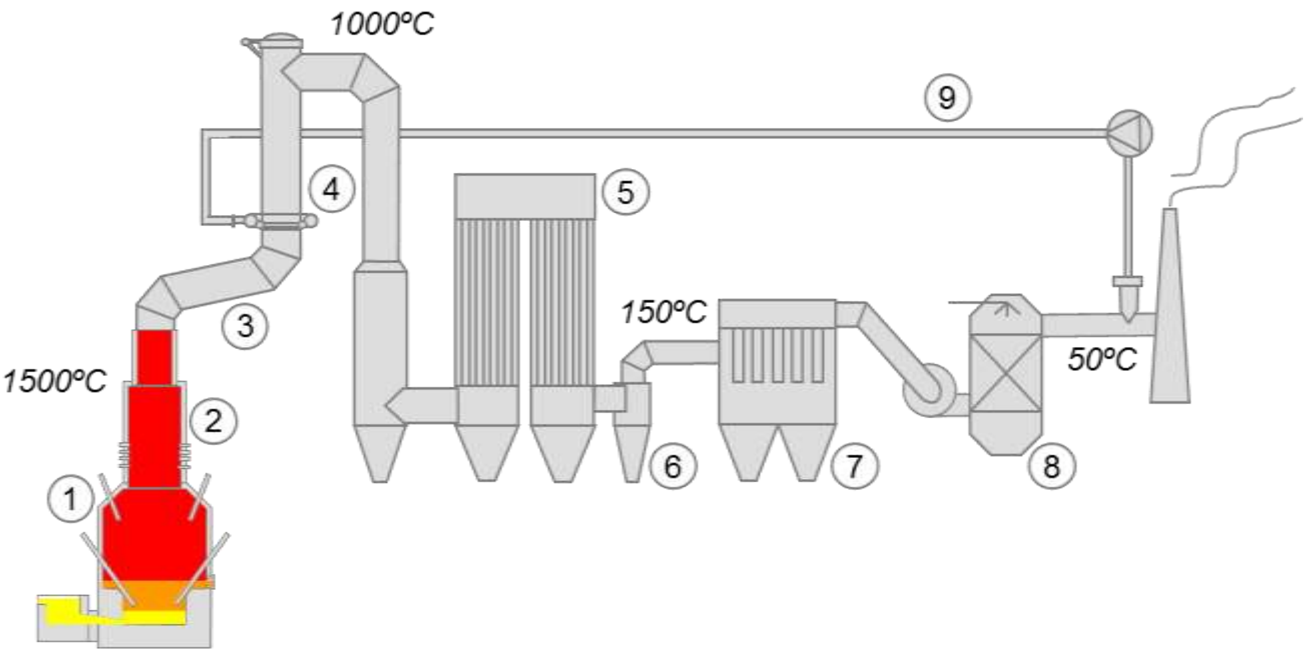


Figure B-2: Schematic overview of the process of the HIsarna pilot plant [3]

Table B-1: Explanation by Figure B-2

1	Smelting-Reduction Vessel (SRV)
2	Cyclone Converter Furnace (CCF)
3	Reflux chamber (dog leg)
4	Gas quench
5	Gas cooling
6	Dust cyclone
7	Bag house
8	SO_x scrubber
9	Off-gas (mainly CO_2) recycle

Appendix C

Zinc cycle

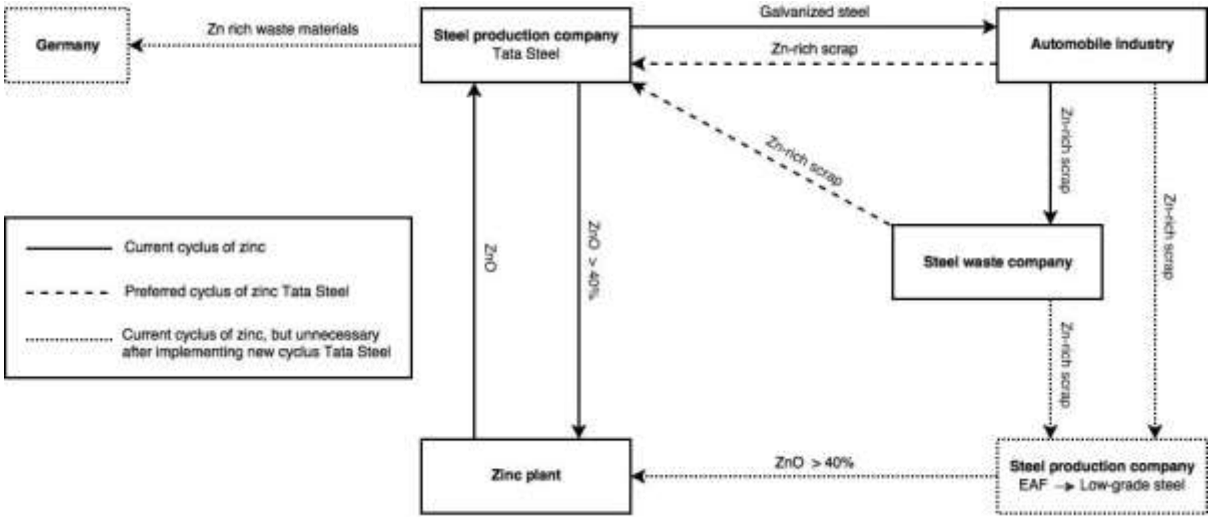
Coal and iron ores contain contaminants, such as zinc. The total amount of zinc that enters Tata Steel is around 600 mt per year. Zinc causes operational, health and safety problems at the blast furnace. For instance, zinc can lead to an unstable process and in addition, it may harm the blast furnace itself during the reproduction procedure. Therefore, zinc must be removed out of the steelmaking process; this is done by concentrating the zinc at the blast furnace and landfilling the zinc rich waste products (BF sludge) from the blast furnace itself. At the moment, the concentration of zinc in these waste products is too low to make reuse economically attractive. Besides, Tata Steel is not able to recycle these zinc rich waste materials in its integrated steel site.

Tata Steel has a high demand to recycle zinc rich materials, to be able to close the loop of zinc at Tata Steel, as can be seen in Figures C-1. This is because of the following three reasons:

- To develop a secondary source of zinc oxide as a replacement of zinc ores for the zinc producing industry.
- To be able to recycle the zinc-rich scrap from the OEM manufactures.
- To be able to recycle zinc-rich waste material from by-products of the Tata Steel plant.

Among the biggest customers of Tata Steel are the Original Equipment Manufacturers (OEM), such as the automobile industry. Tata Steel supplies large amounts of galvanized steel to this industry, a material containing circa 2% of zinc. At the OEM manufacturing lines, steel is used for production and the waste material is disposed of. This is about 250.000 mt per year. At the moment this waste material is sent to a shredder and processed at a Wilz Kiln. The material that is high in zinc is sent to the Zinc Plant. At this point in time, Tata Steel is not able to receive this material and recycle it because of the percentage of zinc. At the same time, the OEM customers would prefer the possibility of sending it back to Tata Steel.

It is Tata Steel's aim to process zinc rich waste materials at HIsarna, to create a by-product with a high zinc concentration. This product can be sold to the zinc plant and helps to close the zinc cycle of Tata Steel.



Figures C-1: Zinc cycle Tata Steel

Appendix D

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[redacted]

Appendix E

Design selection

E.1. Transport

A multicriteria analysis is performed to determine which alternative is the most suitable transport system for the transport of iron ore and coal between the suppliers and the storage and handling area. The selection is described in this section.

Weight factors

First, a pairwise comparison matrix is used to determine the weight factors for transport, as shown in Table E-1. The ranking is based on the requirements of Tata Steel and information gained from the analysis of materials and the current system. Subsequently, the consistency analysis displays that the pairwise comparison is consistent, since the consistency ratio is below 0.10. The order of importance of the criteria is as follows: *reliability – opex – environment – transit time – capex*.

Table E-1: Pairwise comparison matrix – Transport

Criteria		$c_{2,1}$	$c_{2,2}$	$c_{2,3}$	$c_{2,4}$	$c_{2,5}$	**Weights**
$c_{2,1}$	*Environment*	*1*	1/3	2	2	1/2	**0.15**
$c_{2,2}$	*Reliability*	3	*1*	5	4	3	**0.45**
$c_{2,3}$	*Transit time*	1/2	1/5	*1*	2	1/3	**0.10**
$c_{2,4}$	*Capex*	1/2	1/4	1/2	*1*	1/3	**0.08**
$c_{2,5}$	*Opex*	2	1/3	3	3	*1*	**0.23**
						Total	**1.00**
$\lambda_{max} = 5.15, CI = 0.04\ and\ CR = 0.03 \leq 0.1, \text{OK}$							

Multicriteria analysis

Table E-2 shows the MCA performed for the transport of iron ore and coal to the storage and handling area. Consecutively, Table E-3 represents the MCA for the materials BF and currently produced BOF sludge. The ratings are based on paragraph 4-3-1. As can be seen in

Table E-2, the best transport system for iron ore and coal is a conveyor belt. The score is significant higher than that for the truck and train. On the other hand, the most suitable solution for BF and currently produced BOF sludge appears to be transport by pipelines.

Table E-2: Multicriteria analysis transport – Iron ore and coal

	Weights	**Truck**		**Train**		**Conveyor**	
$c_{2,1}$	**0.15**	1	0.15	2	0.30	3	0.44
$c_{2,2}$	**0.45**	2	0.90	1	0.45	3	1.35
$c_{2,3}$	**0.10**	3	0.29	1	0.10	2	0.19
$c_{2,4}$	**0.08**	3	0.23	2	0.15	1	0.08
$c_{2,5}$	**0.23**	1	0.23	2	0.46	3	0.69
	Total		**1.80**		**1.45**		**2.75**

Table E-3: Multicriteria analysis transport – BF and currently produced BOF sludge

	Weights	**Truck**		**Pipeline**	
$c_{2,1}$	**0.15**	1	0.15	2	0.30
$c_{2,2}$	**0.45**	1	0.45	2	0.90
$c_{2,3}$	**0.10**	2	0.19	1	0.10
$c_{2,4}$	**0.08**	2	0.15	1	0.08
$c_{2,5}$	**0.23**	1	0.23	2	0.46
	Total		**1.17**		**1.83**

E.2. Layout

This section represents the selection of the subsystem layout. An MCA and sensitivity analysis are performed to determine the best alternative.

Weight factors

Table E-4 presents the pairwise comparison of the criteria points for the subsystem layout and the resulting weight factors. As can be seen in the table, the order of importance of the criteria is as follows: *precision – process flexibility – opex – equipment utilization – capex – required area / expandability*.

Table E-4: Pairwise comparison matrix – Layout

Criterion		$c_{3,1}$	$c_{3,2}$	$c_{3,3}$	$c_{3,4}$	$c_{3,5}$	$c_{3,6}$	$c_{3,7}$	**Weights**
$c_{3,1}$	*Process flexibility*	*1*	1/2	5	2	4	6	6	**0.26**
$c_{3,2}$	*Precision*	2	*1*	6	1/2	5	7	7	**0.30**
$c_{3,3}$	*Capex*	1/5	1/6	*1*	1/3	1/3	3	3	**0.07**
$c_{3,4}$	*Opex*	1/2	2	3	*1*	3	4	4	**0.22**
$c_{3,5}$	*Equipment utilization*	1/4	1/5	3	1/3	*1*	2	2	**0.08**
$c_{3,6}$	*Required area*	1/6	1/7	1/3	1/4	1/2	*1*	1	**0.04**
$c_{3,7}$	*Expandability*	1/6	1/7	1/3	1/4	1/2	1	*1*	**0.04**
								Total	**1.00**
$\lambda_{max} = 7.55, CI = 0.09\ and\ CR = 0.07 \leq 0.1$, OK									

Multicriteria analysis

An overview of the multicriteria analysis for the layout is depicted in Table E-5. The table shows that the best alternative is the first layout.

Table E-5: Multicriteria analysis layout

	Weights	**Layout 1**		**Layout 2**		**Layout 3**		**Layout 4**	
$c_{3,1}$	0.26	4	1.05	1	0.26	1	0.26	2	0.52
$c_{3,2}$	0.30	4	1.18	1	0.30	3	0.89	1	0.30
$c_{3,3}$	0.07	1	0.07	3	0.21	3	0.21	4	0.28
$c_{3,4}$	0.22	1	0.22	3	0.65	3	0.65	4	0.87
$c_{3,5}$	0.08	1	0.08	3	0.25	2	0.16	4	0.33
$c_{3,6}$	0.04	1	0.04	3	0.11	2	0.08	4	0.15
$c_{3,7}$	0.04	4	0.15	2	0.08	2	0.08	1	0.04
	Total		**2.78**		**1.85**		**2.32**		**2.48**

Appendix F

Estimate of costs involved by moving Harsco Metals Holland Velsen Noord

As discussed in paragraph 4-2, the first location is currently used by Harsco Metals Holland Velsen Noord, the slag processing company located at the Tata Steel site. Selecting location 1 would imply that Harsco must move to another place. In order to give an idea of the financial consequences of selecting this area, a rough estimate of the demolition costs involved is presented in this appendix.
The demolition costs are divided into demolition of open storage and demolition of office and heavy processing buildings. The cost estimate is presented in Table F-1; as can be seen, the expected demolition costs will exceed three million euros. The construction costs for a new location for Harsco are not included in this calculation, but Table F-2 gives an approximation of such costs, based on comparable works of construction.

Table F-1: Demolition costs [50]

Demolition costs (F3008)	**Costs** [*€/m^3*]	**Surface** [*m*]	**Total costs** [€]
Open storage	4	400 x 600 x 3	2,880,000
Office buildings	7	150 x 50 x 4	30,000
Heavy processing buildings	10	150 x 100 x 3	450,000
		Total	**3,360,000**

Table F-2: Construction costs [50]

Construction costs	**Costs** [*€/m^2*]
Office building (F1004)	1050 – 1350
Production building (F1001)	380 – 700
Asphalt (F4003)	65 – 78
General costs (F7007)	15%

Appendix G

Input parameters

This appendix provides an overview and description of the input parameters of the simulation model. The parameters are divided into the following groups: general characteristics of the HIsarna plant, characteristics of the transport, storage and processing of materials, and characteristics of failures. These characteristics are listed in, respectively, tables G-1 to G-6 inclusive.

Table G-1: General characteristics HIsarna plant

Property	Description
Resolution [*ent/h*]	The number of entities moving per hour through the system.
Demand [*mt*]	HIsarna's annual capacity of hot metal.
Operation days [*d*]	The number of days per year that HIsarna will be in production.
Operation hours [*hrs*]	The number of hours per day that HIsarna will be in production.

Table G-2: Material characteristics

Property	Description
Material	The different materials processed at HIsarna, including iron ore, coal, BF sludge, currently produced BOF sludge and historic BOF sludge.
Available amount [*mt*]	The annually available amount of a material to produce hot metal at HIsarna.
Proportion in hot metal [*%*]	The percentage of a material in hot metal.
Handling losses [*%*]	The percentage of handling losses at the storage and handling area, including the moisture content, oversize particles and handling losses.

Table G-3: Characteristics of transport

Property	Description
Transport system [-]	The transport systems used for each material.
Transport capacity [*mt*]	The capacity of a transport system.
Transport time [*min*]	The time required for transportation of the supplied materials to the storage and handling area, based on the travelling distance and transportation system. A triangular distribution is used to express the transportation time.
Capacity ratio of material supply [-]	The relation between the supply capacity of raw materials and the required capacity of HIsarna.
Work schedules [-]	The planning of the transportation of iron ore and coal to the storage and handling area, based on the shift work schedules of Tata Steel.
Interarrival time [*min*]	The time between the supply of materials; this depends on the sludge filter press (for the materials BF sludge and currently produced BOF sludge). A triangular distribution is used to express this property.

Table G-4: Characteristics of storage

Property	Description
Capacity of raw material storage [*h*]	The capacity of the raw material storage.
Capacity of handled material storage [*h*]	The capacity of the handled material storage.
Reorder point [*h*]	The level of storage triggering an action to place a reorder.
Reorder amount [*h*]	The amount of material to be reordered. For historic BOF sludge, BF sludge and currently produced BOF sludge, this is a fixed amount, based respectively on the capacity of truck and the sludge filter press. For iron ore and coal, the reorder amount is based on, among others, the storage level.

Table G-5: Characteristics of processing

Property	Description
Processing capacity [*mt*]	The capacity of the pre-processing line of a material.
Processing time [*min*]	The time it takes for pre-processing a material. A triangular distribution is used to express the processing time.
Capacity ratio of material handling [-]	The relation between the capacity of the handling area and the required capacity of HIsarna.
Ranking rule [-]	(FIFO or LIFO)

Table G-6: Characteristics of failures

Property	Description
MTBF [*d*]	The mean time between two failures, which is expressed using a Weibull distribution[1]: $\mathrm{Weibull}(3{,}10)$.
MTTR [*d*]	The mean time to repair a failure (with a minimum reparation time of one hour) is expressed using an exponential distribution[2]: $1 + \mathrm{Exponential}(10)$.

[1] A Weibull distribution is a commonly used function to express the MTBF [51].
[2] An exponential distribution is selected based on literature [28].

Appendix H

Number of replications

This appendix estimates the required number of replications for the simulation. Replications of simulation runs will produce more accurate and reliable results of the output variables. The input distributions, such as the equipment failures and interarrival time of material supply, lead to variation of the response variables. On the other hand, increasing the number of replications will also result in more computing time required. Therefore, a plausible number of replications must be established to achieve accurate results without imposing a burden on the computing system.

According to the Rule of Thumb, it is recommended to perform at least three to five replications [52]. The Simple Graphical Method by Robinson is used to determine the required number of replications for this simulation model. This method compares the cumulative mean of an output variable to the number of replications [47]. Since the input distributions of failures are the parameters with the most varying values, these parameters are used. In figures H-1, H-2 and H-3, the cumulative mean of, respectively, the maximum time to repair, the average time to repair and the number of failures occurred are plotted against the number of replications performed. The selected number of replications is 15.

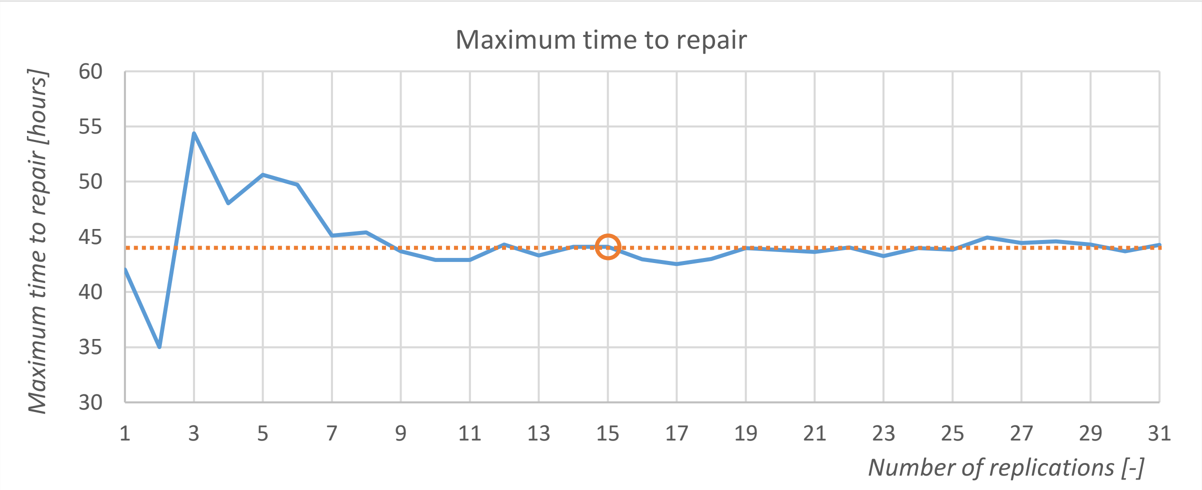

Figure H-1: Number of replications plotted against the maximum time to repair a failure

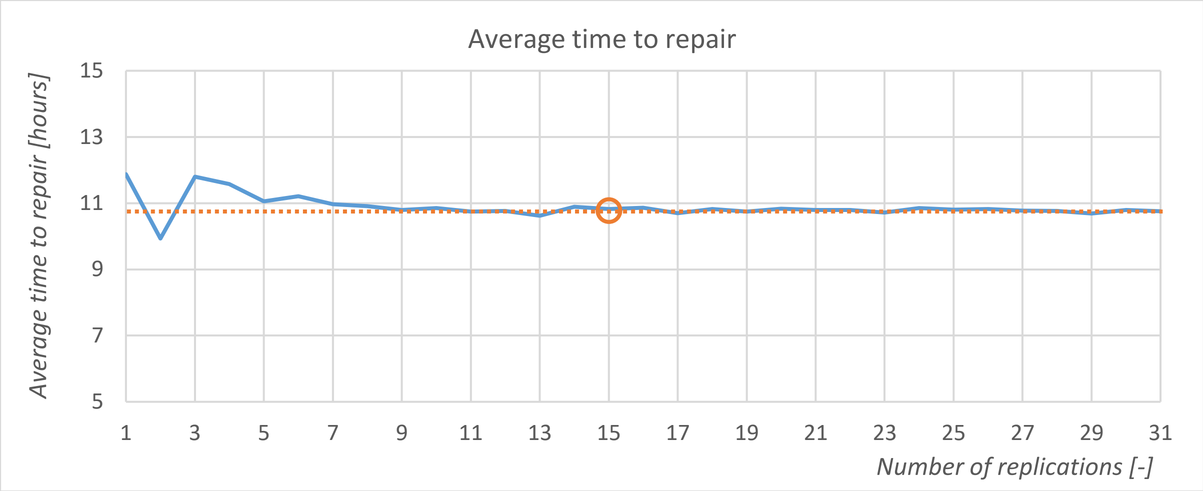

Figure H-2: Number of replications plotted against the average time to repair a failure

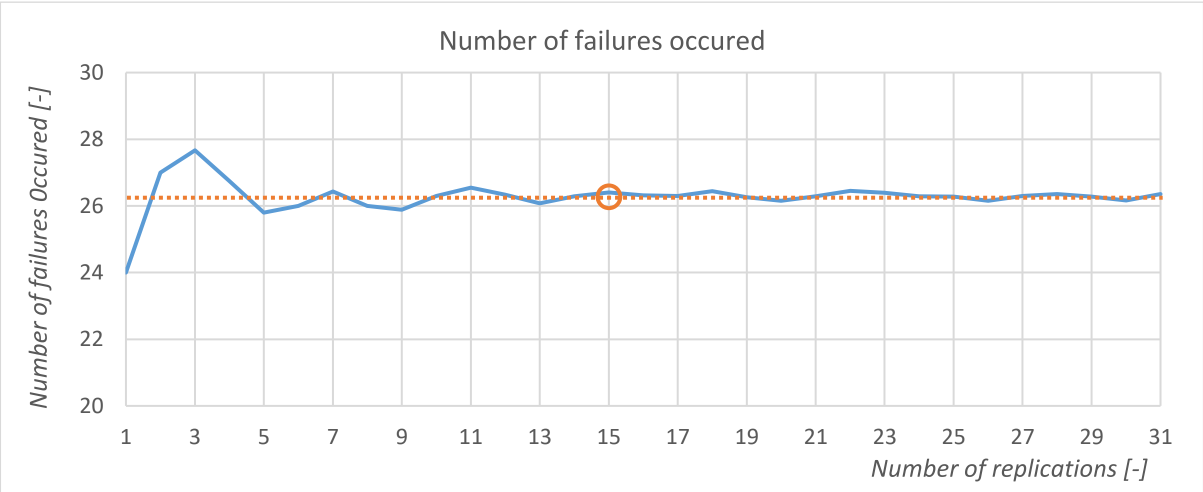

Figure H-3: Number of replications plotted against the number of failures occurred