



Casthouse modelling and optimization for an aluminium primary casthouse

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Casthouse modelling and optimization for an aluminium primary casthouse

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A 60 credit units Master's thesis

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“Cathouse modelling and optimization for an aluminium primary cathouse”

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ABSTRACT

The investment of an aluminium smelter casthouse is a very long and expensive process, therefore it is crucial to carefully model it before the beginning of construction. There is not a lot of research aimed specifically at modelling for aluminium casthouses and this thesis is aimed at fulfilling that need. The outcome is a three-way approach to model a casthouse and using this approach will help management teams to focus on the right path during the modelling process and therefore save money by choosing the right model for them at the outset and use the model selected to avoid costly errors during the construction phase. In the first step research is done on the aluminium market, equipments available, and the quality of metal. That information is used, along with management constraints, to create a binary integer program which is used to select four models. The next step is to simulate those four models and in the simulation the models are tried with different inputs and efficiency on the machines. The sizes smelters that will be looked at are 180,000 – 450,000 tons a year and the efficiency on machines range is from 75% - 95% on the machines. The last step is then to choose the best model of the four, using the AHP method and the information obtained from the simulation. The variables selected in the AHP method are cost, value, metal backlog, throughput, utilization of machines and product mix.

Keywords: Aluminium casthouse, binary integer programming, simulation, AHP method.

ÚTDRÁTTUR

Fjárfesting í álveri, þar með talið steypuskála, er langt og dýrt ferli. Þess vegna er mjög mikilvægt að búa til líkön af steypuskálum og greina áður en bygging hefst. Það er ekki til mikið af heimildum sem eru sérstaklega um líkanagerð steypuskála í áliðnaði og þessari ritgerð er ætlað að bæta úr því. Útkoman er þriggja skrefa leið til þess að búa til líkön af steypuskála og finna það besta. Þessi aðferð mun hjálpa framkvæmdarstjórn við að halda sig á réttri braut í líkanagerðinni og velja strax það líkan sem er best. Þar sparast fé í líkanagerð og þetta kemur einnig í veg fyrir aukakostnað við bygginu og notkun steypuskálans. Aðferðin byggist á því að í fyrsta skrefi er gögnum safnað um álmarkaðinn, steypuvélar sem eru á markaðnum og málmgæði, síðan eru þessi gögn notuð, ásamt skorðum frá framkvæmdastjórn, til þess að búa til heiltölubestunarlíkan. Þetta líkan er notað til að sigta út fjögur líkön til nánari skoðunar. Skref númer tvö er að herma þessi fjögur líkön, sem í þessari ritgerð eru öll hermd miðað við álver með 180.000 – 450.000 tonnum í afkastagetu á ári og með vélanýtni frá 75%-85%. Síðasta skrefið er að nota AHP aðferðina til þess að velja besta líkanið með tilliti til kostnaðar, virðis, ósteypanlegs málm magns, afkasta, mögulegra vörutegunda og nýtni véla.

PREFACE

When I started working at Alcoa Fjarðaál, I became aware that there are so many parts that need to fit together to create the smooth flow of metal through the process. Often I wondered what the decision process had been, and I began to think how I would design the process and what would I look at if I were to simulate the scenarios. The simple simulation thesis I had planned soon expanded and ended up in the ultimate question - what would I do if I had a casthouse to model?

It is not always easy to find all the necessary information in a large company, especially during start-up, since designing and deciding what to produce is a decision involving many people.

I would like to thank my partner Stuart Maxwell for putting up with me on Saturday nights when I was studying, reading over my thesis and be an all-around support, and my parents for their continued support.

I would also like to thank Alcoa Fjarðaál for a once-in-a-lifetime opportunity of being involved in a start-up, and all the people there who helped me with the thesis.

I would like to dedicate this thesis to my son, Vilhjálmur Hinrik Maxwell, who was born during the making of this thesis.

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1 INTRODUCTION

The aluminium industry in Iceland has a history of almost 40 years. Rio Tinto Alcan owns the oldest smelter in Iceland, which was started in 1970. Century Aluminium constructed the next smelter in 1998 and, finally, Alcoa started their smelter in 2007. Currently there are also prospects of the construction of two other smelters; one in Húsavík and one in Helguvík. It is therefore apparent that smelters play a big role in the Icelandic export and job market.

The aluminium production can be divided into two areas: the potrooms, if it is a primary casthouse, and a casthouse. The potrooms produce the aluminium. The casthouse is where molten aluminium is transformed into various products that are either used for re-melt, where customers transform the product at their location, or as a finished product. Aluminium products can be seen all around us; in window frames, aluminium foil, electrical cables, the body and wheels of a car, etc. It has gained respect in industries such as aerospace, automotive, packaging, construction and transportation for its high strength-to-weight ratio, ease of use and low price. It is not expected that any material will replace it soon and new uses are found for it every day. Bearing all of this in mind, construction of a new casthouse facility is a huge investment for any company and therefore it is still very important to investigate both the modelling and simulation phases of a casthouse design.

Alcoa is currently one of the biggest aluminium producer in the world. The company was founded in Pittsburgh in the United States, in 1888. Currently Alcoa has operations in 44 countries with over 100,000 employees. The newest operation site is Alcoa Fjarðaál, in Iceland, which is a smelter producing 346,000 tons of aluminium per year. It has been rumoured that Alcoa is considering another smelter in Iceland.

The aim of this thesis is to help an aluminium company to decide what kind of casthouse would be the best option for their next investment.

1.1 Motivation

The process in an aluminium casthouse can be very complex but in the simplest terms it is the process of “freezing” molten metal. While aluminium production and casting is a known and documented subject, there is not a lot of available information on the subject of casthouse modelling. This could be because such information is highly confidential, can vary between companies, and new smelters are huge investments only built roughly every thirty years, so the methods and findings may not have been well documented and retained.

One of the hardest parts of modelling a casthouse is the variety of machines on the market; both casting machines, and machines to improve the quality of metal and to treat by-products. It is therefore difficult to model a casthouse accurately, since machine prices are very high and the machines are selected based on a market forecast. This information is highly confidential, which is why estimations are needed at the modelling stage.

Simulations have been used before in casthouses and many companies perform simulation studies before construction. This is, of course, a good way since it can uncover models that are not feasible. Simulations for casthouses have previously been used to find the optimal product mix, to find optimized process parameters and production planning but here, capacity, throughput and utilization of the machines are examined. When the model has been made, it can later be improved for product mix optimization, resource utilization, and to link the model to performance management tools.

The AHP method is a very popular method to use on complex multi-criteria problems. There are hundreds of published articles on the subject and there's even a magazine devoted to the method. The reason it is so popular is because it is user-friendly and can be used on problems which have non-numerical values as objectives (Albright and Winston, 2005). Binary integer programming is also a widely known approach and has been used previously, for instance as an investment selection tool (Hillier and Lieberman, 2001). Both of those methods are used in this thesis.

1.2 Objectives

The goal of this thesis is to provide the Alcoa top management with a process to select a casthouse model to be built in their next smelter. The aim is also to give an insight into all the elements needed to model a primary aluminium casthouse. All the necessary elements needed for the modelling are explained. They are: the objectives and organisation of the project, quality objectives, target market, and equipment selection. All of this information is put to use by selecting three machines to continue with this process. Ten models are constructed from those three machines and then a binary integer programming is used to narrow the models down to four that are considered the best, from the management's constraints. The hope for this part of the thesis is that it can be used as a basis for decision making and give an overview of possibilities for someone who is new to working in primary aluminium operations.

In the next step, the four selected models are simulated, with the goal to provide clear process flows of all models and simulate them with real data. The simulation results are then used to reach a decision. The AHP method is used to compare all models together in a systematic way to reach a decision as to which would be the best solution. It is possible to enhance the simulation models even further and connect the results to financial cost and premiums to analyze where it is possible to cut cost and maximize profits.

1.3 Contribution

The goal of the thesis is to answer the following research questions:

1. How is a casthouse modelled?
2. What are the major factors that need to be looked at when modelling a casthouse?
3. What is the best model?

The contribution of this thesis is a three-way approach to model a casthouse. In the first step there should be extensive research on market, quality and equipment available to select a few machines. Model variations from that machine selection are made and then a binary integer programming is used to narrow the options down to the number the company wants, within

the constraints given. Then a simulation study is done and the results used in the AHP method, to reach a conclusion as to which model is the best, from the company's perspective.

The models are validated with real time data from the casthouse at Alcoa Fjarðaál. All models are simulated with the software SIMUL8.

The aim of this thesis is that it should benefit the CEOs of aluminium companies in making a decision on what kind of casthouse should be selected when a new smelter is built. The model selected can then be used for further study before the construction of a casthouse.

1.4 Overview

This section is a general description of the thesis. A schematic overview can be seen in figure 1.

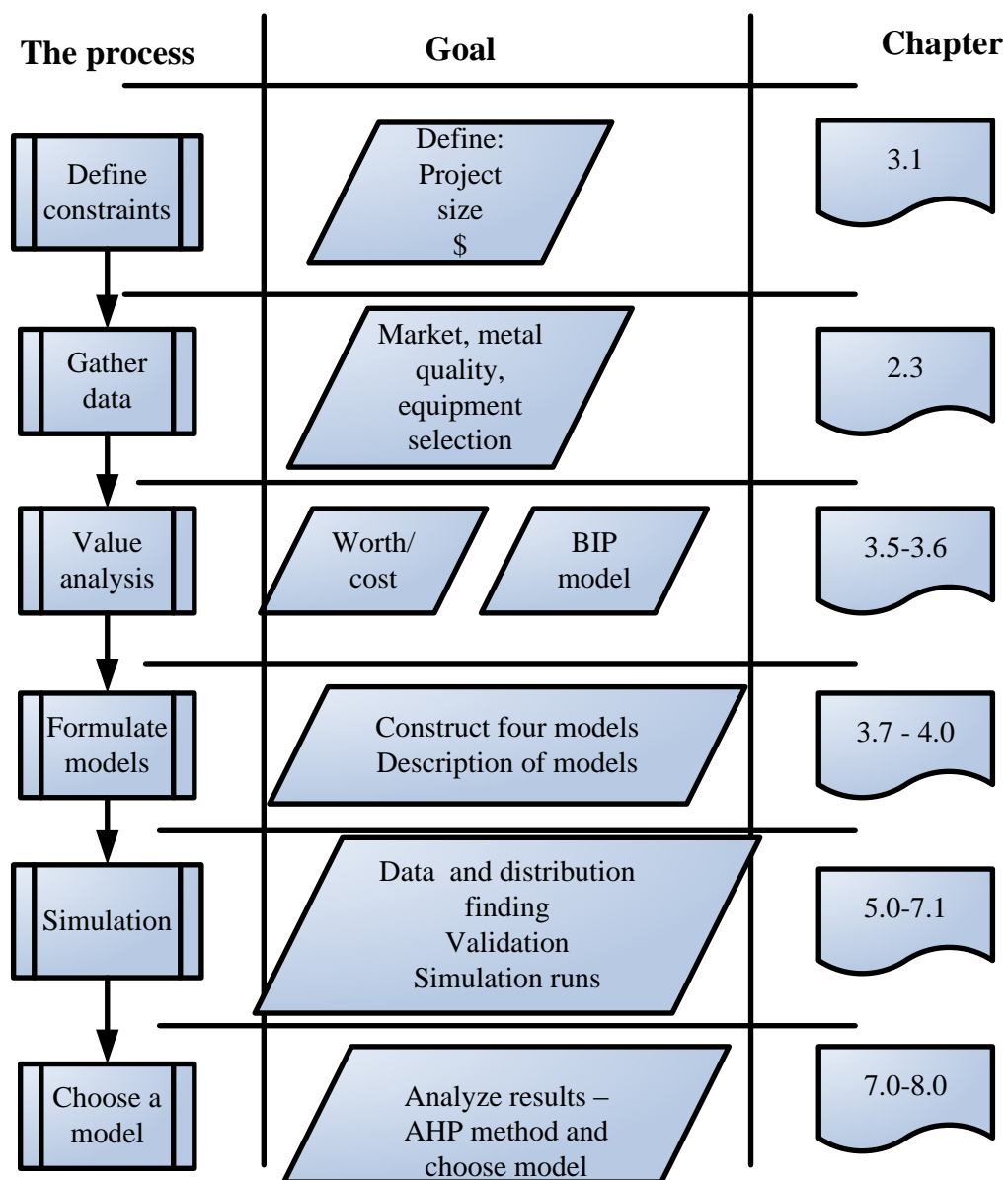


Figure 1: Schematic view of the process used to model a casthouse.

Chapter two focuses on two things; what has been done previously in this field, and a description of the theory and background used in this thesis. The theory discussed is on the AHP method, engineering economics and simulation. As can be seen in figure 1, chapter 2.3 is about gathering data on the background of the aluminium industry, market demand, equipment availability, and quality requirements which is used as a basis for the modelling.

Chapter three is about the casthouse modelling methods. The objective of chapter 3.1, as can be seen in figure 1, is to define the project's criteria of budget and size. Chapter 3.2 – 3.4 uses all the information on the aluminium background to select machines, metal quality and product mix. In chapter 3.5 there is a small value analysis, used to select three machines. From those three machines, ten models are available. To narrow those ten models down to four, a binary integer programming is used. In chapter 3.7, the four models used for further analysis are formulated.

In chapter four, there is a detailed description of all the models chosen. There is a schematic view of them, description of the routing, description of the machines and the assumptions made regarding them.

Chapter five, as can be seen in figure 1, is about the data distribution and model parameters that are used in the simulation model. There is a description of each object being tested for distribution; there are also histograms and descriptive statistics for all of them. For each section, a proposed distribution is used, there is discussion on how the data was assembled and the possibility of flaws in the data gathering. In the model parameter section there is a description of all the factors which had no distribution but were used as an invariable parameter in the model. There are also two tables in this chapter that summarize all the information.

Chapter six is about the validation of the model. There are two kinds of validation, validation using historical data and validation with management review.

In chapter seven there is a description of the simulation trials done. All the results gained from those results are in appendix B. The models were tried with an efficiency range of 75%-95% and an input of 180,000 – 450,000 tons per year. The parameters inspected were metal throughput, metal backlog and utilization of machines. The AHP method is then used to compare the models in order to select the best one. The criteria used are cost, value, metal backlog, throughput, efficiency of machines and product mix. There is a discussion of the elements used for the comparison and the rating of the models. The tables used for the comparison are in appendix C. This is the last step in the process before the model selection, as can be seen in figure 1.

Chapter eight is the conclusion and discussion chapter, where the best model is selected. The results' meaning is discussed, as well as improvement possibilities. This chapter also summarizes the answers to all the research questions.

2 BACKGROUND AND THEORY

This chapter introduces what has previously been done in modelling, simulation and investment selection. Then there is a description of the AHP method, NPV analysis and simulation steps. The factors that influence the casthouse modelling are also discussed, which are project definition, quality of metal, market demand and equipment selections.

2.1 Literature review

There is not a lot of research on the subject aimed specifically at the aluminium casthouse or the modelling of the aluminium industry. Therefore this literature review is based on what is happening in manufacturing modelling and heavy industry as well.

It is the norm to create business cases when deciding whether a project should be undertaken or not. This was done when Alcoa Fjarðaál was being contemplated and is always done if there is investment selection in the casthouse later on. When creating a business case for a large project the OGC¹ (2009) proposes three stages. Step one is to create a preliminary business case which is to see if there is a strategic fit and a business need. The next step is to outline a business case where indicative assumptions are made to support the preferred way forward. The final step is to do a full business case where the assumptions for the investment decision are validated. The business case should include a cost benefit analysis, how the investment will be financed, risk analyses etc.

Engineering economics deal with the situation of choosing a best project from a few options. The methods used are finding net present value, internal rate of return, profitability index, return of investment, rate of return and equivalent annuity (Park, 2002), in this thesis the NPV method was selected and is explained further later on. These methods are often used for calculations and used in the business case. These methods fail in an important matter as they factor neither project risk into the equation, nor the company's strategic policy, although it is possible to do a separate risk assessment, sensitivity analysis on the methods above, or a breakeven analysis (Park, 2002). Baker and Fox (2003) created a new risk premium model to incorporate risk into the NPV calculation. They derive formulas with an appropriate discount rate, a risk horizon - where the risk premium exceeds the expected value - and a maximum default hazard point for projects. Mahmoodzadeh, Shahrabi and Zaeri (2007) recommended using fuzzy AHP and TOPSIS technique where they calculate NPV, rate of return, benefit cost analysis and payback period and have them in the AHP decision tree. For multi-criteria decisions it is also possible to use goal programming and Pareto trade-off curves instead of the AHP but it only works for numeric goals (Albright and Winston 2007). There are also a number of hybrid methods, for instance Ayag (2006), which proposes a hybrid method to select machine tooling with AHP and simulation. First the models are narrowed down with the AHP method then they are simulated. Finally a final model, with the least unit investment cost ratio, is selected. A fuzzy analytical network process has been proposed for R&D project selection by Mohanty, Agarwal, Choudhury and Tiwari (2005). ANP is a more general form of the AHP process, used to evaluate dynamic multi-directional relationships among the decision attributes. The fuzzy set is used to overcome the vagueness in the preferences. This method uses triangular fuzzy numbers for pair-wise comparison and applies extent analysis, then a defuzzification in order to find the weights of the attributes. Angelis and Lee (1996)

¹ Office of Government Commerce

propose using activity-based costing with AHP for investment selection. In activity-based costing the goal is to map all the activities in the business and put a dollar to every activity. That way it is easier to see opportunity for improvement and understand the business. In this method the relationship between all the goals, activities, cost and performance measures is developed and used to make two models, a cost impact model and a performance impact model. Then a cost versus performance graph is made. The decision process then evaluates the investment alternatives based on their impact on activities and how they contribute to the organizational goal. For equipment selection in manufacturing, Dagdeviren (2008) suggests that the AHP method integrated with preference ranking organization method for enrichment evaluations (PROMETHEE) should be used. The AHP is used to analyze the equipment selection problem and to calculate the weight of the criteria and then PROMETHEE is used to get the final ranking and to do sensitivity analysis by changing the weights.

Cochran, Arinez, Duda and Linck (2002) propose a decomposition approach for manufacturing system design. By using this approach it enables companies to simultaneously achieve cost, quality and delivery goals. This method integrates a few areas in the design, such as material supply, labour, operation equipment design, etc. It uses the axiomatic design process but in that process the objectives of the design are denoted Functional Requirements (FR) and the solution's Design Parameters (DP). It starts by interpreting the customer's goal into FR and then the designers determine how the FRs will be met by the DPs. Then the design matrix is evaluated to choose the best set of design parameters and, finally the decomposition is done.

Optimization has been used in the aluminium industry to optimize sequencing of tasks with regard to setup times (Gunnarsson, Jensson & Kristinsdottir, 2004). Two methods were tried; genetic algorithm and integer programming. The simulation to optimize extrusion process parameters was done by Bajimava, Park and Wang (2007). They used the simulation software IGRIP to create a model of an extrusion machine and then simulated the process using graphic simulation language (GSL) to obtain optimized process parameters. Continuous casting simulation has also been done to see what happens to the mould while the casting is ongoing and what causes defects and problems, (Gremaud, 2003). Simulation has also been used to optimize maintenance strategies. Boschian, Rezg and Chelbi's paper (2009) examines two kinds of maintenance strategies. In the first strategy the production rate and the periodicity of preventive maintenance is independent and the second strategy suggest an interaction between the two to minimize production loss. These two strategies are then simulated and compared in order to find the best timing of preventive maintenance of the machines.

2.2 Engineering economics

It is a big decision to invest in new companies. It is considered a capital investment to purchase all the machines and companies want to have a very good idea whether they will make profit or not, as well as how long it will be until full profit is made, etc. Below is a description of the most popular tool for investment selection. This tool was used extensively when the decision about Alcoa Fjarðaál was being made.

2.2.1 NPV analysis

NPV analysis or net present value, sometimes called NPW (net present worth analysis), is a method to evaluate long term projects. It is used to determine if the anticipated cash flow from the project is enough to make it feasible to invest in the project, by using the time value

of money. It is very popular in capital budgeting projects and it measures the excess or shortfall of cash flow in present value terms. The definition of NPV is the total present value of a time series of a cash flow.

Steps to find the NPV

1. Determine the required rate of return or minimum attractive rate of return (MARR). This decision is normally made by top management and can both change during the lifetime of the project or be a single rate, this is denoted i in figure 2.
2. Estimate the lifetime of the project, denoted n in figure 2.
3. Estimate the cash inflow for each period of the life time.
4. Estimate the cash outflow for each period of the life time.
5. Calculate the net cash outflow (net cash outflow = cash inflow – cash outflow), denoted A_n in figure 2.
6. Find the present worth of each net cash flow at the MARR, which is shown in figure 2.

$$PV(i) = \sum_{n=0}^N A_n / (1 + i)^n$$

$PV(i)$ =NPV calculated at i

Figure 2: the NPV calculation

If the equation shows positive value, the investment should be accepted, if it is negative, the investment is not feasible. If it is zero, this method does not give more weight to either decision. If there is a decision to be made on a variety of projects then the project with the highest NPV should be selected, if the focus is to maximize profit, or the least negative if the focus is to minimize cost (Park, 2002).

2.3 Influential factors when modelling a casthouse

In this section the following subjects will be investigated that influence how a casthouse is modelled; the project definition, the quality of metal, the market, and machine selection, including the machine operation cost estimation and finance analysis.

2.3.1 Project definition and organizational structure

The top management team decides on the project definition and selects the final project - they make a decision on the goals and objectives of the project along with budget constraints. A project manager works on behalf of the management to manage the project. The teams working for the management and project manager have to obey those budget constraints and gather data. The major teams are the sales team, the technical team and the financial team, which all report to the top management of the company. All of the teams must work together in order to find the best solution and they all have their specific tasks.

- The sales team has to look at product range, future market prospects and shipping.
- The technical team concentrates on what kind of equipment to buy, machine requirements, flexibility, throughput, etc.

- The financial team has to work with information from the sales team and the technical team in order to do value analysis and see what design would maximize profit.

2.3.2 Quality of metal

In a primary smelter the quality, sometimes referred to as purity of the metal produced depends on the potrooms; both with regard to material and operations. In addition, there are many variables when alloying with other elements in the casthouse. This chapter will explain how metal is classified when it enters the casthouse, and how it is classified after it has been alloyed. The market depends on a certain quality and in order to produce certain products, different addition or quality requirements are needed.

Properties of aluminium

Aluminium is a metal element, with the symbol Al and the atomic number 13. Its atomic weight is $26.982 \text{ g}\cdot\text{mol}^{-1}$ with a melting point of 660°C , a boiling point of 2270°C and its crystal structure is FCC (face centred cubic). It is a soft and ductile metal with a greyish appearance when exposed to air. Aluminium is the third most common element in the earth's crust and accounts for about 8% of its weight (Hatch, 1999).

Benefits of aluminium

- Easy to cast in hot, liquid state
- Due to the oxidized layer it has very good resistance to corrosion
- Good conductor of electricity and thermal heat
- Easily painted and welded
- High impact resistance and good barrier against gases
- Easily malleable when it is cold, through machining
- Non-toxic, non-magnetic and non-sparking
- High strength to weight ratio

Drawbacks of Aluminium

- Splashes very easily when molten – highly dangerous
- High explosion risk if molten aluminium comes into contact with water

Aluminium alloy designation

The Aluminium Association has designated three major groups for products; cast alloys, wrought alloys, and un-alloyed aluminium. The difference between cast alloys and wrought alloys is that wrought alloys have been subjected to mechanical working by processes such as rolling, extrusion, and forging, while cast alloys are cast straight into moulds from a molten state. Un-alloyed aluminium is pure and without any additives (The Aluminium Association, 2007).

Cast alloys

Casting alloy is pure aluminium, mixed with other materials to obtain desired properties. It is very common to make specialised specifications for certain customers. Figure 3 shows what each symbol means in the designation. The first digit is the alloy group, the next two digits represent the minimum percentage of aluminium and the last digit denotes if it is a casting or ingot (Hatch, 1999).

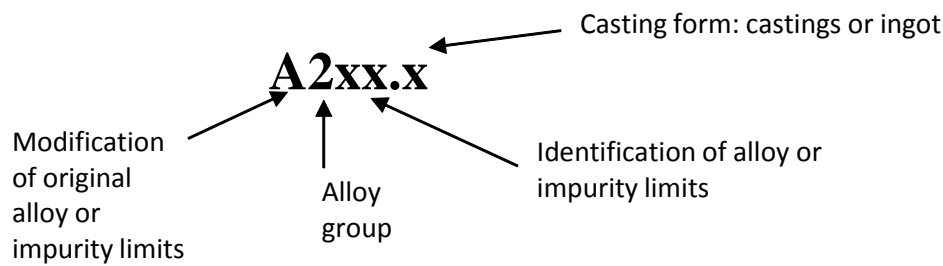


Figure 3: Identification of aluminium casting alloy designation.

There are eight groups from 1xx.x – 8xx.x that represent different alloys and purities.

Un-alloyed aluminium

When the aluminium is in pure metal form, with no added elements in it, the most important data is the silicon and iron content - from which we get the purity number. There are four major groups - P2055, P1020, P0610 and P0406 - but within each group there is a more detailed breakdown. To be included in a group, the silicon and iron content of the product must be less than or equal to these numbers. Figure 4 shows an example of the P value. Maximum silicon content is denoted xx and maximum iron limit is denoted yy (The Aluminium Association, 2007).

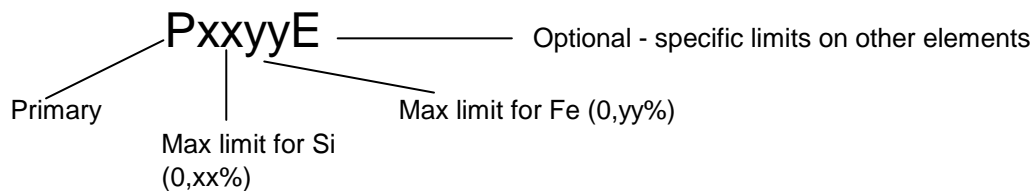


Figure 4: Unalloyed aluminium designation.

P1020 is a standard metal and is in steady demand since it can be sold on the LME (The London Metal exchange, 2008a).

P1535 is not considered good quality and therefore demand is very low. Grades that are higher in iron than that this are considered “Off-Grade”.

Wrought alloys

Alloys are put in series from 1xxx to 8xxx, with the numbers representing the major elements added. Figure 5 shows what each symbol represents. As stated before, a wrought alloy is an aluminium alloy which is available in the form of worked products such as rod, wire, forgings, extrusion, etc. It is not possible to see which product it applies to in the designation, as with the cast alloys (Hatch, 1999).

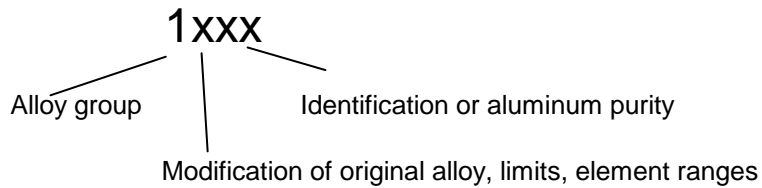


Figure 5: Identification of the wrought alloys.

2.3.3 The Sales Team – Market research and proposal of goods

The Sales Team is the team that looks at the current aluminium market and makes a suggestion on the product mix that would be the most suitable output of the plant. This group has to analyse the current market and forecast how the market will grow, what the premium is, and what it will be in the future.

Premium is the amount paid above the London Metal Exchange (LME) price, which is the market price on a standard P1020 ingot/sow/T-bar (The London Metal Exchange, 2008a). If the product is of a higher quality, the premium is normally higher than the LME price. If the quality is lower, the price is normally discounted. There are different kinds of premiums and demand for certain kinds of products, for instance: small and large ingots, rods, T-bars, sows, billets and slabs – both alloyed and pure. Of course it is possible to cast aluminium into whatever shape, size and lot size, but it is usually preferable to produce standard products and sizes in large batches, and then leave it to the customers to rework the product downstream.

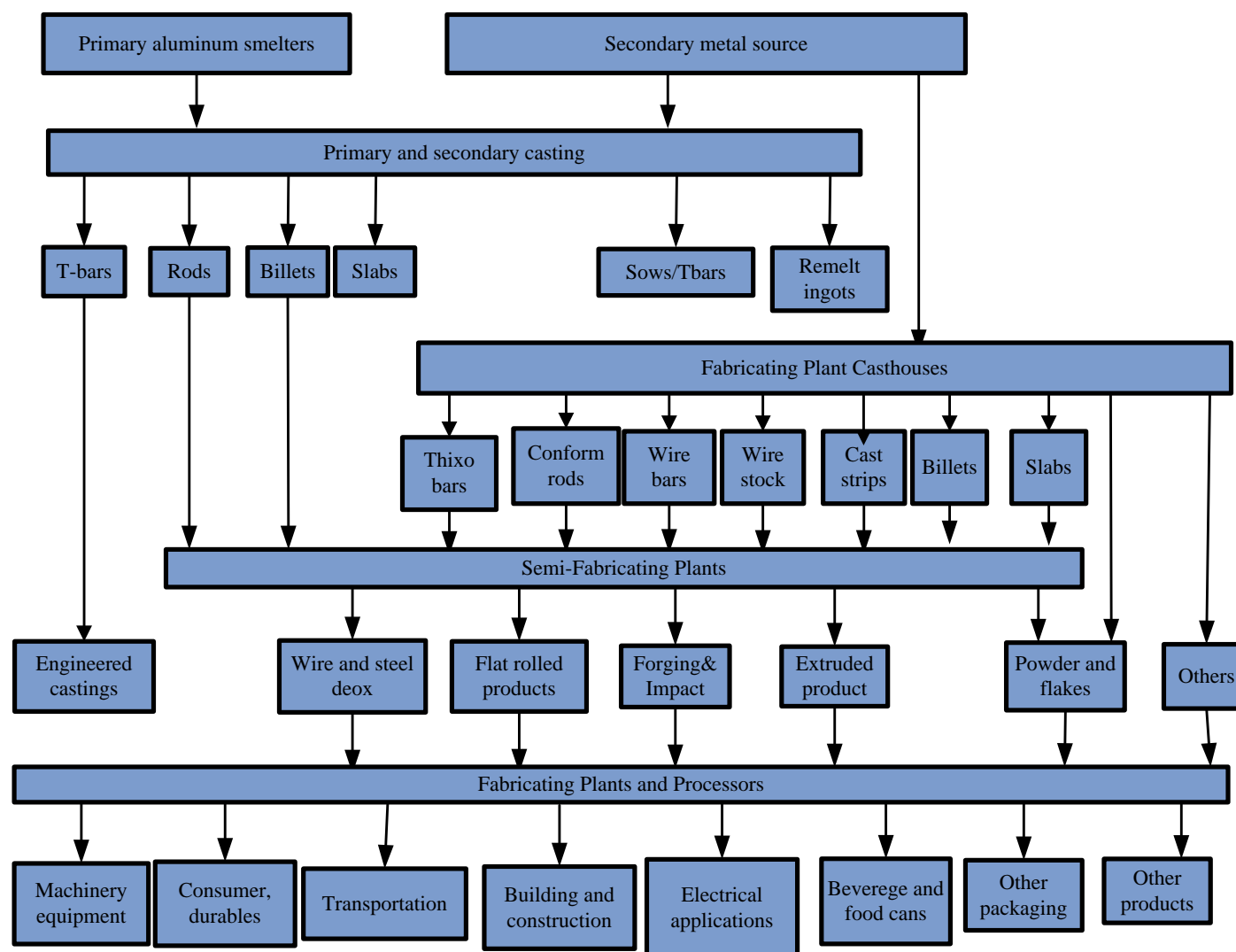


Figure 6: Aluminium production activities (Becker, 1999).

Figure 6 shows from where in the casthouse process the products can derive and the lifecycle of a product. The models that are considered in this thesis are considered primary casting since the potrooms are the primary metal source. The product range available is also shown in this figure: T-bars, rods, billets, slabs, sows, and ingots. These products are then reworked to a final product. Those final products are for, amongst others, consumer durables, transportation, building and construction, etc.

Product range

While it is possible to cast whatever shape one wants it is not the most economical way, so there are a range of standard products produced and sold and this section will introduce a selection of the most common ones.

T-bars and sows

T-bars and sows are both used in the re-melting industry. They can be seen in figures 7 and 8 and they are produced in this shape because they can be easily handled with forklifts in order to put the material in the furnaces. The sows can be cast in open top mould casting and are mostly pure grade. This means the purity is dependent on the supply from the pot lines; varying from very low iron to very high iron.

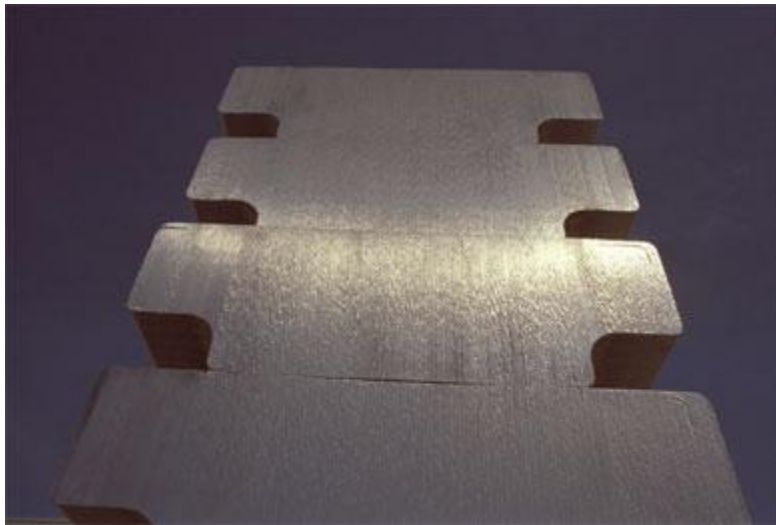


Figure 7: T-bars stacked together (Alcoa, 2008).

The T-bars can be cast in VDC (Vertical Direct Chilled) or HDC (Horizontal Direct Chilled) machines and can be both pure and alloyed. The T-bars are more popular than the sows because the T-bars don't contain any oxides. When a sow is cast, oxides form on top, which are skimmed away, but residues of oxides can remain, which is not the case with the T-bars. Also, they are all of exactly the same shape and size which means easier handling. T-bars, sows, small and large ingots are products which can be used in all sectors for re-melting given, the right chemistry.



Figure 8: Sow product (Alcoa inc, 2008).

The customers buy this type of product to use in a final production process at their location, where they have their own furnaces to re-melt the product. This is mainly done where electricity is expensive and/or there is no smelter close by.

Rods

Rods can be sold straight to the customer and can be either EC grade for cables, or Deox for the steel industry. The wire can be sold in varying diameters and the coils in a variety of sizes – the chemistry is also down to the customer's request but it is very common to produce wrought alloys 1350 or 1370. Aluminium coils are popular because, amongst other things, they can carry twice as much current as copper of the same weight and have high thermal conductivity (Hatch, 1999). Figure 9 shows a sample of a coil.



Figure 9: Rod caster and a coil (Alcoa inc, 2008).

Billets

Billets, or extrusion ingots, (Fig. 10) are used for extrusion and forging applications, and are used by the customer in their finished form. There are extremely strict quality conditions on the billets and normally they need to undergo a homogenizing process to ensure that quality specifications are met. It is possible to produce billets in different sizes and diameters and with the chemistry that the customer requires.



Figure 10: Billets (Alcoa inc, 2008).

Ingots

Small ingots can be both pure and alloyed. When they are alloyed they are called foundry ingots and they are used extensively in the automotive industry. Some customers prefer the small ingots as “re-melts” if their furnaces are small. Normally the ingots are 5-30 kg and are sold in bundles up to, and including, a ton. Figure 11 shows an example of small ingot bundles (Alcoa inc, 2008).



Figure 11: Small ingots (Alcoa inc., 2008).

Slabs

Slabs (Fig 12) are used in the rolling industry and are normally alloyed as per customers' requirements. Sizes can also vary according to the customers' wishes.



Figure 12: Slabs (Alcoa inc, 2008).

Purchasing the metal

There are different ways to buy metal. Long term contracts can be made directly with the suppliers by the sales team, or a bid can be made on the London Metal Exchange. Normally, if a contract is proposed with an individual customer, a series of trial loads is sent to them before a contract is signed.

The LME is a market that exchanges non-ferrous metals such as aluminium, copper, lead, zinc and tin. It is the largest market of its kind in the world and was founded in 1877. The purpose of the market is to provide daily prices on the metals, to provide futures and trading options for hedging and to provide physical delivery of products per contracts. They have over 400 warehouses in 12 countries, and have roughly 440 brands of metal from 65 countries. Standard aluminium products in the LME are T-bars, sows and ingots as shown in Tables 1 and 2. Table 1 shows the standard product sizes for pure aluminium products and table 2 shows alloyed products. It is clear that the difference lies in a bigger product range for the alloyed products and bigger lot sizes for pure products (The London Metal Exchange, 2008b).

Table 1: The standard pure product on the LME (The London metal exchange, 2008a).

| LME Primary aluminium | | | |
|------------------------------|-----------------|---------------|--------------|
| Shape | Ingots | T-bars | Sows |
| Weight | 12-26 kg | 750 kg (+5%) | 750 kg (+5%) |
| Lot size | 25 tons (+/-2%) | | |

Table 2: The standard alloyed product on the LME (The London metal exchange 2008a).

| LME Aluminum alloys | | | | |
|---------------------|-----------------|------------|------------|------------|
| Shape | Ingots | T-bars | Small sows | Large sows |
| Weight | 4-25 kg | 408-726 kg | 408-590 kg | 300-726 kg |
| Lot size | 20 tons (+/-2%) | | | |

All prices and contracts made by the sales team are highly confidential and information is hard to acquire. Each week there is an update on stock levels and contracts in order to maximize profit.

Future prospects

In 2007 and at the beginning of 2008, the global aluminium market was not able to supply fully the market demand. There were many reasons for this shortfall; power supply problems, closure of smelters, rising electricity prices etc., and although prices were very high - which would normally create demand for another material - no material has been found that can fulfil customer needs as well as aluminium can. The market of aluminium at the end of 2008 and early 2009 has been very tight and the LME prices have not been as low in years, but it is forecast that price and demand will pick up when the world economic depression eases up.

The European aluminium market is expected to grow in the home building industry due to an increase in construction, and the container and packaging industry is also expected to grow at CAGR (Compound Annual Growth Rate) of over 2% during the 2008-2012 period according to the European aluminium market research (RNCOS, 2008). The forecast is shown below in figure 13.

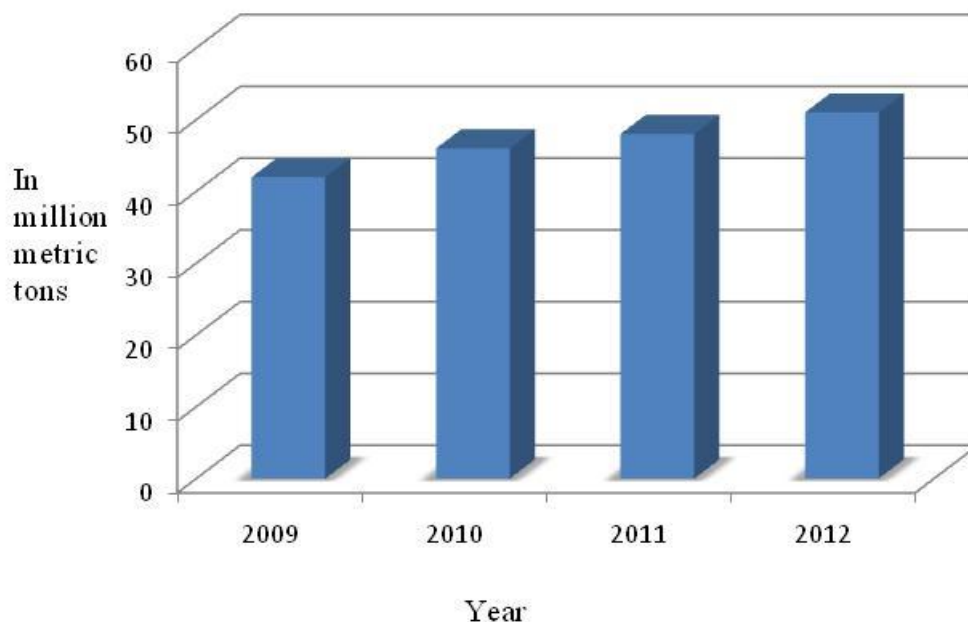


Figure 13: Forecast for consumption of primary aluminium (RNCOS, 2008).

The outlook on the future market is that there will be more demand from the construction and automobile industries because of rising demand from the developing countries. It is forecast that consumption of aluminium will go from 42 million tons in the year 2009, to 51 million tons in the year 2012, as can be seen in figure 13. The market consumption today, by end

user, is shown in figure 14, from which it is obvious that the transportation and construction sectors are currently the largest markets. It is forecast that the electrical industry will increase and transportation will be steady, or grow, because of new CO₂ taxes on cars – car manufacturers have to make the cars lighter and will therefore choose lightweight aluminium for production. It is also forecast that the construction sector will pick up because of rising concern for the environment – aluminium being an environmentally friendly product – and also because a lot of the aluminium products are prefabricated which reduces costs for the construction companies. It is also expected that the consumer products market will grow for cooking equipment, cleaners, sewing machines, gas grills etc. (RNCOS, 2008). Even though the transportation industry is getting stronger, the billet market seems to be soft now and it is unknown when it will pick up (CRU market analysis, 2008). The same thing goes for slabs, but the flat-rolled market has shown the biggest weakness of all markets (Markham, 2008). The small foundry ingot is used in car manufacturing, which has a steady demand (RNCOS, 2008).

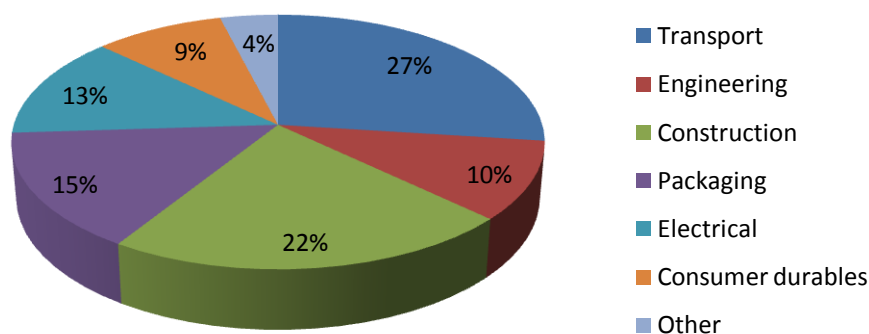


Figure 14: Consumption of aluminium by end use (RNCOS, 2008).

2.3.4 Equipment selection in a casthouse

There are two types of casthouse operations; primary and secondary. Primary operation is when the casthouse is connected to a smelter so most, if not all, of the metal that goes into the casthouse is molten. Secondary casthouses are a re-melting operation where solid metal is liquefied in furnaces and then cast into the desired shape. Process-wise, the difference between these two is that in primary operations the potrooms need to be tapped on regular basis and therefore machine stability and capacity in primary casthouses is essential. Conversely, if a secondary casthouse stops it is less problematic because there is no push of metal in the system. This thesis is focused on primary casthouses.

In this section, the aim is to discuss the different machines, their production rate, their functions, and general information that could be used in order to choose a certain kind of machine. This part will be divided into sub-chapters, in line with the process, as shown in figure 15. There will not be a discussion about degassers, filters and grain refiners since these are part of what is known as “in-line treatment” and are optional, depending on the product

mix (shaded area in figure 15). Also, dross coolers will not be discussed as they are not vital for production rate purposes, and are relatively cheap, compared to casters and furnaces.

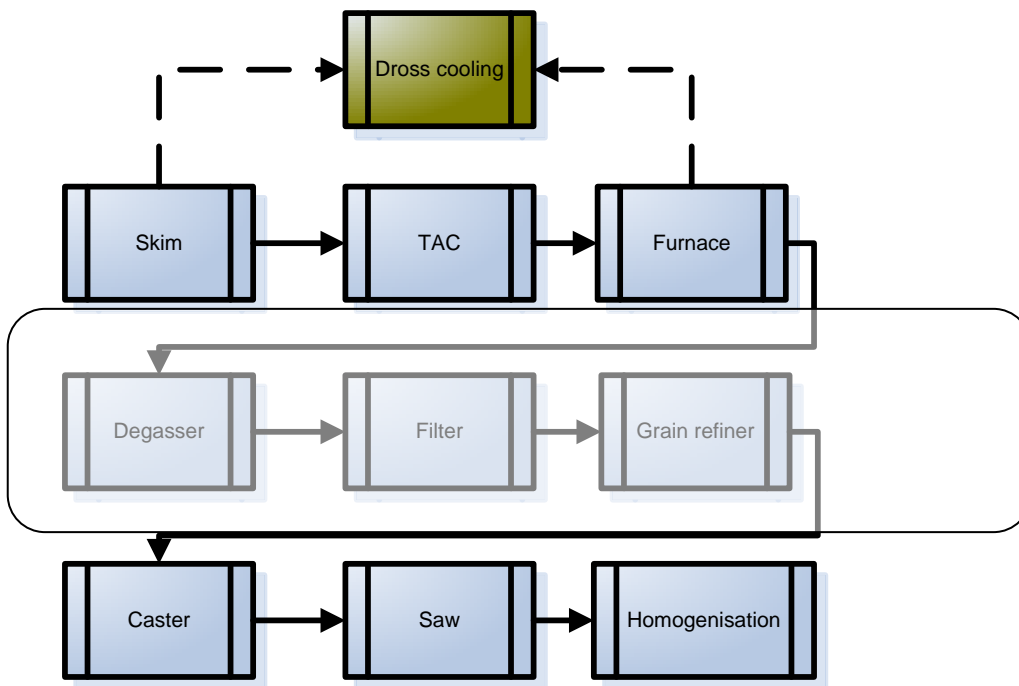


Figure 15: The casting equipment process

Treatment of aluminium / TAC&Skim

Skimming is to remove the oxidation (dross) that forms on top of the crucible and any extra bath. TAC stands for Treatment of Aluminium in Crucible and its primary purpose is to remove alkaline metals (Na and Li) and to remove inclusions. This is a quality issue and is not necessary for re-melt ingots but is recommended for coil and foundry ingots. A diagram of a TAC&Skim process can be seen in figure 16, where it can be seen that the crucible is fed AlF_3 and then there is an impeller that rotates in the crucible to blend it in. It is possible to have only one station with both functions or with bays and moving TAC&Skim stations, which means that they can both be used simultaneously (Taylor, 2002).

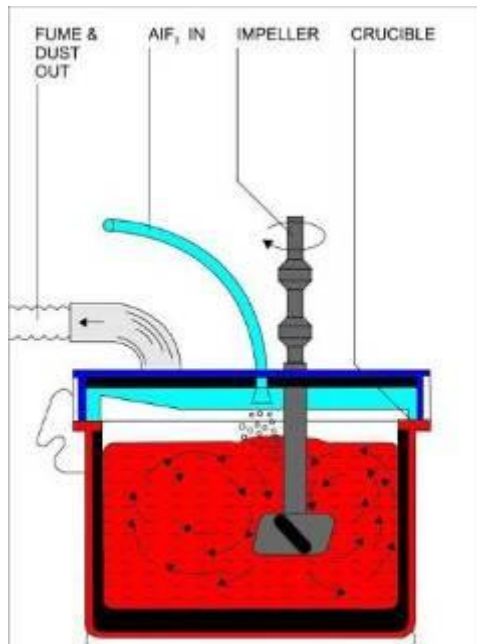


Figure 16: TAC&skim station (Taylor, 2002).

Furnaces

Furnaces are necessary when casting in continuous casters such as the HDC, VDC and rod casters. It is most common to have them custom-made for the process, in whatever size is required. There are basically two kinds of furnaces; melting and holding. Melting furnaces are used when the source of metal for the casthouse is solid and has to be re-melted for the casting process. When all the supply metal has been re-melted, it gets transferred to a holding furnace where the metal is prepared for casting. Both melting and holding furnaces can be powered by oil, gas, electricity, and induction heating.

Melting furnaces

Melting furnaces are designed for re-melting scrap and/or ingots and are normally used in plants where approximately 100% of their source metal comes in solid form. There are heating elements at the top of the furnace, and top and bottom temperatures can be carefully controlled. Melting furnaces can be either tiltable or static, depending on the customer requirements and it is also possible to open the front of them for stirring, skimming, maintenance and cooling. Figure 17 shows an example of a melting furnace (Solios, 2007b).

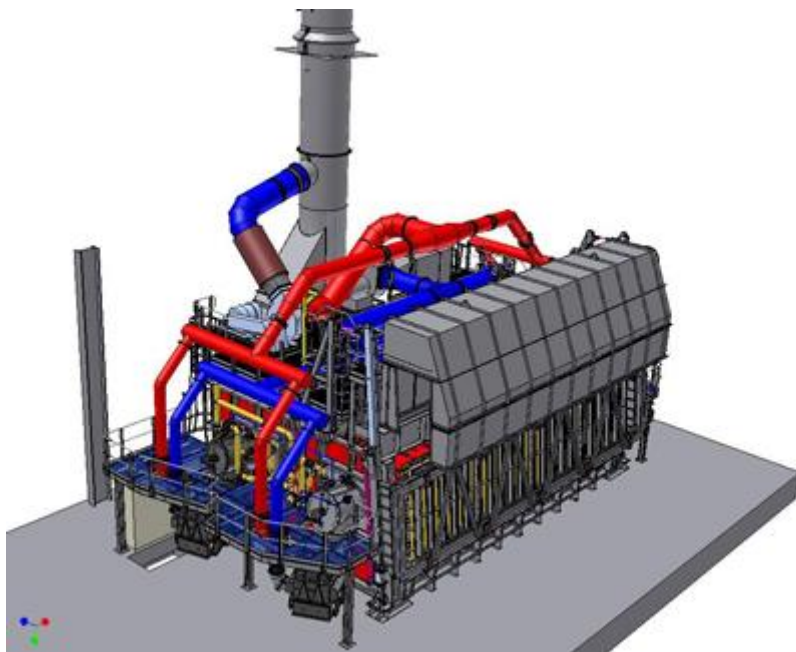


Figure 17: An example of a melting furnace (Solios, 2007b).

Holding furnaces

The holding furnaces can either be stationed after the melting furnaces in the process, as previously stated, or as a single furnace. This means that while the holding furnace is casting, it is possible to fill up the melting furnace. The main purpose of a holding furnace is to prepare the metal for casting. A holding furnace can range from 20-120 tons and it is possible to get the same heating elements and temperature control set-up as in the melting furnace.

Depending on what the customer wants, some holding furnaces can have a small re-melting capacity for alloys and scrap. This makes them popular for use in a primary casthouse where the metal source is normally molten with small and infrequent amounts of additives, which removes the need for another melting furnace (Solios, 2007a).

Casters

Casters are for “freezing” molten metal as one of the following: finished goods shaped for the customer, re-melt ingots, or as a semi-finished product for a customer with another plant to complete the process. In the following section there is a short description of casters that are commonly used in primary aluminium casthouses and are designed for mass production and high productivity, rather than precise casting. There is also a table for each caster that enlists the following data: capacity, cost, consumable cost, labour needed, complexity of machines, need of supporting equipment, flexibility in product range, and scrap rate. The information in those tables was confirmed both with specialist at Alcoa Fjarðaál and some of the manufacturers of the machines.

Table 3: Stock and ingot casting abilities of the casting equipments (Becker, 1999).

| Product \ Machine | Machine | | | | | |
|-------------------------|---------|-----|-------|------------|------|------------|
| | HDC | VDC | Wheel | Open mould | Roll | Belt/block |
| Rolling slab | X | X | - | - | - | - |
| Extrusion billet | X | X | - | - | - | - |
| Wire bar | X | X | - | - | - | - |
| Bus bar | X | X | - | - | - | - |
| Rod coil | - | - | X | - | - | - |
| Strip stock | - | - | - | - | X | X |
| Remelt ingot | X | - | X | X | - | - |
| Remelt sow | - | - | - | X | - | - |
| T-bar | X | X | - | - | - | - |

Table three shows the versatility of the machines, or how many products one machine can hypothetically have. For instance, HDC has the possibility of at least six product types while roll and belt/block only have one. Strip stock is quite a unique product and the demand for it is not very high. Only two machines produce strip stock, as can be seen in table 3; the roll and belt/block machines. So, because of little demand and very little flexibility of these two machines, the roll and belt/block machines are not examined further. Sheet casters will also be skipped since that product is aimed at specific customers, and specification is unique to each customer (J. Olszewski , personal communication, September 5, 2008).

Open Mould Casting

This is one of the most basic casting methods. It can either use big moulds that can take up to 700 kg or small moulds that range from 5-50 kg. The most common machines using the bigger moulds are called sow casters, rotary sow casters, sow carousels or sow circles. The types using the smaller moulds are called Gautschi ingot casters, ingot conveyor machines, ingot machines, pig ingot machines, ingot chains, or Showa ingot casters.



Figure 18: A Gautschi ingot machine (Gautschi, 2007).

An example of the Gautschi small ingot machine can be seen in Figure 18. The process is the same as for both sow casters and ingot casters, except the moulds are smaller. The process is as follows: Molten metal is poured either straight from the crucibles or from furnaces into a

mould, then the carousel moves and dross is skimmed off the product. The aluminium is cooled either with water or air. After sufficient cooling of the ingots/sows, they are marked, weighed, and stacked together – ingots usually in bundles as can be seen in figure 18 but bigger sows are stacked freely together (Gautschi, 2007).

Table 4: Summarized data of production and operating factors of open mould casting

| Element | Range |
|-----------------------------------|--|
| Capacity | High to very high |
| Cost | Very low – low |
| Consumable cost | Low |
| Labour needed | One - two operators |
| Complexity of machine | Low |
| Need of other supporting machines | No |
| Optional extra equipment | TAC&Skim, furnace if there are not tilters |
| Flexibility in product range | Low |
| Scrap rate | Very low |

Table 4 shows that the benefits of this machine are its simplicity, that it needs very little extra equipment, and has low costs. On the other hand the flexibility in product range is limited.

Horizontal Direct Chill casting – HDC

The Direct Chill casting process was invented around 1925 and has been very popular in the industry ever since. With this technology, product variety increased and the product characteristics improved (Emley, 1976).

There are numerous varieties of products which can be cast in this caster; T-bars, ingots, bush-bars, billets, slabs, and a variety of any thick walled shapes (Becker, 1999).

The process is as follows: the furnaces feed the HDC caster; normally there are two or more furnaces to ensure continuous casting. The molten aluminium is fed to the caster from the furnaces via launders and the caster casts the product horizontally through moulds. The moulds are critical for the physical quality of the product and determine the shape of the product. When the molten metal has been cast in the desired shape, it is sawed, weighed, marked, and stacked. The continuous casting is the greatest asset of this machine as the manufacturer claims it can run for up to six days continuously. (Hertwich Engineering, 2008a). An example of an HDC can be seen in figure 19 but in that figure a T-bar is being casted from a four mould HDC machine.



Figure 19: HDC caster

It is possible to get many models with different production rates, with different kinds of moulds, and levels of automation (Hertwich, 2008a).

Table 5: Summarized data of production and operating factors of HDC casting

| Element | Range |
|-----------------------------------|------------------------------------|
| Capacity | Low to high (depending on product) |
| Cost | Medium |
| Consumable cost | Medium |
| Labour needed | Two - three operators |
| Complexity of machine | Medium |
| Need of other supporting machines | Yes (furnaces) |
| Optional extra equipment | In line treatments and TAC&Skim |
| Flexibility in product range | Very high |
| Scrap rate | Medium |

Table 5 shows the production data and it can be seen that HDC has high flexibility with medium cost - both capital cost and operating cost (labour and consumable). Also, it does not need any extra equipment unless the product range demands it.

VDC casting

Vertical Direct Chilled (VDC) casting is a similar process to the HDC except that it is cast in vertical pits. It is not a continuous process since the cast length depends on the pit length and normally, one drop, or one cast, takes a full furnace load. After the drop, the product is pulled out of the pits, using special equipment. Usually, when a VDC caster is used, it is normal to have a saw as an extra unit in order to have the option to cut the product to whatever size the customer wants.



Figure 20: VDC casting machine (Hertwich engineering, 2008b)

The VDC is the most popular machine for the casting of billets and slabs – billets are then extruded or forged and slabs are commonly rolled. Production rate depends on the unit and the limitation of the equipment is its length, since the cast is stopped when the furnace becomes empty (Becker, 1999).

With VDC casting it is possible to cast bus bars, T-bars, slabs, wire bars, and billets. An example of a VDC caster is shown in figure 20 and in that figure billets are being pulled out of the casting pit

Table 6: Summarized data of production and operating factors of VDC casting

| Element | Range |
|-----------------------------------|--|
| Capacity | Low to medium (depending on product) |
| Cost | High |
| Consumable cost | Medium |
| Labour needed | Two - three operators |
| Complexity of machine | Medium |
| Need of other supporting machines | Yes (furnaces) |
| Optional extra equipment | Saw, homogenizing furnace, in-line treatments and TAC&Skim |
| Flexibility in product range | High |
| Scrap rate | Medium |

In table 7 the production data can be seen, which shows that it is similar to the HDC data, except VDC has a little less product range and does not have as high a production rate – mainly because the VDC is not a continuous caster. Since it needs more additional equipment than HDC, it is a little more expensive.

Wheel casters

This is sometimes referred to as CCR or Continuous Casting and Rolling machine and was first made by the Italian manufacturer Properzi. They still have 85% of the market, which is

significant, given that they were one of the first to introduce continuous casting to the industry (Emley, 1976). There are many machines available, with different levels of automation, product sizes, and product ranges. It takes a long time to ramp up to the full production rate since this is a highly complex machine – because the sequencing of the rolling stands is quite complex – and it takes time for the operators to learn how to run the machine efficiently. Scrap rate is very high compared to the other machines and even higher in the beginning, when it is being started up (Continuus Properzi, 2008). Electrical transmission line manufacturers are the biggest customers and it could be argued that aluminium has no competitors in this area since it is the easiest and most cost-effective material for producing this type of product (Ulucac).

Table 7: Summarized data of production and operating factors of Wheel casting

| Element | Range |
|-----------------------------------|--|
| Capacity | Medium |
| Cost | Very high |
| Consumable cost | Very high |
| Labour needed | Five – six |
| Complexity of machine | Very high |
| Need of other supporting machines | Yes (furnaces, TAC&Skim, in-line treatments) |
| Optional extra equipment | Machine to bundle ingots |
| Flexibility in product range | Medium |
| Scrap rate | High |

In table 7 it can be seen that this machine is the most complex, with the highest labour need. It also needs the most extra equipment and has high scrap rate.

2.4 Simulation modelling

Simulations are used to gain insight into processes and to study them. Assumptions are made about the system in mathematical or logical form. If the model is simple enough, it is possible to construct mathematical methods to get the information required, which is called an analytical solution. In reality this is not always possible though, because of the complexity of the system. In these cases, it is possible to make a computer program to simulate the system. In simulation the system is evaluated numerically and data is gathered to estimate the information needed.

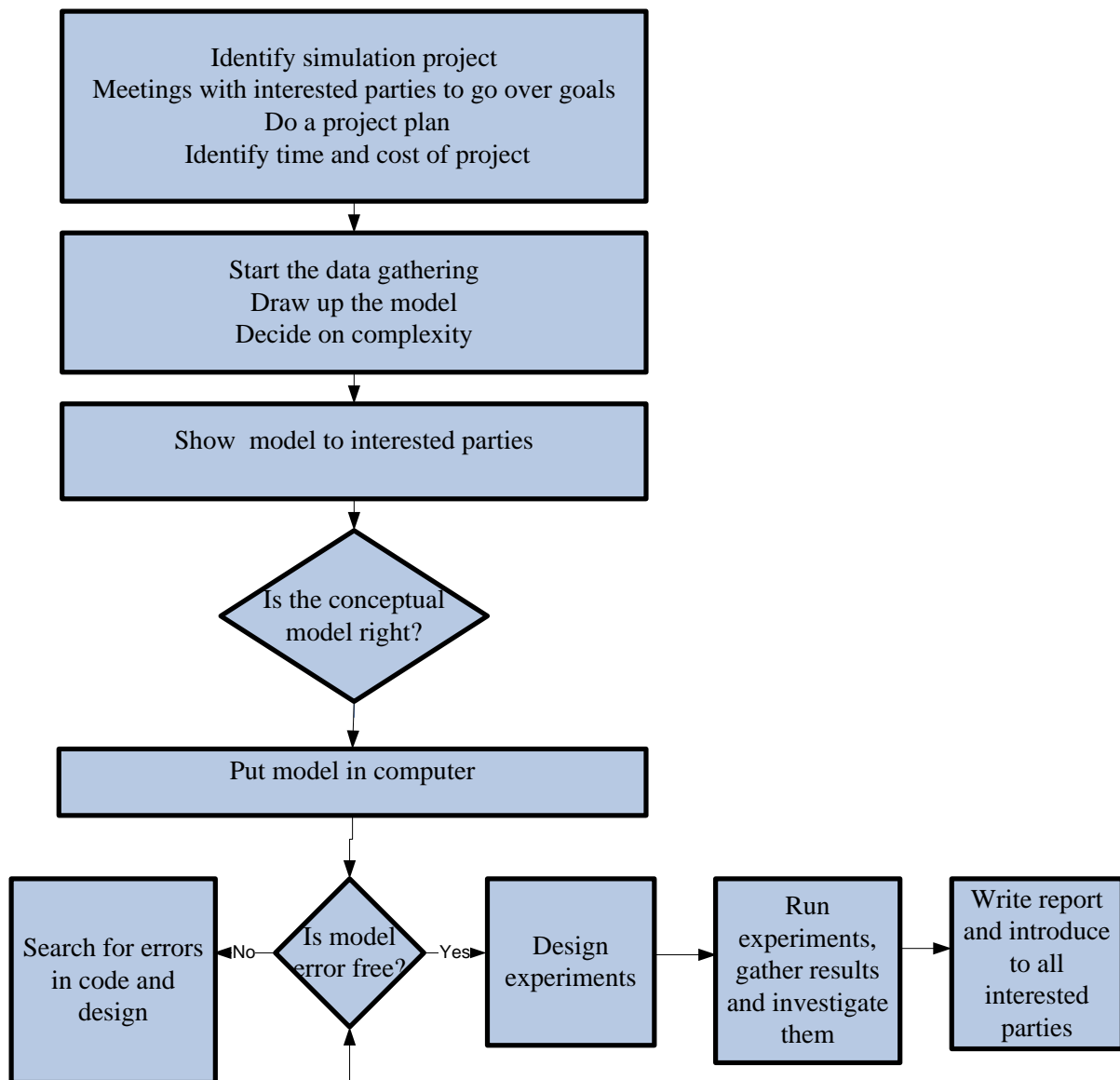


Figure 21: Schematic view of the steps to a sound simulation (Law, 2007).

In figure 21 the steps to get a good simulation are shown. A simulation is not a process that simply goes through the steps and then it is over. Throughout the simulation it might be necessary to reiterate some steps.

The first step is to formulate the problem and plan the study. Normally the problem is stated by top management. It is very important that the creators of the model go back to this to make sure that they are in sync with the management. It is good to have a kick-off meeting with all parties involved to discuss the overall objectives of the study, specific questions that the study should answer, the scope of the model, the time frame for the study and performance measures.

The next step is to collect the data and define the model. Information such as operating procedures and information on the system structure can be used. Data collection is needed to specify model parameters and to find input probability distributions. An assumption document should be written. Data should be collected on the performance of the current system; this can be used for validation. It is best to start with a simple computer program and then add to it.

The next question concerns the validity of the assumptions. This is checked with a structured walk-through of the assumptions document with managers and analysts. This should be done before the beginning of programming to avoid reprogramming later.

The next step is to construct the computer model. There are numerous programming languages such as C or C++ and also simulation software such as Arena, Extend, FlexSim, ProModel and SIMUL8. The benefits of using a programming language for simulation software is that it is cheaper, it offers more program control, and it may result in shorter execution time on the model. Using the simulation software can therefore often shorten programming time and thus reduce the cost of the project (Law, 2007).

Making pilot runs for the validation is the next step. There are a few ways to validate a model. If there is an existing system, then it is possible to compare the performance measures of that system to the model. Still, the model should always be reviewed by the simulation analysts and the subject matter experts. Sensitivity analysis is also popular to determine which of the model factors have the greatest impact on the performance measures.

The next step is to design the experiments. Included in that is to determine the length of each simulation run, the length of the warm-up period, and the number of independent simulation runs, using different random numbers. When this is done, the production runs can be executed and analyzed.

When this is done, everything needs to be documented and presented to stakeholders.

A manufacturing analysis with a simulation gives a manager an opportunity to see the system as a whole. The effect of changes to the system can be seen. There are also other benefits, such as analyzing performance, throughput analysis, time-in-system analysis, and bottleneck analysis. There is also analysis on the need of equipment and resources, and analysis of operational procedures. Popular metrics are throughput of system, sizes of in-process inventory, utilization of equipment and resources, and proportion of the time that a machine is broken, etc. (Law, 2007).

2.5 Selecting the investments

Selecting investments can be a difficult problem. In many cases there are number of factors that need to be considered. This calls for multi-criteria decision making. There are ways to solve those kinds of problems, for instance the Analytical Hierarchy Process (AHP), goal programming, and some hybrid methods of those two. It is also possible to portray investment selections with binary integer programming.

2.5.1 The AHP method

The Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty in the 1970s, is a method to solve multi criteria problems. This method may not find the “best” solution but it helps the decision makers to find the best solution for their needs and will. This method enables the decision maker to take into account both numerical and non-numerical values. When using this method, the decision maker needs to split the problem into a hierarchy of sub-problems that can be analyzed separately. These sub-problems can be clear or fuzzy, well understood or poorly understood, numeric or non-numeric. When the hierarchy has been set up, the decision maker has to compare those sub-problems together, two at a time, and evaluate them. The beauty of the AHP method is that when the decision maker is evaluating he can use his own judgment, if there are no numerical values, because AHP converts those

judgments into numerical values. Those values are then compared to the overall problem and a numerical weight is obtained for each element in the hierarchy. This way it is possible to compare a vast range of elements together in a consistent way. In the end, there is a calculation of weights for each decision alternative and the decision which receives the highest value should be chosen. It is possible to do all the calculations in an Excel spreadsheet but for very complex problems it is common to use special AHP software.

It is also possible to use AHP when decisions are made by groups. Several approaches are available, as introduced by Al-Harbi (2001), which compared the Delphi approach and the use of the software Expert Choice. It is possible to use the Delphi approach, where the experts are asked to compare the values in the first round. In the second round, the experts are given the value from the previous round and allowed to change their results or stay with them. This method was developed to avoid the dominance of any one group member. It is also possible to use Expert Choice software to deal with the situation. The benefit of using Expert Choice is that the criteria are evaluated in a structured way and they allow for group interaction that the Delphi method does not allow for. Expert choice also allows for some of the group members to have different weights in the decision. According to Altuzarra, Moreno-Jiménez and Salvador (2004) there are three ways of decision making: a) group decision with the individuals acting jointly to find a common decision b) negotiated decision, where each member compares individually and then agreement and disagreement zones are analyzed in order to reach conclusion c) systemic decision, where each member compares individually and a tolerance principle is used in an attempt to integrate all solutions. Bayesian statistical approach is used to reach consensus on negotiated decisions.

Using the AHP – step by step

1. Set up the problem in a hierarchy. The decision goal is on top, and the alternatives for reaching it are at the bottom. In the middle is the criteria for evaluating the alternatives; see figure 22.

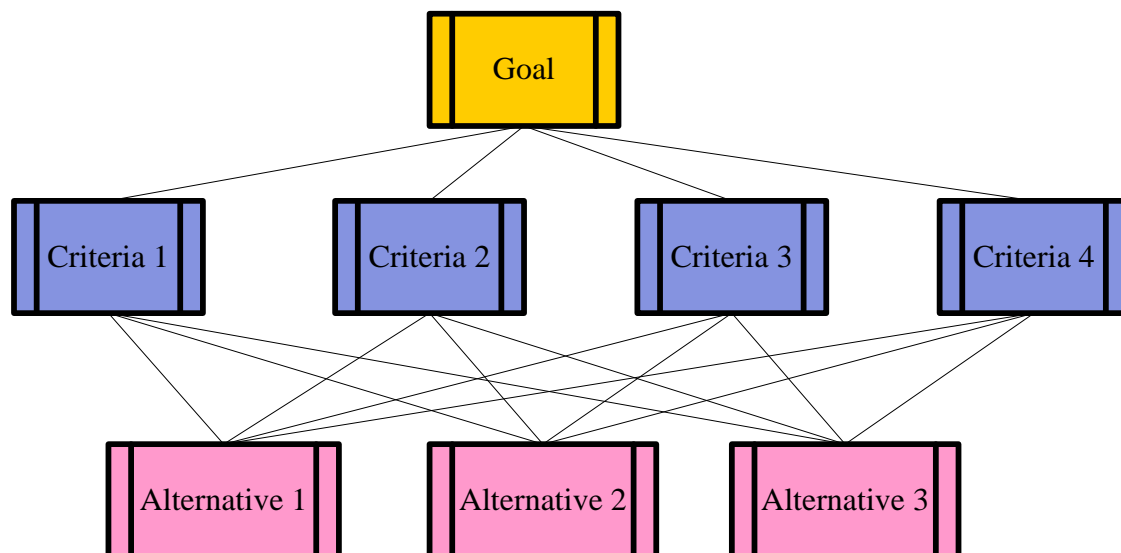


Figure 22: Example of the AHP hierarchy

In the hierarchy, each box is called a node. A box descending from another is called a child and the node that the child descends from is called its parent. Therefore the goal is the parent of a criterion and the criterion the child of goal etc.

2. Compare the evaluating elements in pair-wise manner and put in the pair-wise comparison matrix. There is a special scale used in this comparison, which it can be seen in table 8.

Table 8: The pair-wise comparison scale

| Value of importance | Definition |
|---------------------|------------------------|
| 1 | Equal importance |
| 3 | Moderate importance |
| 5 | Strong importance |
| 7 | Very strong importance |
| 9 | Absolute importance |

This means, for instance, that when two elements are being compared, a and b , and the decision maker feels that a is more important than b , he needs to use the comparison scale shown in table 8 to select how much more important a is compared to b . That way, if he gives a the value 3 compared to b it means that a is moderately more important than b .

3. Normalize the matrix.
4. Calculate the weights of the elements. The weight of each group of criteria and alternatives should equal 1.0 – that is the priority. For the goal the priority is 1.0, and for the group of criteria all the priorities should add up to 1.0, and the same goes for all the alternatives.
5. Check if the rankings are consistent. This is done by calculating the consistency index, CI, and then dividing it with the random indices for consistency, RI. To be perfectly consistent, CI should be zero. Saaty suggest that if $CI/RI > 0.10$, there is not consistency (Teknomo, 2006).
6. Compare each element for each alternative, as shown in steps 2-5. That is how the score for each decision alternative on each objective is obtained. The order of elements to compare is not important.
7. Calculate the overall score for each alternative.
8. The alternative that received the highest score is the best decision for this problem.

The reason why the AHP method is so popular is that it takes a wide range of complex problems and forces the decision maker to simplify them in a structured manner (Teknomo, 2007). Also, it allows the decision maker to combine evaluation on numerical values and values that can be based on feelings or judgment.

The AHP method has been criticized on several accounts. The main criticism is the scale from 1-9 and also that there can be inconsistency in the ranking selection. To avoid that, the consistency test is done. Another thing is that if there is a large number of criteria that needs to be evaluated it can make the quantity of comparison tables too large, pushing the decision maker to have fewer options and, therefore, fewer tables for simplicity, but at the expense of the solution. Rank reversal is also a controversial issue but in simple terms, explained by Saaty (2001), it refers to the instances where “adding or deleting alternatives to or from the set may not introduce new or eliminate old attributes yet the rank of the existing set may

change due to the number of alternatives.” There is no proven principle that needs to be upheld when making decisions and Saaty also suggests that rank reversal must be allowed when appropriate. For further reading on this issue, there is Saaty’s *Fundamentals of Decision Making and Priority Theory With the Analytic Hierarchy Process* (2001).

It is possible to use the AHP method, together with other methods, in order to find the best solution. For instance, simulation can be used to get values in order to be able to compare results rather than rough estimations (Albright and Winston 2005). It is also possible to do a sensitivity analysis on the comparison by changing the weights of the elements that are considered sensitive to see what it does to the final weight – does the solution change or not (Drake 1998). For further reading about the method see McCaffrey (2005) and Drake (1998).

2.6 Summary

This chapter has focused on two things - what has been done previously in this field – and a description on the theory and background used in this thesis. The theory discussed is on simulation, engineering economics, and the AHP method. The background information regards the aluminium industry, market demand, equipment availability, quality requirements, and project structure. This information will be used in the next chapter as a basis for what machines and models will be selected and simulated. The simulation steps are used in the simulation chapter and the AHP method is used to find the best model.

3 MODEL SELECTION METHOD

In this chapter four models will be chosen for further analysis. This approach uses information from the theory and background chapter to reach a decision. First there is discussion on the objectives of the project, then on metal quality, after that on product mix and equipment and, finally, on value analysis. Then a binary integer program is used to narrow down the options of models.

3.1 Objective

The objective of this modelling project is to design a casthouse that can cast at least 346,000 tons of molten metal per year, or 41 tons per hour. This will be denoted m_t (metal throughput). The management team also wants to see the flexibility of the models' throughput – how well they perform with different inputs.

It is very hard to quantify the budget since it is linked to many variables that are not fully available at this stage. For the calculations later on, the capital cost will be denoted c_c . The team would also like to look into the operating cost which will be denoted c_o .

In the following chapters, suggestions are made as to what to choose. Those suggestions come from the theory and background chapter regarding what is relevant to a casthouse.

3.2 Metal quality

Using the information from chapter 2.3.2, together with analysis of the market from chapter 2.3.3, the project team would make a decision as to which products to manufacture. This would vary depending on the target market(s) but P1020 is, as stated previously, a standard metal in the LME market which should therefore be the minimum purity requirement. The premium should be higher with improved purity, although it is always a question of how much premium can be had for a quality product and how much cost is involved. This question is more aimed at the potrooms since the metal quality depends on the pots.

3.3 Product mix

After a look at the market reports and articles cited below, regarding the aluminium market, the product mix was decided.

- European Aluminium Market Analysis (RNCOS, 2008).
- Aluminium Market Report (Global analysts, 2008).
- New Reports on Recent Aluminium Market Trends are in (Easten, 2008).
- Extrusions demand takes crunching hit (CRU market analysis, 2008).
- All's Quiet on the Nonferrous Front, (Markham, 2008).

It can be stated that slabs and billets are forecast to be in the least demand. Coil rod could have a really good market since it will be needed in the developing countries, the process requires a complex machine which few companies would invest in, and the supply is not high in Europe. Small foundry ingots also are a good option since the transportation industry is increasingly using aluminium alloys, so it is a rising market. Re-melt ingots, such as T-bars

and sows, are always in steady demand in a number of grades and are easy and cheap to produce. They are also easy to sell on open markets such as the LME.

Table 9: Summary of forecast demand for available products

| Machine | Range |
|----------------|--------------|
| Billets | Very low |
| Slabs | Very low |
| Coils | High |
| Foundry ingots | High |
| Pure ingots | Medium |
| Sows | Medium |
| T-bars | Medium |

Table 9 shows the summary of the market data. From that, the team would recommend coil rods, small foundry ingots and T-bars/sows as a product mix. This was confirmed by the Alcoa Fjarðaál representatives.

3.4 Equipment

From chapter 2.3.4 (equipment selection), it is easy to see that the most flexible machine is the HDC, as it has the largest product range. Also, as it casts on a continuous basis, it has a relatively high production rate. The rod mill should only be chosen if the company is willing to make the high initial capital cost and acquire the additional staff and equipment. If the management prefers something simpler, with high production rate, the open mould caster is a winner. With the VDC it is recommended to buy extra equipment to produce billets, such as a saw and a homogenizing furnace, and this extra expense is usually prohibitive. The production rate will be denoted p_i and \bar{p} is the minimum production rate of the models.

From this information, the recommended machines would be HDC and open mould casting for high production rates, and, if the budget allows, a rod mill as well. Consequently, those are the machines that were selected for Alcoa Fjarðaál. It does not mean that for future investments those three would necessarily be selected. It is likely that the next project will not get as high an initial investment budget and therefore the rod mill would not be an option. In that case, a better option is HDC and open mould casting.

3.5 Finance

The finance team's role in the process is to do a value analysis on which machines they should buy, with regard to potential profits. It is possible to create a value matrix for investment cost versus potential output and use linear programming to maximize the profit (Becker, 1999). Costs involved include machine costs, additional equipment costs, manpower, transportation, packaging, energy, consumable costs, etc. All the costs and premiums must be forecast for at least 20 years, so flexibility and the ability to expand also have to be considered.

The turnover is the estimated sum of the premium of the product, or the LME price, if it is a sow or an ingot, over the selected time span.

The costs are the investment costs, operating costs, and maintenance costs over the time span.

The value is the turnover/cost, normally ranging from 1.5-4.5. This has to be done for every product that the machine can produce and works best if set-up times are included as well (Becker, 1999).

In this value analysis the cost was simplified from Very low to Very high, based on the complexity of the machine, labour need, extra machines needed, etc. The premium can depend on whether a large, long-term contract is made, whether there will be smaller one-off orders, and everything in between. Again, this is simplified and the turnover value will be in the range from Very low to Very high, based on market forecast, production rate and product flexibility.

3.5.1 Investment cost

The ranges will be from Very low to Very high, or 1-5. Number one is the lowest cost and five the highest cost. The cost estimation is dependent upon what was stated in the equipment chapter. Cost factors considered are complexity of machines, labour need, extra equipment need, consumable cost, scrap rate, etc.

Rod: This is a very complex and labour-intensive machine, and hence one of the most expensive on the market. It has high labour costs, with at least six operators working on it per shift. Consumables and packaging are also high since it produces delicate products which need careful packaging and handling. There is also a lot of expensive additional equipment and consumables required when producing EC-grade coils. Therefore, the rod machine has been given the cost number Very high, or the highest cost number.

HDC: As stated in the previous chapter on machines, this one has up to six products to choose from, which is the most of all the casters available – making it a very versatile machine. The moulds are quite expensive but should last up to five years and the labour required is roughly two-four people per shift. Packaging and handling depend on the product but they do not need as much attention as with the rod machine. It is necessary to have two furnaces since this is a continuous casting process and therefore some kind of dross treatment is also required. TAC is not necessary but skimming is preferable. From this, the HDC gets the cost number of Medium.

VDC: This is the second most versatile machine with five products possible, but it is most popular for producing slabs and billets. The labour cost is around three operators per shift and packaging and handling depend on the product. If billets are being produced it is highly recommended to have homogenization equipment and also a saw. This machine has to have at least one furnace and dross treatment. TAC&Skim is optional along with a degasser and filter boxes. This means it gets the cost number High.

Open mould casting ingots: This is the cheapest way of producing aluminium ingots – it doesn't require any additional equipment although it is the norm to have furnaces. Labour cost is very low, requiring only one-two operators per shift. Therefore, this machine gets the cost code of Low.

Open mould casting sows: It is possible to get this type of machine very close to full automation, which means labour cost would be almost zero. Even if this is not achieved, it will still never be considered expensive equipment. Labour cost can be assumed to be one-two operators per shift, packaging cost is very low, and it does not need any other equipment,

although skimming crucibles would be preferable. This machine gets the cost code Very low. Compared to the open mould casting ingots, which received the cost code Low, the main difference between them price-wise, is that the open mould casting ingots normally need a furnace whereas open mould casting sows uses tilters, which are cheaper than furnaces.

Table 10: Estimation on cost of machines

| Machine | Range | Value |
|--------------|-----------|-------|
| HDC | Medium | 3 |
| VDC | High | 4 |
| ROD | Very high | 5 |
| Sow caster | Very low | 1 |
| Ingot caster | Low | 2 |

Table 10 summarizes the estimation of cost.

3.5.2 Turnover

The only public price for aluminium products is the LME price. The premium that is paid above this is very confidential on products. For this thesis, the estimation on the rate of return of the investment will be based on market forecast, production versatility and production rate. The range for the rate of return will be the same as for the cost – Very low to Very High. This number is denoted v_i .

Rod: The production rate can range up to 12 tons per hour and this is considered to be one of the best products on the market now. It can both be sold as Deox to the steel industry or as EC grade for cables. There is a high demand for it in Europe so the rate of return will be High.

HDC: In 2008 there was high demand for foundry small ingots, and there is a steady demand for re-melt T-bars (preferred to sows because of their higher quality). The production rate can be high and the product versatility is very high. The estimation on the rate of return for the HDC will therefore be High.

VDC: This is mostly used to produce slabs, billets and T-bars. T-bars have continued to be in steady demand, but demand for billets and slabs has decreased. It is still a versatile machine with a good production rate. The estimation of the rate of return will therefore be Medium.

Open mould casting ingots: These kinds of machines have a steady production rate and the products are in steady demand but very low production versatility. Therefore the estimated rate of return is Very low.

Open mould casting sows: These machines have a higher throughput rate than the ingot machine and a steady demand for the products. It is estimated Low in the rate of return because the product range is not very versatile, but it gets a higher rate of return than the ingot since it has a higher production rate.

Table 11: Estimation of rate of return for the machines

| Machine | Range | Value |
|----------------|--------------|--------------|
| HDC | High | 4 |
| VDC | Medium | 3 |
| Rod | High | 4 |
| Sow caster | Low | 2 |
| Ingot caster | Very low | 1 |

Table 11 shows a summary of the data, which shows that the products that have the highest likelihood of a high rate of return are the rod mill and the HDC, followed by the VDC, the sow caster and the ingot caster.

3.5.3 Value analysis

In a normal value analysis it would have been necessary to calculate the value for each product and from there to do linear programming (LP) on what machine to select, then a product mix optimization from that to maximize profit. It was not possible to obtain all of those figures in order to do the LP product mix analysis, therefore a simplified version was done and the results confirmed with an Alcoa Fjarðaál representative. The aim here is also to select machines, not products. The values in table 12 are turnover/investment cost and it's best to select a machine that has the highest investment to cost ratio.

Table 12: Estimation on the value of the investment

| Machine | value |
|----------------|--------------|
| HDC | 1.33 |
| VDC | 0.75 |
| ROD | 0.8 |
| Sow caster | 2.0 |
| Ingot caster | 0.5 |

In the simplified value analysis the calculation is for worth/cost for each machine. The results can be seen in table 12.

3.5.4 Results of the finance team

From this simplified value analysis the finance team would select the rod, the HDC, and an open mould sow caster. It is strange, however, to have both sow caster and T-bar productions, since they go to the same market, but the open mould sow caster is considered a very safe way to “freeze” metal and has a high throughput rate. This means that even if the other machines are down it should be able to take most of the metal until the others are up again. Also the HDC has high product flexibility and therefore does not have to cast T- bars unless there is a market for it.

The reason for not using numbers in these calculations is because they are highly confidential and more thorough analysis on cash flow would be needed. Also, there are so many factors

that come into this that it was considered better to simplify and get confirmation from specialists. Finally, those numbers are also confidential.

3.6 Model selections

In order to select four models, further constraints were obtained and some estimation on factors such as capital costs, LME and premiums, operating costs, and extra costs were made. These estimations were partly obtained from the estimation made when Alcoa Fjarðaál was being modelled, and partly from the manufacturer of the machines. From there, binary integer program was used to select four models for further analysis with simulation. A general binary integer program model will be presented. The variables used as input can be seen in appendix A.

As previously stated, the objective is to find four models that will be able to sustain a production of 41 tons per hour. It is estimated that the machines operate with 85% efficiency. The cost of these machines (c_c) should not exceed \bar{c}_c million dollars. Further constraints are that at least one model must have a production rate of over 60 tons per hour in order to see which model is flexible with the production rate. All variations of those three machines will be put into the BIP (binary integer program) – a total of 10 variations. Of those variations, one model should contain one three of the same machine. Another constraint is to select at least one model that has an operating cost of less than c_o per ton. The mathematical model that was used to solve this can be seen in figure 23, and in appendix A, the Excel set-up is shown, as well as the optimal solution. This problem is relatively small since there are only 10 variations and three of those variations do not have the production capacity of 41 tons per hour, so they automatically fall out, and the constraints of having at least one model with a low operating cost takes out another two. Even if this is a small example this is an excellent way to choose an investment and there is no problem in expanding the BIP model to as many options as needed.

$$\text{Maximize } Z = \sum_{i=0}^{10} v_i x_i$$

Subjected to constraints

$$c_c x_i \leq \bar{c}_c \text{ (max capital cost on investment)}$$

$$p_i x_i \geq \bar{p} \text{ (production capacity must be over 41 tons per hour)}$$

$$\sum_{i=0}^{10} x_i \geq 1 \in \text{models with production capacity over 60 tons per hour}$$

$$\sum_{i=0}^{10} x_i \geq 1 \in \text{models with operating costs less than \$100 per ton}$$

$$\sum_{i=0}^{10} x_i = 1 \in \text{models with three same machines}$$

$$\sum_{i=0}^{10} x_i = 4 \text{ (select only four models)}$$

$$x_i \text{ is binary, for } i = 1, 2 \dots 10$$

$$x_i \begin{cases} 1 & \text{if model is selected} \\ 0 & \text{if model is NOT selected} \end{cases}$$

Figure 23: BIP mathematical model.

These constraints were put into a binary integer program and solved in Excel. The model can be seen in appendix A.

The value was estimated for a year's period and it was always assumed that all the rod mill products could sell first, then HDC products and, lastly, sow caster products. It was also estimated that all scrap could be sold at a discounted price. All this data can be seen in appendix A.

3.7 Results

From all of the above chapters and the BIP, the models chosen to be simulated are:

Model 1: Three sow casters

Model 2: Two HDCs and one sow caster

Model 3: Two sow casters and one rod

Model 4: One sow caster, one HDC and one rod

When deciding how much safety capacity is enough, each company has its own ways and normally looks into the history of its casthouses. Table 13 shows the hypothetical capacity of the simulation models that will be tested. For this thesis, a model casthouse within Alcoa was examined, which has 40% extra capacity and estimates machine availability to be roughly

85%. The less extra capacity a plant has the less availability for foundry they have, since it takes longer to cast foundry, therefore the less flexible the casthouse becomes (F. Caron, personal communication, 14 June, 2008).

Table 13: Hypothetical capacity of the models

| Model | Max. capacity (100% efficiency) | % over capacity | Max. capacity (85% efficiency) | % over capacity |
|--------------|--|----------------------------|---|----------------------------|
| | [tons per hour] | | [tons per hour] | |
| 1 | 90 | 120% | 76.5 | 87% |
| 2 | 64 | 56% | 54.4 | 33% |
| 3 | 72 | 76% | 61.2 | 49% |
| 4 | 59 | 44% | 50.15 | 22% |

The management team was particularly interested in seeing how models with three sow casters would work as well as a sow caster with HDC. They were also interested in seeing how the current model at Alcoa Fjarðaál would function, compared to the other models.

In the following chapters these models will be simulated and analyzed.

3.8 Summary

In this chapter the method on how a casthouse is modelled was introduced. All the information about the aluminium background, covered in chapter 2, was used and a small value analysis was done in order to select three machines. From those three machines there were ten model variations possible. To narrow those ten models down to four, binary integer programming was used. The four models that were chosen were model 1: three sow casters; model 2: two HDCs and one sow caster; model 3: two sow casters and one rod mill and – finally – model 4: one rod mill, one HDC and one sow caster. In next the chapter there is a detailed description on those models and process flow pictures.

4 THE MODELS

In this section all the proposed models are introduced and presented with a process flow diagram. The goal is to see the difference between the models and look at process parameters, before moving on to the data analysis.

The models, as previously stated, are:

1. Model with three sow casters
2. Model with two HDCs and one sow caster
3. Model with two sow casters and one rod mill
4. Model with one sow caster, one HDC and one rod mill

The metal is tapped in the potrooms and put into crucibles. The crucibles are then transported to the casthouse, using haulers. This is the point where the simulation models start.

4.1 Model 1 – three sow casters

In the model shown in Figure 24 there are three sow casters, no furnaces and no TAC&Skim machine. The only production would be sows and, because there is no foundry production, no alloying area would be needed. It is only possible to get crucibles on and off the machine with a crane and, in the model, it is assumed that only one crane is in use. There is also a crucible cleaning area for empty crucibles which need cleaning. There is a check for scrap sow, which goes into a special container.

4.1.1 Assumptions of Model 1 in the design phase

Process for crucibles – identical for all models

In the design phase it was assumed that crucibles take a maximum of 12.6 tons and that they will need cleaning and servicing in the crucible cleaning area. It is therefore assumed that there are 14 crucibles in circulation.

When a crucible has been emptied of metal, a certain check needs to be performed to see if the crucible needs cleaning. This check is included in the model as shown in figure 24:

If the crucible has been used 20 times in a row, it should go to the crucible cleaning for cleaning and preheating before returning to the system.

If the crucible has been used 1200 times, it should go to the crucible cleaning for relining and baking before returning to the system.

After cleaning, the crucible needs to be preheated, for which there are three stations. After that, the crucible can be used again. In the crucible cleaning area, the crucibles are cleaned, relined and preheated. This is also where clean crucibles are stored.

The crane

The crane, as can be seen in figure 24, will have to service all tilters, but a back-up solution needs to be in place in case of crane failure. This could be outsourced and only used in extreme emergencies. When a process includes an item as critical as this one, it is also

standard practice to have a complete set of spare parts available to minimize downtime. Each crucible can go on a free tilter, no special routing order is necessary.

The sow caster – the same applies to all models

Crucibles are removed with the crane and put on tilters – one tilter can take one crucible. It is possible to put a fresh crucible in place whilst another one is being poured. There are no alloys blended in the crucibles and it is preferable, but not necessary, to have the crucible skimmed before it is put on the tilter.

According to the design, the sow caster should be able to process 30 tons per hour and the carousel has 38 moulds. It takes roughly 30 minutes to change a mould. The lifetime of the moulds varies from one week to several months.

The scrap rate on this machine is very low and scrap only occurs if there is not enough metal at the end to provide a full mould. Since there are no furnaces, the plant will not have any re-melting capacity which means they would have to ship out all the scrap for selling.

The shipping

The shipping employees will only service these casters and each container takes 40 sows. This is not a limiting factor in the model since it is possible to store finished products both inside and outside the factory. It is estimated that it takes 40-60 minutes to load the container.

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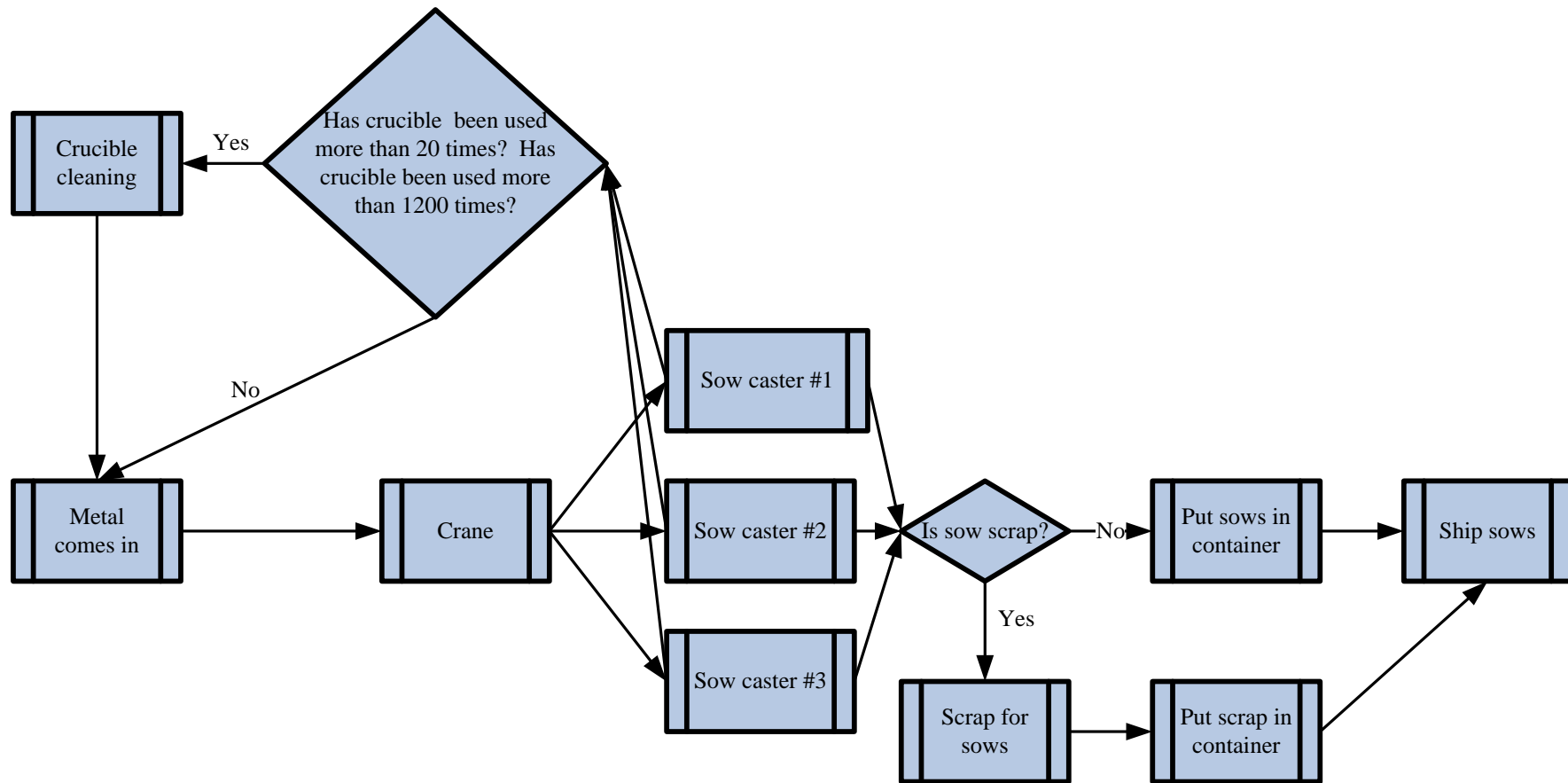


Figure 24: Simulation model number 1

4.2 Model 2 – two HDCs and one sow caster

This model is for two HDCs and one sow caster, as shown in Figure 25. This gives the plant a lot more variety in the product mix. Two holding furnaces go with one HDC, so a total of four furnaces are needed, each with a capacity of 100 tons, but the TAC&Skim station is still unnecessary since there will not be any rod production – if foundry production is desired then a TAC&Skim station would be preferable. It is assumed in this model that there is no TAC&Skim. This plant would need an alloying area since foundry is an option in the product mix, and re-melt is also possible. This figure also contains a scrap check. If there is scrap, there is now an option of re-melting or selling.

4.2.1 Assumptions of model 2

The sow caster and crucible cleaning area have the same characteristics as in model 1.

The crane

The crane should service all stations; the tilters for the sow caster and the furnaces for the HDC, as can be seen in figure 25. There is only one crane and since this is critical equipment there should be a complete set of all spare parts in stock in order to minimize downtime. Regular preventive maintenance is also crucial as the effect of a long crane downtime on potrooms and the casthouse is enormous.

The haulers

There are three haulers available. Two are normally used to take the crucibles to the potrooms and back, and the third one is a spare which is used if there is a backlog of metal or as a stand-in during preventive maintenance. It is possible to fill up the furnaces using a hauler, which is an option if the crane cannot handle everything or has broken down, but it should not be a standard operating procedure. The routing between crane and hauler is shown in figure 26, which shows that a hauler should only be used if there are more than three crucibles waiting and if the crucible is not going to the tilter, because the hauler cannot put a crucible on the tilter.

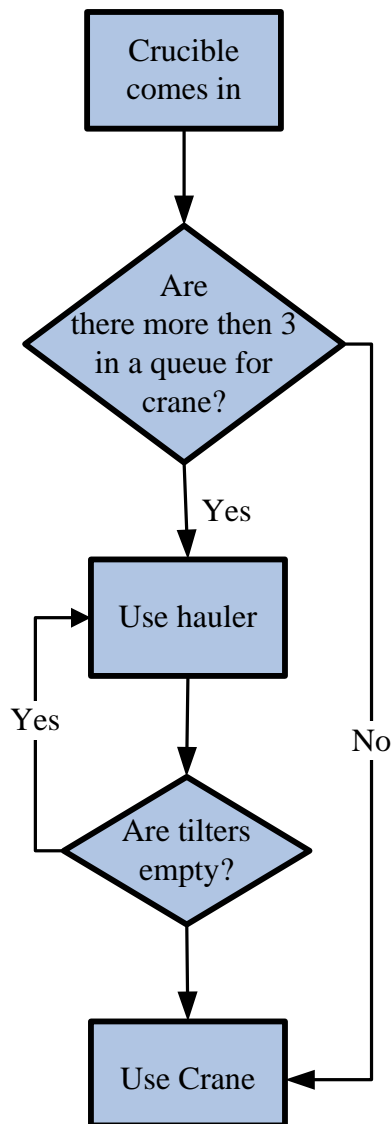


Figure 26: Routing decision, crane or hauler

Furnaces

The furnaces have a 100 ton capacity and it is possible to put both scrap and alloys in them. It is normally assumed that 100 tons means seven crucibles since there is always one crucible in the furnace, so it is therefore possible to use the siphon. It is possible to fill a furnace with both a crane and a hauler at the same time – if there is a time constraint the hauler uses the siphon and the crane pours, but this is not standard practise.

There is a certain scrap rate from all machines; all scrap goes to a storage area and can be used in the furnaces again or sold at a discounted price. Normally, scrap is put in at the beginning of furnace filling and the alloys at the end, but it should also be possible to do it in between, when molten metal is being poured into the furnace. It is not possible to put crucibles in a furnace or put scrap/alloys in while that furnace is casting, as can be seen in the routing in figure 27 – if there is enough room in the furnace that is not being used for casting, the crucible should be put there. If that furnace is full, the crucible should be put on the sow caster tilter. The furnace emptying rate is directly related to the casting rate of the caster.

The routing

The HDC should have supply priority when it is casting, as can be seen in figure 27. This is the first check in the process and if the HDC is not casting then a crucible is put on a tilter, providing a tilter is free. The detailed routing of the crucible can be seen in figure 27.

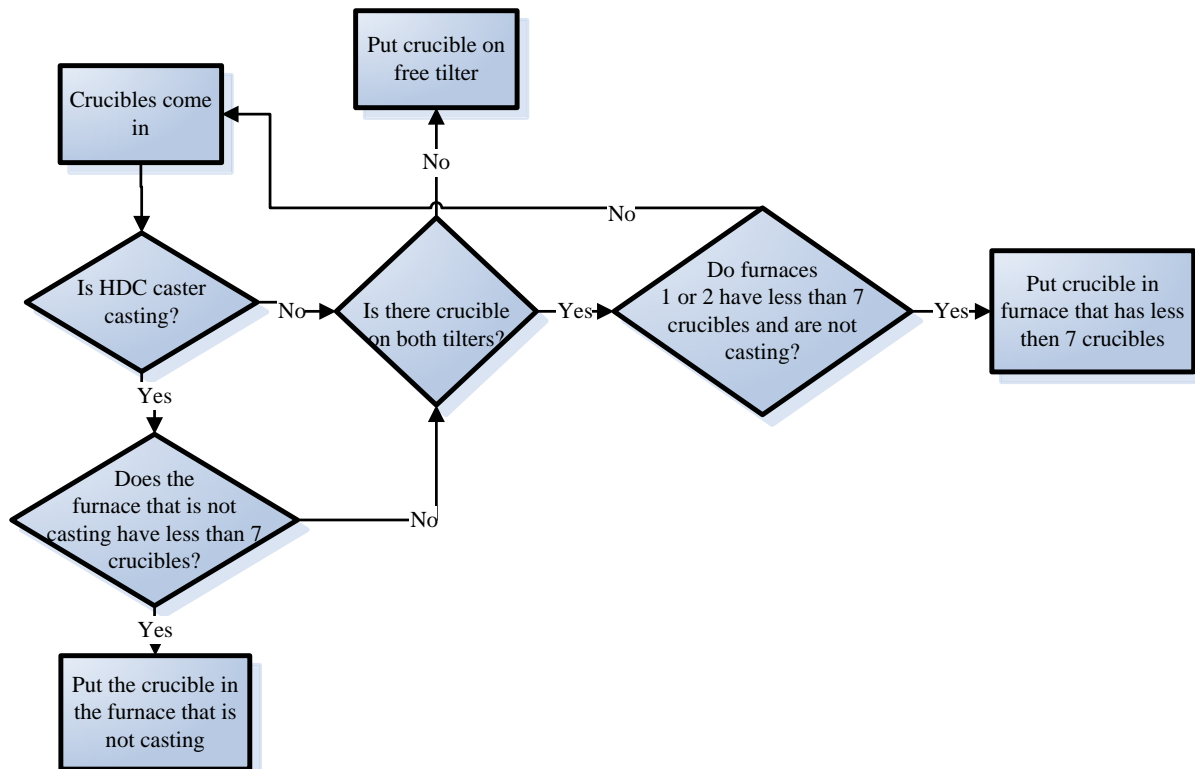


Figure 27: The routing of crucibles in Model 2

As can be seen in figure 27, the first check is to see if the HDC is casting – it has priority because of its long set-up time if it does not get metal. If the HDC is not casting, the sow caster has priority and a check is done to see whether there are crucibles on the tilters. If the HDC is not casting and the sow caster has full tilters, the crucible is put in the furnace that has the least amount of crucibles, providing that it is not full.

A furnace can take up to 100 tons, but normally there is always some metal in the furnace already; around 10-15 tons. When routing is done it is always assumed that seven crucibles fit into one furnace. Therefore the quantity is not checked but rather how many crucibles have been put into the furnace. If there are less than seven in the furnace which is not casting, then more crucibles can be added into that furnace.

HDC caster

The HDC has a maximum capacity of 17 tons per hour for T-bars and 12 tons per hour for small ingots. In the design of this process it was assumed that the HDC machine could run for six days and then have a change-over in six hours. When changing from T-bars to small ingots, a longer set-up time is assumed and when producing small ingots the likelihood of a breakdown is higher than when producing T-bars. Every product has a different production rate; the 10 kg ingots and 12 kg ingots are put in bundles of 1.1 tons. The scrap in this machine is mostly briquettes, saw chips and the first metres of the product, from the beginning of the cast. The T-bars go to the elevator three at a time, and the small ingots go

into bundles. There are three mould sets available and each time a cast is stopped, a new set must be put in and heated. It takes around 10-20 hours to fix one set and then four hours to heat it.

The product range

For pure sows and for the HDC, both T-bars and small ingot are options, with or without alloys. For small ingots, it is common to add silicon to the mix. Other alloying products are possible as well, if needed or wanted.

The shipping

The ingots, sows and T-bars are easily stored; T-bars and sows are 40 to a container and for the small ingots, there are 25 bundles per container.

4.3 Model 3 – two sow casters and one rod mill

This model is similar to model number 2, with the difference being that there is a rod mill instead of the HDC. This means it is also necessary to have a TAC&Skim machine in the process. The model can be seen in Figure 28, showing the check whether the crucible is going to the rod mill, in which case it needs to undergo the TAC&Skim treatment.

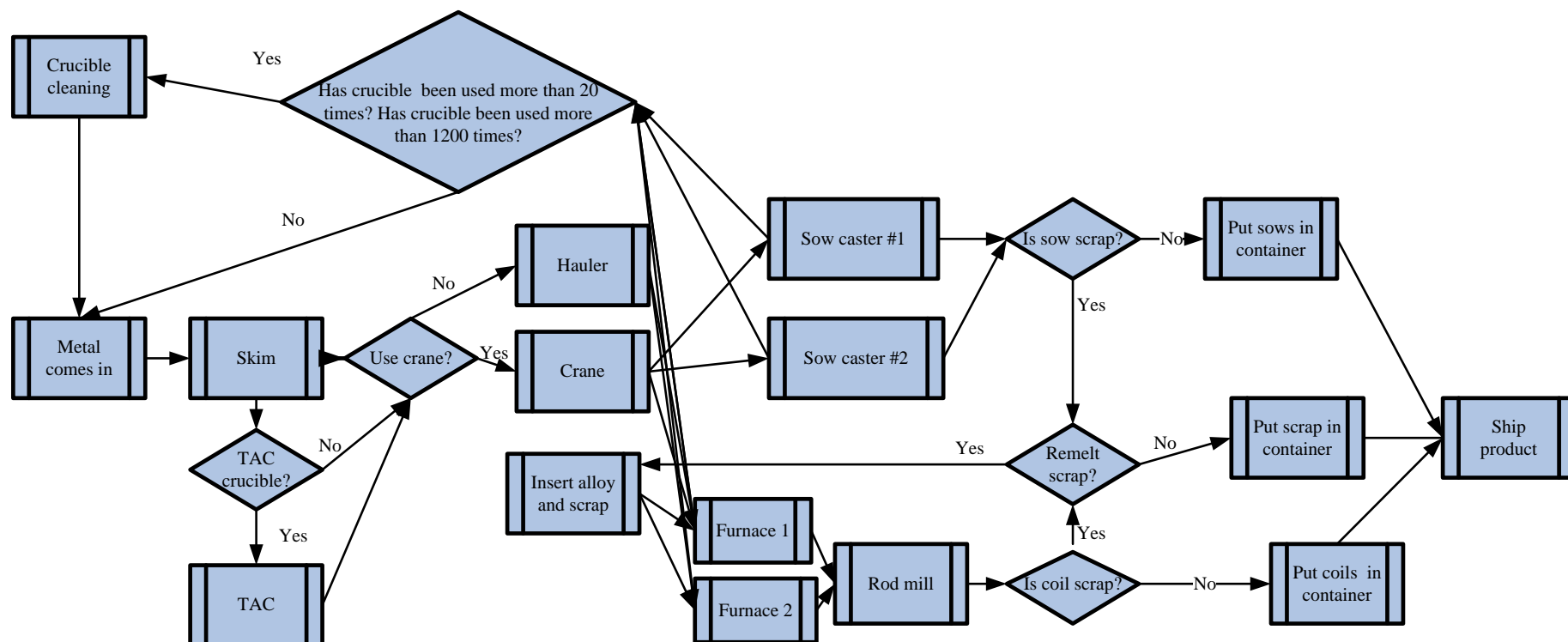


Figure 28: Simulation model number 3

4.3.1 Assumption of Model 3

This model has the same assumptions with regard to metal coming in, production rate on the sow caster, and crucible information as in models 1 and 2. In addition, it was assumed that the rod mill had a production rate of 12 tons per hour, with a possibility of casting for 60 hours continuously and then stop for 8 hours. With Model 3 the TAC&Skim station was added and only crucibles that undergo that kind of treatment should go to the rod mill furnace, so if the TAC is broken then nothing should go into the rod mill furnace. The rod mill is one of the most delicate machines so it needs more manpower and attention than the other machines.

TAC&Skim station

All crucibles should be skimmed, if possible, but they have to have more than 10 tons of metal in them for that part of the process. The same goes for the TAC treatment. If crucibles are to be TAC-treated they usually need to be skimmed first, but in emergencies it is possible to use only the TAC treatment. There are six bays on the TAC&Skim station but only one of each machine. They can both be used at the same time but a crucible should always be skimmed before the TAC treatment and only the rod-destined crucibles should be TAC-treated. First, a check is needed to determine whether there are bays available for the crucible. In the TAC&Skim station, a first-in-first-out system should always be used to prevent the crucibles from “freezing”. Crucibles that are only skimmed can leave as soon as their skimming is over, but if they need to be TAC-treated as well, the treatment should start straight after the skimming. In the design phase it was assumed that the skimming took five minutes and the TAC treatment five minutes.

The routing

The routing is similar to the one in model two, with the rod mill having priority when it is casting. The difference is that is that all crucibles going to the rod mill must undergo TAC treatment. The routing in this model can be seen in figure 29, which shows that if the TAC is not working, then no crucibles go to the rod mill and crucibles are put on the tilters only. This is the first check, unlike in the routing for model 2 where the first check was to see if HDC was casting. It is also preferable for all crucibles to be skimmed.

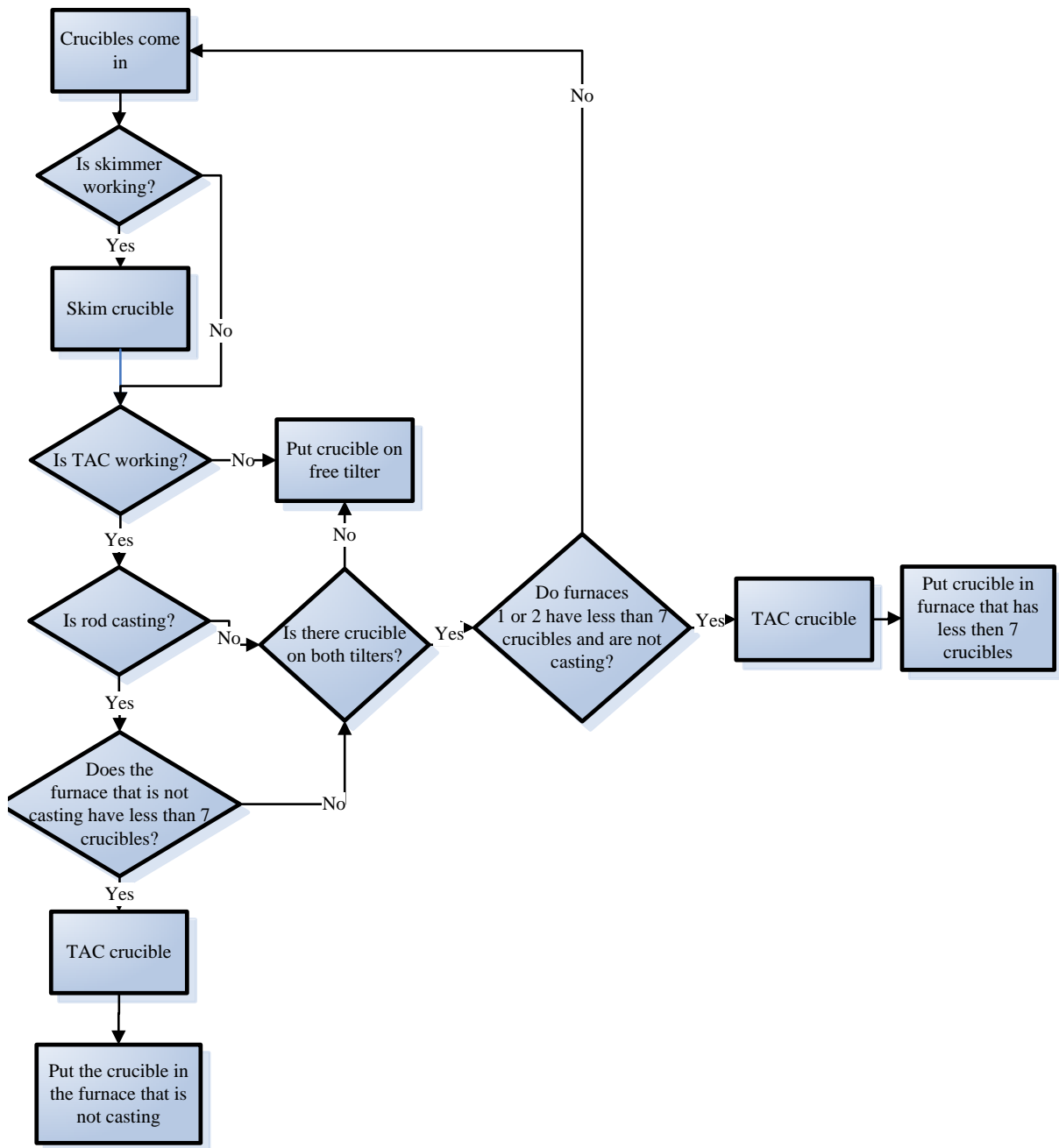


Figure 29: Routing in Model 3

Rod caster

The rod caster is the most sensitive machine of the three and produces the most valuable product. It produces high conductivity wire, so more testing needs to be done on this machine. It normally does not cast for more than 60 hours and the scrap rate is extremely high, or 8% in a start-up phase. It takes around 4-16 hours to turn the machine around and then moulds and stands need to be cleaned. Each coil goes down with a crane to the shipping area, when samples have been taken from the coil.

Product range

The rod mill coils can vary in size, but the design phase assumption was for 3.5 ton coils. It is also possible to produce small ingots, if a bundling machine is bought.

The shipping

The sow packaging is the same as in models one and two. Loading coil onto the container is more time consuming than for other products, since it needs more packaging and each coil needs to be packaged a certain way. There are seven coils in one container.

4.4 Model 4 – one sow caster, one HDC and one rod mill

This model is the closest to the real one used in Alcoa Fjarðaál and by far the most complex, as can be seen in figure 30. It has three different machines; a rod mill, HDC and a sow caster. It also has TAC&Skim and an alloying area. What makes this model so complex is the routing of the crucible flow when there are two furnaces to be filled, with only one crane. This is basically model number 2 and model number 3 combined in one, as can be seen in figure 30.

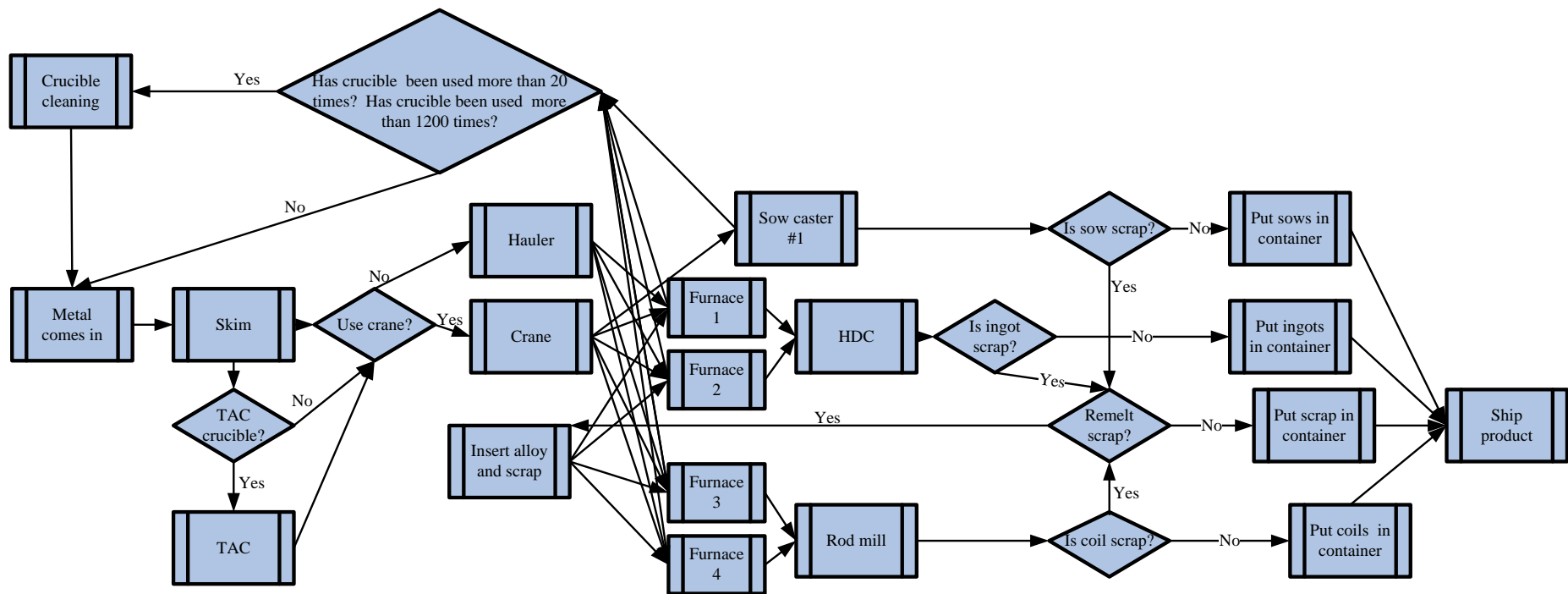


Figure 30: Simulation Model number 4

4.4.1 Assumption of Model 4

The routing

The routing of this process can be seen in figure 31, which shows that if the rod is not casting, the HDC has priority. If the HDC is not casting, the rod has priority, and if both the rod and the HDC are casting, the priority is on the HDC furnace and then keep the rod going. This is because it takes a longer time to get the HDC machine ready again. It is also necessary to put crucibles on the sow caster to make sure that all metal coming from the potrooms is processed.

The products

There are four products: T-bars, ingots, coils, and sows, as shown in models 2 and 3. Nevertheless, there is always an option of more products, if the capacity allows.

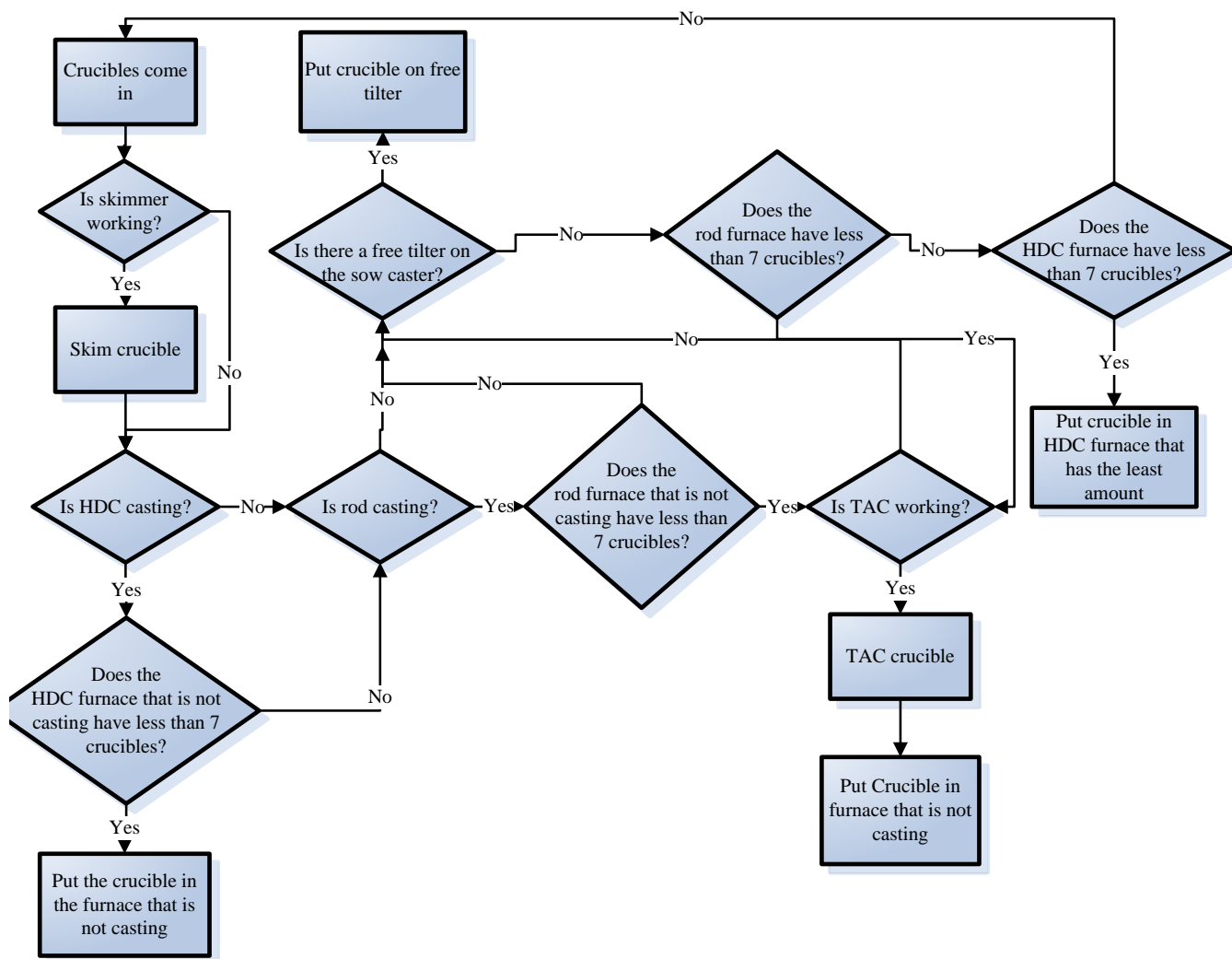


Figure 31: Routing for Model number 4

4.5 Summary

In this chapter there was a detailed description of all the models. The process flows and the routings were depicted. All the machines necessary for all the models were described and design data was given. In chapter eight, these four models will be used in a simulation study. Before the simulation can be done, the distribution and parameters must be found for the model, which is dealt with in the next chapter.

5 DATA DISTRIBUTIONS AND MODEL PARAMETERS

The difference between data in the design phase, the real data in a start-up and then the data after a plant becomes stable, can vary greatly. The main reason is that when a process is designed, the data from the machine manufacturer is used; often the highest production figures possible – a number only obtainable when a plant has been stable for a considerable time. In the start-up phase, the data is very different; everything is new so there is almost no way to achieve the ideal production rate. The best time to accumulate data is in a stable plant because then there is the least variance.

It was decided to find distribution to data that was considered very important to the model and the ones that had variability in them. The model parameters are used in the model as fixed elements. Often those parameters are based on computers and are therefore invariable.

5.1 Data distributions

It is very important to find the right distribution with the right parameters because if they are wrong, the whole model can give the wrong information. The data was collected in June, 2008 and October, 2008. The following data parameters were collected; sow weight, T-bar weight, coil weight, amount of metal in crucible, arrival times of crucible, casting time of the HDC, turnaround time of the HDC, crane travelling time and downtime, and casting time of rod mill. The plant was not fully stable when the data was collected and other factors, such as inexperienced staff, influence the data but the goal was to make a reliable enough model, despite those factors. Machine casting speeds, availability, scrap rate, travel time of product, cleaning time, relining time, TAC&Skim time, and crane unloading and loading times were also noted. In the following sections, distributions are proposed for certain data sets of critical process factors.

The software to find these optimal distributions is called STAT::FIT. The reason it was chosen is that it integrates the best with SIMUL8, the simulation program used to simulate the process (Hauge and Paige, 2004).

STAT::FIT tries for Beta, Binomial, Cauchy, Chi Squared, Discrete Uniform, Erlang, Exponential, Gamma, Geometric, Hyper geometric, Inverse Gaussian, Inverse Weibull, Johnson SB, Johnson SU, Laplace, Logarithmic, Logistic, Log logistic, Lognormal, Negative Binomial, Normal, Pareto, Pearson V, Pearson VI, Poisson, Power Function, Rayleigh, Triangular, Uniform and Weibull distributions.

It uses the Anderson-Darling (AD) and Kolmogorov–Smirnov (KS) tests to see whether the distribution fits and ranks the distribution according to the best fit. The KS test compares the empirical distribution function with the distribution function of the hypothesized distribution. The benefits of this test are that there is no need to specify interval since it is a step function that increases by $1/N$ at the value of each ordered data point, and it is valid for any sample size. The AD test differs from the KS test in that not all the intervals have the same value – there is more weight in the tails, and the AD test uses information from the distribution that is being tested whereas the KS does not. That way the AD test is designed to detect discrepancies in the tails (Law, 2007). All of the distributions selected were accepted by both the AD and KS tests with a confidence level of $\alpha = 0.05$.

Some of the data was collected with the shop floor system, ACES. ACES logs all metal that enters the casthouse. It logs the crucibles when they come into the system – the time when they enter the system, the weight, crucible number and where the crucible is put (sow caster or furnaces). Some data collection is automatic, for instance the crane scale sends the system automatically the empty and full weights of a crucible. Some of the data relies on the operator to enter some input, for instance where the crucible is going. ACES also logs each product with a lot number, a sub-lot number and the weight of each piece. This happens automatically, when the product goes onto the scale of the machine, but if the product does not go the normal route, it will need to be manually entered into the system. The benefits of collecting data from ACES, is that it is kept very tightly controlled for quality reasons. A lot of effort goes into keeping ACES correct, so its data should be accurate and reliable. Still, it sometimes has to rely on an operator's input, which can lead to errors. The following section clarifies how data is collected and what shortfalls can arise from collecting data from ACES.

A summary of all the elements found, and their distribution, can be seen in table 14. The following sections describe in more detail how they were found and the assumptions made.

Table 14: Objects and their distributions.

| Object | Date | Distribution | Location | Shape | Scale | Sample # |
|-----------------------------|---------------|--------------|----------|---------------------------|---------|----------|
| Sows | June, 2008 | Erlang | 0 | 370 | 1.75E-3 | 1208 |
| T-bars | June, 2008 | Empirical | - | - | - | 751 |
| Amount of metal in crucible | October, 2008 | Empirical | - | - | - | 2551 |
| Time between crucibles | October, 2008 | Empirical | - | - | - | 2213 |
| Coils | October, 2008 | Empirical | - | - | - | 998 |
| Turnaround time on the HDC | October, 2008 | Uniform | 1280 | - | 5490 | 10 |
| Casting time of the HDC | October, 2008 | Triangle | 424 | 1416 | 424 | 10 |
| Crane travelling time | June, 2008 | Weibull | 6 | 2.71 | 3.47 | 21 |
| Rod mill down time | October, 2008 | Raleigh | 74 | 2 | 864 | 31 |
| Rod mill casting time | October, 2008 | Beta | - | alfa1=1.68 alfa 2=2.18 | | 31 |
| Siphoning/pouring time | October, 2008 | Weibull | 4 | 1.22 | 1.57 | 21 |

5.1.1 Distribution on the sows from the sow caster:

The data was collected in June, 2008 from ACES.

| Descriptive statistics | |
|------------------------|--------------|
| data points | 1208 |
| minimum | 0.549 |
| maximum | 0.792 |
| mean | 0.645714 |
| median | 0.645 |
| mode | 0.6315 |
| standard deviation | 3.37102e-002 |
| variance | 1.13638e-003 |

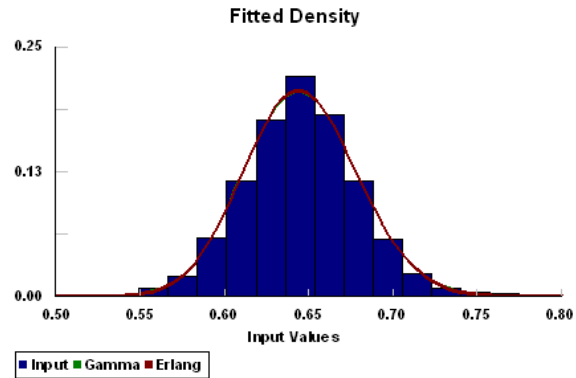


Figure 32: A histogram and descriptive statistics of comparison of the fitted Erlang distributions from STAT::FIT on the sow.

This is the production data from ACES and is therefore very reliable. If the weight is not correct, customers will complain. The only thing that is missing here is that if sows are very small (below 350 kg) they cannot enter the system and are re-melted right away. At the time when this data was collected, the goal was to put as high amount of metal in each mould as possible, but in the future all sows should be 650 kg \pm 5% because they are being sold in a standard way on the LME. Therefore this range on the data should be tighter than the current range, shown in figure 32.

The results of the distribution fits was that Erlang, Gamma, Pearson 5, Pearson 6 and Lognormal were possible, but the Erlang distribution, with the parameters (0.646, 370), was chosen, as it ranked as the best in STAT::FIT.

5.1.2 Distribution of the HDC T-bars

Data was taken in June, 2008 from ACES. None of the distributions fit the T-bar samples, which is why an empirical distribution was used.

| Descriptive statistics | |
|------------------------|--------------|
| data points | 712 |
| minimum | 0.677 |
| maximum | 0.687 |
| mean | 0.681346 |
| median | 0.681 |
| mode | 0.68 |
| standard deviation | 1.10172e-003 |
| variance | 1.21379e-006 |

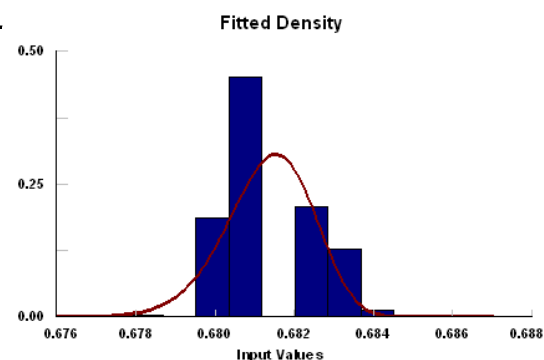


Figure 33: A histogram and descriptive statistic from STAT::FIT on the T-bars.

The reason for the small variance on this, as can be seen in figure 33, is that all the products are the same length and therefore the difference in weight is very small. This is a standard length/weight product, unlikely to be changed in the future. It is possible to have different products with this machine, in which case new data would have to be collected.

In this data the start and end bars are not included, but calculated in the scrap rate later on.

5.1.3 Distribution of amount in crucible

This data was taken from the whole month of October, 2008 from ACES, so a considerable number of measurements was obtained. Again, no known distribution fitted so an empirical distribution was used.

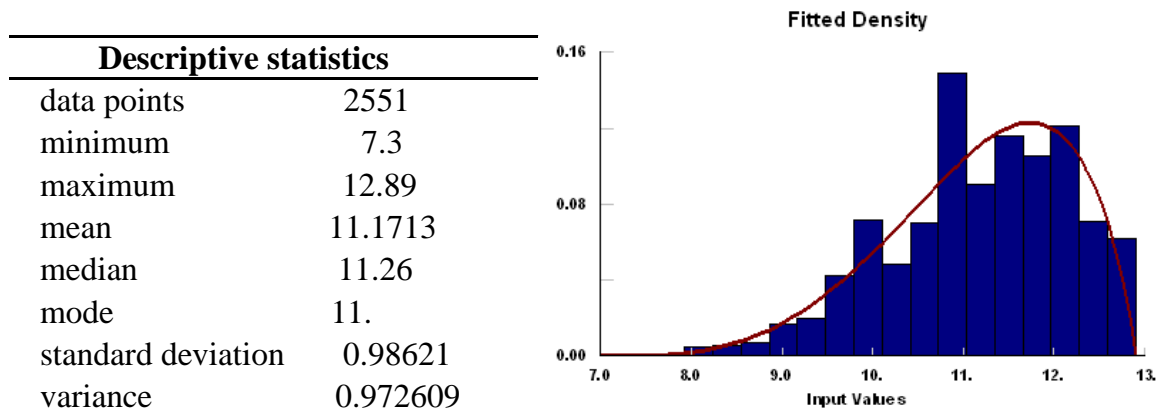


Figure 34: Histogram and descriptive statistic on the weight in crucibles.

Since the data came out of the shop floor system, it had to be checked before it was used. Sometimes operators need to manually enter the weight of the crucible when the crucible has not been weighed. This poses two kinds of error possibilities in the data.

- Sometimes numbers such as 0 or a negative number appear – those numbers were taken out of the data set since it is not possible to put zero or negative numbers for weight.
- Some operators write a bogus number in the system, which is impossible to detect, providing the number is between 7.0-12.9 tons. These manual entries are due to extra manual casting lines, where it is not possible to weigh the crucibles. Fortunately, it is a small proportion of the data set, but it needs to be kept in mind. It was therefore not possible to verify the manual entry points that were between 7 and 12.9 tons.

This should not present a problem in the future, when the manual casting has stopped. The range of the data can be seen in figure 34, and in the future the aim is to have every crucible weight closer to 12.6 tons.

5.1.4 Distribution of the time between arrival times of crucibles

Data was taken from the month of October, 2008, from ACES. All known distributions failed so empirical distribution is used.

| Descriptive statistics | |
|------------------------|---------|
| data points | 2213 |
| minimum | 1.0 |
| maximum | 417.0 |
| mean | 19.8242 |
| median | 16.0 |
| mode | 12.0 |
| standard deviation | 18.3306 |
| variance | 336.012 |

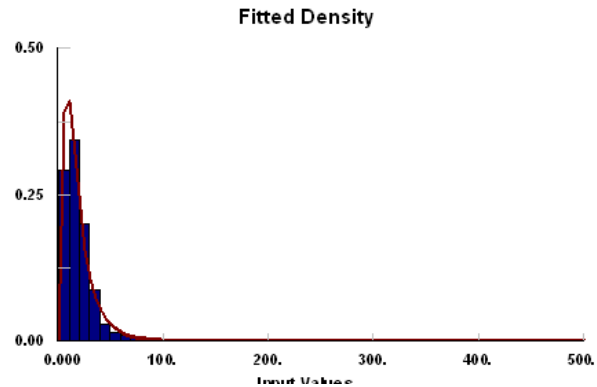


Figure 35: Histogram and descriptive statistic of the minutes between crucibles.

The same problem appears in the data collection here as with the amount of metal in crucibles. Therefore, the data needed to be checked before it could be used. When an operator needs to manually enter a crucible in the system and the crane has not been used, the timing is not right between the crucibles. All zeros were taken out of the data set, since some time always passes between the crucibles. Another thing that needs to be considered with this data set is that when it was collected, the goal of the production was to catch up on metal backlog so more metal needed to be cast than normally. Therefore the arrival time is more frequent than under normal circumstances. In the future, the aim is to have as paced an arrival pattern as possible so the range will not be as wide as in figure 35.

5.1.5 Distribution of the coil weight

Data was taken from the month of October, 2008 from the Aces system. No distribution fits this and since there are so many measurements, it was decided to use empirical distribution.

| descriptive statistics | |
|------------------------|----------|
| data points | 998 |
| minimum | 0.415 |
| maximum | 3.596 |
| mean | 3.14203 |
| median | 3.486 |
| mode | 3.483 |
| standard deviation | 0.692735 |
| variance | 0.479881 |

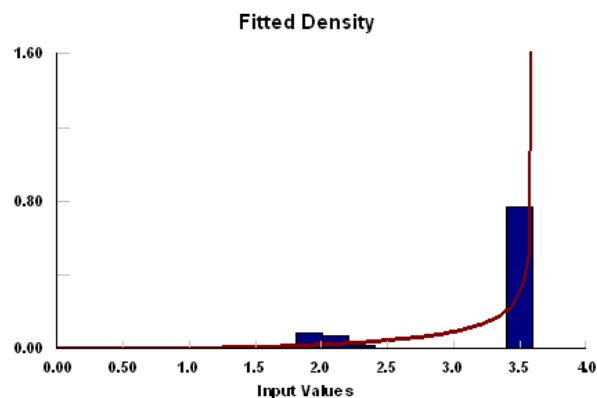


Figure 36: Histogram and descriptive statistics of the coil weight.

The reason for the gap in the data seen in figure 36, is because a normal production is for 3.5 ton coils but during that month a trial was ongoing for 2.2 ton coils. In the future the aim is to produce only 3.5 ton coils. As the coils have very strict quality requirements, their weight will not vary much. Still, it is possible in the future to have more variety in the product mix. The start and end coils are considered a part of the scrap rate.

5.1.6 Distribution of the turnaround time of the HDC

Data was taken from the month of October, 2008 from operators' check sheets and ACES. In this case the Triangle distribution is acceptable and was used.

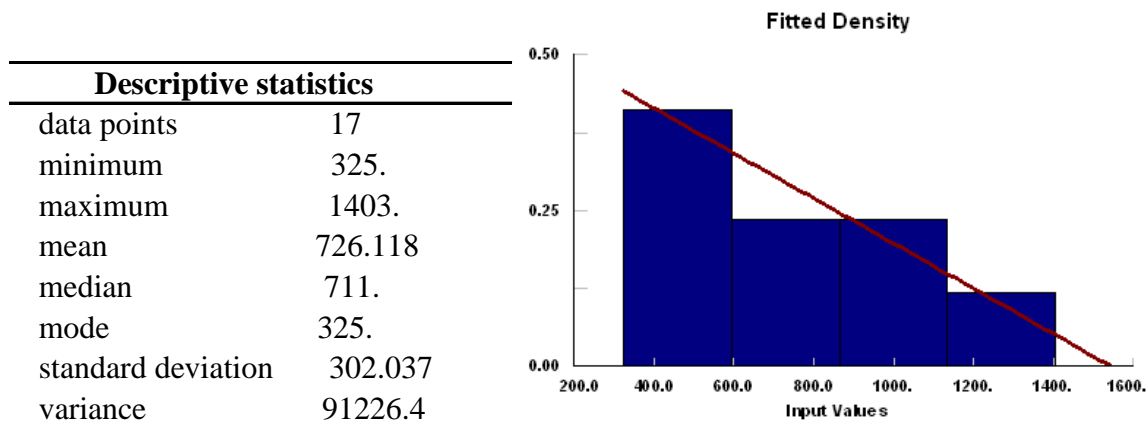


Figure 37: A histogram and descriptive statistics of comparison of the fitted Triangle distributions from STAT::FIT on the turnaround time of the HDC.

Other distributions that fitted were Beta, Weibull, Pearson 6, Lognormal and Gamma. The Triangle distribution was chosen because it was ranked the highest by STAT::FIT.

This data was tricky to collect since there is not a direct link to the start and stop of casting in the shop floor system. Therefore, the data was gathered from checklists that operators fill in when they start and stop the cast. It is not fully reliable, since sometimes they forget to put in the numbers or enter the wrong values. Therefore, that particular data was used as a base and then compared with production numbers from ACES. Combining those two gave a more accurate representation of the reality.

5.1.7 Distribution of the casting time of the HDC

Data was taken from the month of October, 2008 from operators' check sheets and ACES. The uniform distribution fits with the parameters (1280, 6770).

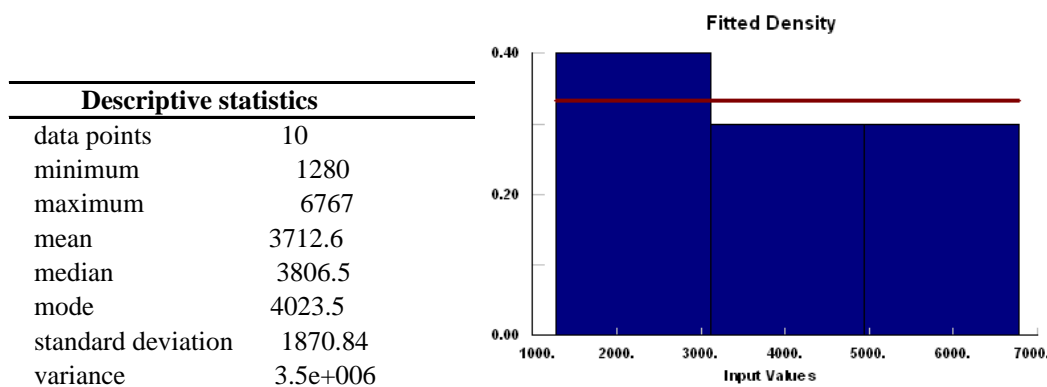


Figure 38: A histogram and descriptive statistics of comparison of the fitted Uniform distributions from STAT::FIT on the casting time of the HDC.

Other distributions that fitted were Beta, Weibull and Pearson 6 but Uniform was chosen because it is the simplest one to use and the difference between the rankings was not that great.

The same problem occurred with this data set as the previous one, therefore the same approach was used. Initially, the check sheets were used as a base and then compared with the production numbers to get realistic data.

5.1.8 The crane travelling time

Data was taken from the month of October, 2008 and the data was measured by an operator on the shop floor, with a stop watch. The best fitting distribution is the Weibull distribution with the parameters (2.71, 3.47 with a fixed offset of 6).

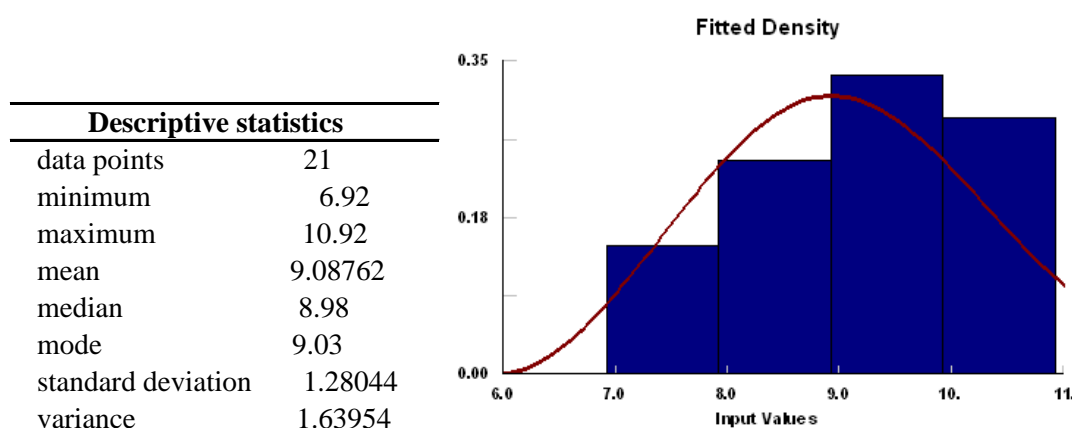


Figure 39: A histogram and descriptive statistics of comparison of the fitted Weibull distributions from STAT::FIT on the crane travelling time.

Other distributions that fitted were Rayleigh, Lognormal, Beta and Pearson 6. The Weibull was chosen because it ranked highest.

Comparing this data to data taken from another Alcoa casthouse, it seems that the variance could possibly be higher than this. The goal is, of course, to keep this time to a minimum, which will happen with more experienced operators. On the other hand, the crane failure rate might go up with age, resulting in a higher range than shown in figure 39.

5.1.9 The crane siphoning/pouring time

Data was taken from the month of October, 2008 by an operator on the shop floor, with a stop watch. The best fitting distribution is the Weibull distribution with the parameters (1.22, 1.57 with a fixed offset of 4).

| Descriptive statistics | |
|------------------------|---------|
| data points | 21 |
| minimum | 4.24 |
| maximum | 9.07 |
| mean | 5.45952 |
| median | 5.1 |
| mode | 4.42 |
| standard deviation | 1.32116 |
| variance | 1.74547 |

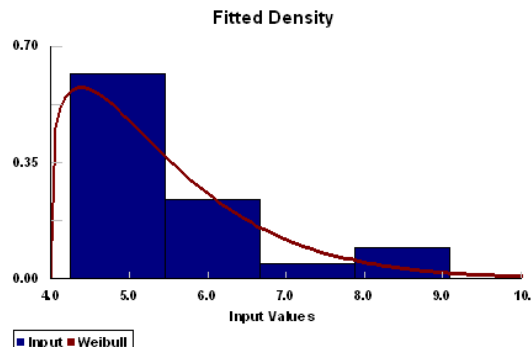


Figure 40: A histogram and descriptive statistics of comparison of the fitted Weibull distributions from STAT::FIT on the crane pouring/siphoning time.

Other distributions that fitted were Lognormal, Gamma, Exponential and Beta. The Weibull distribution was chosen because it ranked highest in STAT::FIT.

This data set was compared to an Alcoa casthouse in a different location and, again, the variance range was wider, therefore collection of more data would be advisable in future models.

5.1.10 Down time of the rod mill

Data was taken from the month of October, 2008 from the ACES system. The Rayleigh distribution best fits the data. The Rayleigh distribution was created with a combination of a fixed offset of 74 and Weibull with parameters (2, 864).

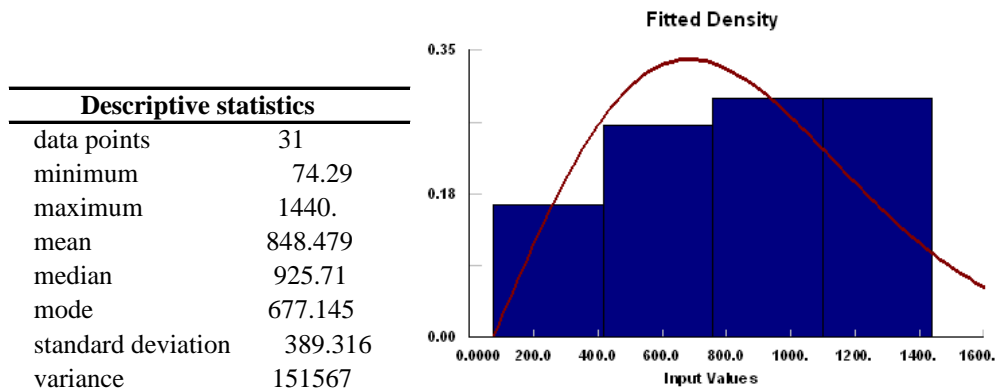


Figure 41: A histogram and descriptive statistics of comparison of the fitted Rayleigh distributions from STAT::FIT on the down time of the rod mill..

Other distributions that fitted were Uniform, Beta, Power function and Weibull.

There were no operators' check sheets for this data, so it is completely based on the production numbers from ACES. It was calculated how much was produced during specific casting times and, from that, it was possible to get machine downtime minutes. The data set was then verified by a rod mill specialist who confirmed that it represented the reality. The rod mill was in a start-up phase when the data set was taken and, in the future, operators will have more re-starting experience.

5.1.11 Casting time of the rod mill

Data was taken from the month of October, 2008 from the ACES system. The Beta distribution fits the data set best and is used with a min 0 and max 1520 with parameters (1.68 and 2.18).

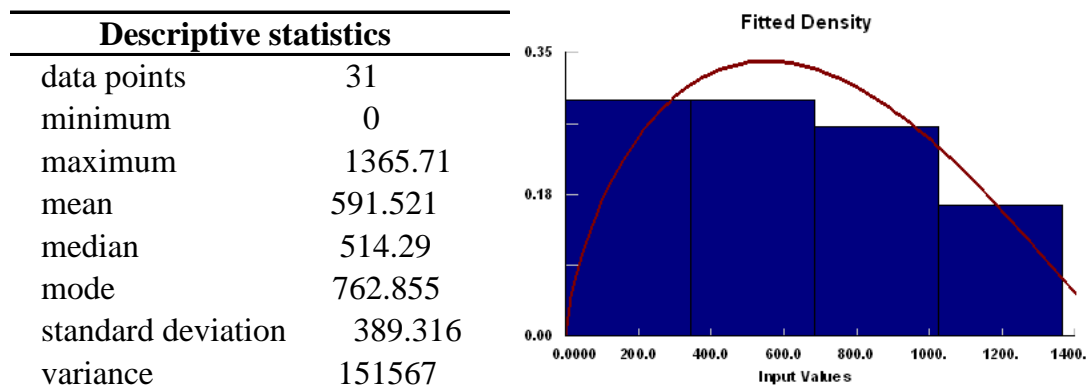


Figure 42: A histogram and descriptive statistics of comparison of the fitted Beta distributions from STAT::FIT on the casting time of the rod mill.

Other distributions that fitted were Weibull, Rayleigh, Pearson 6 and Lognormal. The same problem occurred here as with the downtime of the rod mill and, therefore, the same procedure was used to find the data.

5.2 Model parameters

This chapter describes other parameters that are used in the model. The parameters that are discussed in this chapter have fixed values and there was no distribution fitting. The data is summarized in table 17.

Table 15: Summary of all fixed model parameters.

| Machine | Element | Value |
|--------------------------|--|--------------------------|
| Sow caster | Casting speed | Fixed 30 tons per hour |
| | Availability | 82% |
| | Scrap rate | 0.5% |
| | Elevator | Fixed 3 minutes |
| HDC | Casting speed | Fixed 17 tons per hour |
| | Scrap rate | 1% |
| | Elevator | Fixed 3 minutes |
| Rod | Casting speed | Fixed 12 tons per hour |
| | Scrap rate | Everything below 1.9 ton |
| | Elevator | Fixed 5 minutes |
| Crane | Unloading and loading time on sow caster | Fixed 2 minutes |
| | Availability | 95% |
| Skim | Treatment and travelling | Fixed 5 minutes |
| | Availability | 93% |
| TAC | Treatment and travelling | Fixed 13 minutes |
| | Availability | 93% |
| Crucible cleaning | Cleaning | Fixed 60 minutes |
| | Pre heating | Fixed 180 minutes |
| | Relining | Fixed 96 hours |

5.2.1 Throughput of machines

The throughput of the HDC in October, 2008 was 120 mm/min of T-bars, which means 17 tons per hour when it was running. When the sow caster gets a supply of metal it is able to produce 30 tons per hour, as per the design. The rod mill has a production rate of maximum 12 tons per hour, which was the casting speed in October, when the machine was running.

5.2.2 Metal quality

The quality can be a factor in routing the metal into various machines. For instance, the rod mill needs P1020 or better in order to produce the right product. Therefore, if the quality were to range from P0406 to P1535, or worse, this factor would need to be considered in the model. The crucibles would have to have metal quality linked to them and only certain qualities would be allowed into the rod mill. Table 15 shows the distribution of the metal quality in June, 2008. As can be seen, the quality is very good and stable. Therefore this factor is not needed in the simulation model at this time. With such good, stable quality, no further analysis is needed on the data from the table.

Table 16: Quality distribution at the end of June, 2008.

| Quality | 20.6.2008 | 21.6.2008 | 22.6.2008 | 23.6.2008 | 24.6.2008 | 25.6.2008 | 26.6.2008 |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| P0406 | 16.5% | 15.0% | 15.9% | 14.9% | 15.8% | 15.8% | 25.6% |
| P0610 | 72.7% | 72.1% | 70.3% | 69.9% | 68.2% | 67.9% | 58.6% |
| P1020 | 10.2% | 12.3% | 13.2% | 14.9% | 15.8% | 16.4% | 15.8% |
| P1535 | 0.6% | 0.6% | 0.6% | 0.3% | 0.3% | 0% | 0% |
| P2055 | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Worse than P2055 | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

The reason for checking this factor is that in older potrooms, the quality can range from very low iron content to very high. Therefore, to optimize the production, different quality metals must be directed to different places.

5.2.3 Crucible cleaning

The crucible cleaning area is where the crucibles are cleaned and maintained. An important factor is how fast that can be done in order to get the crucibles back into circulation again.

Cleaning the crucibles

It takes one hour to clean a crucible, after which it goes to the pre-heating station for four hours. A crucible should be cleaned every time it reaches a certain weight, or has been used 20 times. The reason that these factors are not measured and their distribution found is that these are parameters in a computer program and therefore are assumed to stay the same.

Relining crucibles

Relining of a crucible, which takes four days, should be done after 1200 trips. Therefore, the total unavailability of a crucible is 96 hours. The reason that this is not measured is that this has only been done once at Alcoa Fjarðaál, so times from Alcoa Deschambault were used.

Number of crucibles used

In the model, it is assumed that the casthouse has 14 crucibles in circulation; the same number as in Alcoa Fjarðaál.

5.2.4 Shipping area

The shipping area is not a bottleneck since items can be stored outside if lack of space arises, but the shipping area is needed in the model to get the full process.

The time it takes a sow/T-bar/coil to go to the shipping area

It takes a stack of four sows and a stack of 3 T-bars three minutes to go to the shipping area. It takes a coil five minutes to go down to the shipping area, including testing. These are parameters in the computer and are therefore invariable. Therefore there was no need to collect data on this.

5.2.5 Scrap rate

Estimated scrap rate in the design phase on sow casters was 2.6% but in reality it is closer to 0.5%, so the latter percentage will be used. Scrap rate for HDC in October, 2008 was 1%, but this number can vary from one product to another and it also depends on the frequency of stops and starts. As an example, the scrap rate is higher for foundry ingots because they are harder to produce. A T-bar is not scrapped unless there are “bleed-outs” on the product. Scrap rate for rod is 8% but in a stable plant it should be around 6%. This is one the highest scrap rate there is, with most of the scrap being put straight into the furnace. The reason for putting this in the model was to get the right amount of final products that are produced. This could be analysed further when a final model has been chosen.

5.2.6 The TAC&Skim station

The skimming and TAC treatment are based on computer programs and are therefore the parameters are constant. The skimming itself takes three minutes. With travel time between bays it is five minutes. It takes seven minutes to do the TAC treatment; with travelling time it is 12 minutes.

5.2.7 Failure of machines

For the HDC, machine failure is counted in the cast length and turnaround time, since all maintenance is done within the turnaround period. This is because it is difficult, if not impossible, to do maintenance while casting and if something stops, either because of a failure or normal stop, the maintenance will be done in that downtime and therefore is counted as part of that. The same thing applies for the rod downtime, which is the reason why it is not included here.

For the rest of the machines, the data can be seen in table 17; the availability of the TAC&Skim machine, sow caster and crane. What is interesting here is the high availability of the crane but that is because it is a critical machine in the casthouse and it is under high surveillance and undergoes a lot of preventive maintenance.

Table 17: Failure of machines.

| Object | Availability |
|------------|--------------|
| Tac | 93% |
| Skim | 93% |
| Sow caster | 82% |
| Crane | 95% |

5.3 Summary

This chapter has explored data distributions and model parameters which will be used in the simulation model. There was a description of each object being tested for distribution; there was also a density graph and descriptive statistics for each. For each section a proposed distribution was used. There was also discussion on how the data was assembled and if there might be any flaws in the data gathering. In the model parameter section there was a description of all the factors where no distribution was found, in which case they were used as fixed parameters in the model, and a reason given. There are also two tables that summarize

all the information from the chapter. In the next chapter all these numbers will be used in the simulation model in order to validate the model.

6 THE SIMULATION AND VALIDATION OF MODEL

The models that were presented in chapter 5 were simulated in the program Simul8. Model 1 was created first as it was the simplest, and then Model 2, Model 3 and lastly Model 4 - which was the most complex to program. Simul8 is a very user-friendly program when the models are simple, but as soon as some complexity is added to the model it becomes harder to use. There was frequent use of visual logic for the routing of the crucibles (Fig 27, 29 and 31) and this is easier when one has mastered the label usage in Simul8 however, it is still not as user friendly as one would have hoped for. There was also a problem with the crucibles because there are a fixed number and the usage needs to be counted, but unfortunately there was no easy way to do that in simul8. Overall simul8 is a great tool for small models such as model 1, but becomes increasingly more difficult to use for more complex models, such as model 4.

During the validation process the fourth model was validated, with some additions and simplifications, to have it as close as possible to the actual model used in Alcoa Fjarðaál. The modifications were done on model four. An extra manual casting line was added, as well as a different route for the crucibles, and a manual casting line #2 in a different location. The new route can be seen in figure 43, the biggest difference being that instead of first checking whether the HDC or the rod mill are working, the loop now checks if the sow caster has a crucible or not, before moving on to the HDC and the rod mill.

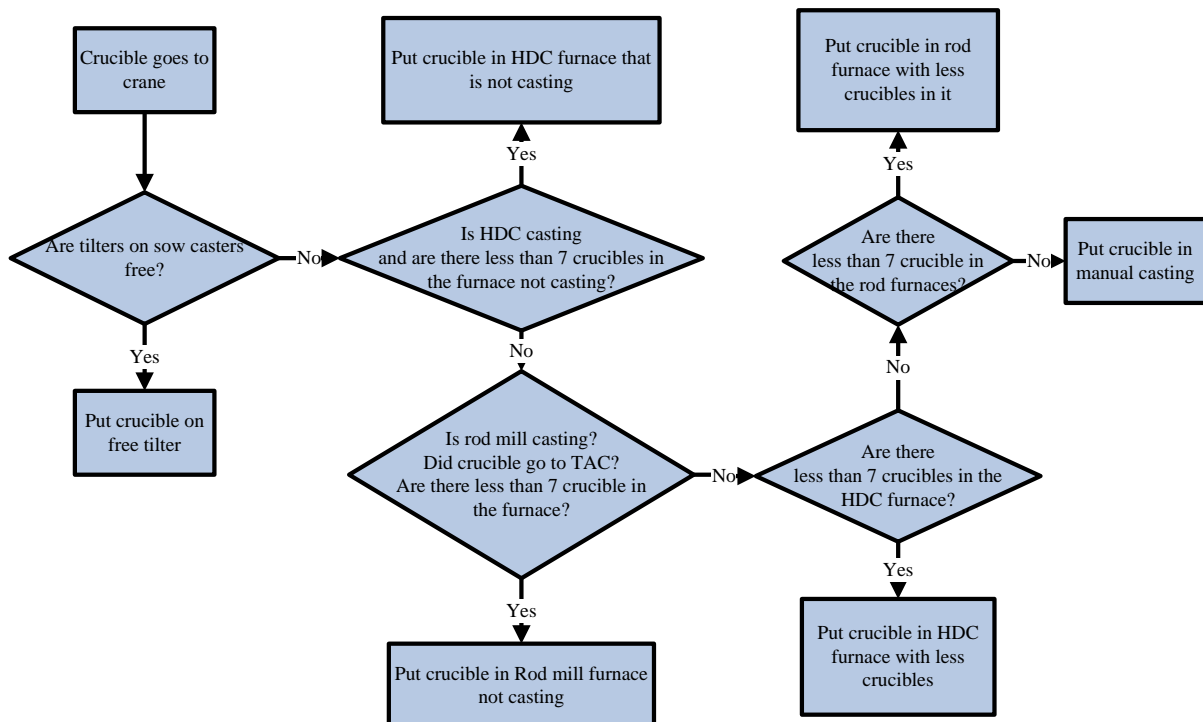


Figure 43: New routing for crucibles

The reason for this modification was because there was a large backlog of metal at Alcoa Fjarðaál during the month of October, 2008, so the manual casting and sow casting had to be

increased to try to clear it. Unfortunately, the model does not allow for two manual casting locations so this extra material from manual casting #2 is put into storage as a backlog, in the model, when in actual fact it had already been cast in a different location.

The model was both validated using historical data and in a review meeting with the management team at Alcoa Fjarðaál.

6.1 Validation using historical data

30 trials were done. The simulation run was for a month, with the first week as a warm-up period. A trial warm-up period of a week, three weeks and a month were tried, with no change difference in the results, so a week was chosen as a warm-up period. This was considered adequate since the plant is operating 24/7 with constant work. In order to validate the results, the production figures from October, 2008 were compared to casting figures from the simulation runs. The real production numbers from Alcoa Fjarðaál are shown in table 18, and table 19 shows the metal backlog.

Table 18: Production numbers from Alcoa Fjarðaál in October, 2008.

| Machine | Value [tons] |
|------------------|---------------------|
| Rod | 3.113 |
| HDC | 8.569 |
| Sow caster | 10.840 |
| Manual casting | 2.180 |
| Total production | 24.702 |

Table 19: Metal backlog in Alcoa Fjarðaál in October, 2008.

| Source | Value [tons] |
|---|---------------------|
| Manual big sows | 2.350 |
| Back log from pot rooms at the end of October | 170 |
| Back log from pot rooms at the beginning of October | 700 |
| Total metal not in system at the end of October | 1.820 |

Table 20 shows that all production and metal backlog figures fit within the 95% range and therefore it is concluded that Model 4, with the previously mentioned adjustments, is believed to be very close to representing reality. Another adjustment made was to have a fixed number of crucibles going into furnaces, whereas, in reality, more could possibly go in. Also, for the crucible cleaning, there is only a check of how often the crucible has been used in the model, so the weight check, which is done in reality, is skipped.

Table 20: Production numbers from the simulation runs.

| Simulation object | Performance | | | | |
|-------------------------|-------------|--------|---------|--------|------|
| | measure | -95% | Average | 95% | |
| Total rod production | Value | 3.027 | 3.123 | 3.219 | tons |
| Total HDC production | Value | 8.345 | 8.503 | 8.662 | tons |
| Total sow production | Value | 10.472 | 10.738 | 11.003 | tons |
| Total manual production | Value | 2.081 | 2.203 | 2.325 | tons |
| Total quantity cast | Value | 24.246 | 24.560 | 24.874 | tons |
| Total metal back log | Value | 1.797 | 2.111 | 2.425 | tons |

6.2 Management review and structured walk-through

It is not enough to validate only historical data; the historical data may not fully represent the truth about the system at the time when the data was taken. Therefore it is vital to validate the model with a management review as well. This is done with a structured walk-through of the system with specialists, and going over the results with the management team to see if they think that the model represents the truth.

The structured walk-through of the system was done before the model was built in SIMUL8. A number of the members of the casthouse technical team and management were interviewed, in order to have the model as accurate as possible. In those interviews it was decided how detailed the model should be, what data should be collected, and what output they wanted out of the model. This was done several times during the construction of the model in order to achieve the most accurate model. The challenging part was to eliminate the factors that did not matter in the model and to decide on the complexity.

In the management review, there was an introduction to the project, the data collected, and the validation. The historical data and the data output from the model were compared and discussed. Other factors were also contemplated, such as utilization on machines and crane. After the review there was a discussion about what the next steps should be.

6.3 Summary

After both validating the model using historical data and with a management review, it can be assumed that the model is adequate for answering the third research question: which one is the best model?

Since there is no way of validating the models 1-3 it is assumed that since Model 4, with additions, is considered to represent the truth, the other models also represent the truth. Therefore it is possible to continue the study using those models.

In the next chapter, the validated models will be explored with different kinds of input and efficiency on machines, in order to find the best model.

7 MODEL SELECTION USING THE AHP METHOD

The AHP method is now used to find the best model as per the following criteria:

- **Cost:** The cost considered is the capital cost of buying the machines, the operational cost of running them, and extra cost, like extra machines which are needed, for instance TAC&Skim with the rod mill. The same cost values are used as used in the BIP model shown in appendix A.
- **Value:** The value is estimated as the value that is gotten from selling the product. An LME price is used and then a premium is assumed on higher value product and a discounted LME price is assumed for scrap products. It is assumed that it is always possible to sell the highest paid product at full capacity and then the capacity is used for the lower value products. The scrap rate is used to find out how much of the production would be scrap and it is assumed it can all be sold at a discounted price. The values can be seen in appendix A.
- **Metal backlog:** This value is obtained from the simulation model. It is the amount of metal which cannot go through the model. High metal backlog indicates that, for some reason, the model is working badly.
- **Throughput:** This value is obtained from the simulation as well and it examines if the models are capable of producing more than 360,000 tons a year.
- **Utilization of machines:** This value comes from the simulation model and is the percentage of the working time of the machines. The models should not be kept idle for long, but they should not be over-utilized either because it could result in metal backlog or not allow for any flexibility for extra casting.
- **Product mix:** This value is obtained from table 3 in chapter 2.3.4 and is the sum of the maximum products each machine can have in the model. The more product variety, the better.

All of the criteria were compared together in a pair-wise manner. Input in the comparison came from the production manager, manager of sales and export, casthouse manager and casthouse process owner at Alcoa Fjarðaál. The following chapter deals with the results from the simulation of the metal backlog, throughput and utilization of machines.

7.1 Model trials

All the models were tested with various sizes of tonnage per year. The test sizes were 180,000, 270,000, 360,000 and 450,000 tons per year throughput, respectively. The models were also tested with 75%-95% efficiency on machines. The aim was to get a sensitivity analysis on the models in order to see which model performed the best, by looking at the parameters of metal throughput, metal backlog and utilization on machines. Those results are then used in the comparison part of the AHP. All the results tables from the simulation are in appendix B. 30 runs were executed and the time was 30 days, with a week for a warm-up period.

When comparing the metal backlog of the models, a weighted average is used to get one number from the three efficiencies (75%, 85%, 95%) the 85% gets the weight 70% and the other two 15% each. The metal backlog is found for the input 360,000 tons a year and the results from those calculations can be seen in table 22, as well with the results from the 85% efficiency trial with standard deviation. When comparing the models it is considered best to

have as little metal backlog as possible so it is obvious when looking at table 22 that Model 1 is doing significantly better than the other three models. It can also be said that 200 tons is hardly a metal backlog in a continuous operations. However, metal backlog as can be seen for Model 4 is extremely large, which indicates that there might be a bottleneck in the model and it needs to be invested further.

Table 21: Weighted average of the metal backlog

| Trial: 360.000 tons per year with 85% efficiency | | |
|---|-----------------------------|-------------|
| Model | Metal backlog [tons] | |
| 1 | 199 | 190 ± 64 |
| 2 | 850 | 576 ± 106 |
| 3 | 1.577 | 1.403 ± 407 |
| 4 | 4.290 | 4.224 ± 387 |

The throughput is calculated in a similar way but then the weighted average was taken of the maximum production of the model. The more the models could produce, the better, so the weighted average was taken from the 450,000 tons a year trial. The results from those calculations can be seen in table 23, which shows that Model 1 has the highest possibility of throughput. The difference between Model 2 and Model 3 does not seem to be large so a t-test was done to see if the difference between Models 2 and 3 was statistically significant, which it was. Again, Model 4 is the worst model for this.

Table 22: Weighted average of throughput

| Trial: 450.000 tons per year with 85% efficiency | | |
|---|--------------------------|---------------|
| Model | Throughput [tons] | |
| 1 | 35.587 | 35.986 ± 347 |
| 2 | 30.652 | 31.017 ± 521. |
| 3 | 29.476 | 29.561 ± 608 |
| 4 | 25.570 | 25.658 ± 384 |

When the utilization of machines was compared, it was checked how evenly the utilization was distributed and if there were any bottlenecks in the models. It is not desirable to have one or more machine underutilized, because it means that it could have been possible to buy a cheaper machine with less production capacity, or skip the machine altogether. Overutilized machines, on the other hand, do not allow for much flexibility in the production – they cannot produce much more. Therefore a balance of both was looked for.

When looking at utilization for the models, table 23 shows the utilization of a machine for 360,000 tons a year of input with 85% efficiency on the machines. From the table we can see that Model 1 has one machine that is only working 27% of the time. Model 2 has the most evenly distributed utilization and some extra capacity on machine three. Model 3 has very even utilization on the casting machines but is using the hauler a lot more than the other two models, which is not preferable. Model 4 behaves strangely, with machine one only working

66% of the time, and it has a huge metal backlog. This indicates that there is a bottleneck in the system and the model needs to be analyzed further.

Table 23: Summarized utilization on machines for Models 1-4 for input of 360,000 tons a year smelter with machines at 85% efficiency.

| Model | Machine 1 | Machine 2 | Machine 3 | Crane | Hauler |
|-------|--------------|--------------|--------------|--------------|---------------|
| 1 | 27% \pm 3% | 81% \pm 1% | 81% \pm 1% | 73% \pm 1% | |
| 2 | 69% \pm 2% | 81% \pm 2% | 84% \pm 2% | 86% \pm 1% | 1% \pm 0.3% |
| 3 | 70% \pm 2% | 71% \pm 2% | 82% \pm 1% | 69% \pm 2% | 7% \pm 1% |
| 4 | 66% \pm 2% | 79% \pm 2% | 80% \pm 2% | 73% \pm 1% | 2% \pm 0.6% |

From table 23 it could be interpreted that Model 2 and Model 3 are performing best since the utilization is the most even and the machines all have utilization of more than 65%. Then comes Model 1 which has, unfortunately, one of its machines only used 27% of the time, followed by Model 4 which has a bottleneck somewhere in the model.

7.2 Comparison of elements

In order to get the best decision, all the criteria need to be compared against each other. This was done by asking a few managers, as previously stated, to compare all the elements. There was not full consensus between all the managers, neither on what was more important, nor on the degree of importance. It was decided to integrate those answers into one comparison and then try each individual comparison to see if the results would change. The things that were agreed upon were that metal backlog is always more important than the element that it is being compared to. This is because a huge metal backlog tells us that the model is not functioning and a model like that would be very costly. All the managers thought that value was more important than utilization on machines and throughput was more important than cost and utilization on machines. The disagreement was about the following comparisons:

- *Cost and value*: two thought that they were equal and two thought that value was more important. It was decided to have the value more important.
- *Cost and utilization on machines*: two thought that cost was more important and two thought that utilization was more important. It was decided to have them equally important in the integrated comparison.
- *Cost and product mix*: three thought product mix was more important and one that cost was more important. Therefore product mix will be considered more important in the integrated comparison.
- *Value and throughput*: three thought that throughput was more important and one thought that value was more important. Therefore throughput will be considered more important in the integrated model.
- *Value and product mix*: two thought that value was more important, one thought product mix was more important, and one thought they were equally important. Therefore the value will be considered more important.
- *Utilization on machine and product mix*: two thought utilization was more important and two thought that product mix was more important. Therefore the integrated comparison had them as equally important.

- *Throughput and product mix:* Here, as well, two thought throughput was more important and two thought product mix was more important. Therefore it was decided to have them equally important.

Table 24 shows the comparison integrated by those four comparisons described above. In appendix C, the tables for each individual comparison are shown.

Table 24: Integrated pair-wise comparison of objectives.

| A | B | More important | Intensity |
|-------------------------|-------------------------|----------------|-----------|
| Cost | Value | B | 3 |
| Cost | Metal backlog | B | 9 |
| Cost | Utilization of machines | A and B | 1 |
| Cost | Throughput | B | 3 |
| Cost | Product mix | B | 3 |
| Value | Metal backlog | B | 9 |
| Value | Utilization of machines | A | 5 |
| Value | Throughput | B | 3 |
| Value | Product mix | A | 3 |
| Metal backlog | Utilization of machines | A | 9 |
| Metal backlog | Throughput | A | 9 |
| Metal backlog | Product mix | A | 9 |
| Utilization of machines | Throughput | B | 5 |
| Utilization of machines | Product mix | A and B | 1 |
| Throughput | Product mix | A and B | 1 |

7.3 Comparison of models

In this section there is a description on how the models were compared and ranked together on each criterion.

Cost

When the models are compared by cost, a cheaper investment is considered better. Model 1 is therefore the best one in the cost comparison, followed by Model 2, then 3, and Model 4 is the most expensive. In the ranking that means that Model 1 is absolutely more important than Model 4, very strongly more important than Model 3 and strongly more important than Model 2. Models 2 and 3 are considered equally costly and both are considered strongly less costly than Model 4.

Value

A higher value is considered better and the model that scored the highest in value was Model 4, followed by Model 3, then 2, and Model 1 had the least value. Therefore when they were compared together, Model 4 was considered absolutely more important than Model 1, moderately more important than Model 2 and strongly more important than Model three. Models 2 and 3 were considered equally important and both of them strongly more important compared to Model 1.

Metal backlog

When comparing the metal backlog, it is possible to see from table 21 that Model 1 is doing the best, followed by Models 2, 3 and 4. Therefore Model 1 is considered absolutely more important than Model 4, strongly more important than Model 3 and moderately more important than Model 2. Model 2 is considered moderately better than Model 3 and strongly better than Model 4. Model 3 is considered strongly better than Model 4 as well.

Throughput

Looking at throughput is to see the possibility of using extra casting capacity. As can be seen from table 22, the model which can take the highest throughput is Model 1, followed by Models 2 and 3, and then, lastly, Model 4. The ranking is therefore very similar to the ranking of the metal backlog.

Utilization of machines

When comparing the models in utilization, Model number 2 was considered the best model and it was considered strongly better than Model 1, moderately better than Model 3 and very strongly better than Model 4. This is because Model 1 has one machine that is used very little and Model 4 seems to have a bottleneck and therefore needs to be analyzed further. Model 3 is considered moderately better than Model 1 and strongly better than Model 4. Model 1 is considered moderately better than Model 4.

Product Mix

In the product mix, the number of how many products the model could theoretically produce were calculated and then compared. The more products a model can produce, the better. Model 1 can only produce one product and gets the lowest score. Model 4 scores the highest here with the greatest variety in product mix and is therefore absolutely better than Model 1, strongly better than Model 3 and moderately better than Model 2. Model 2 scores higher than Model 3 because the HDC can have up to six products but the rod mill only two. Therefore, Model two is considered moderately better than Model 3 and strongly better than Model 1.

All the Excel models can be seen in appendix C and the results can be seen in table 25, which shows that the “best” model found by using the AHP method is Model 1, followed by Model two. Models 3 and 4 get the lowest score.

Table 25: The results from the AHP method

| .Model | Weighted scores |
|---------------|------------------------|
| 1 | 0.40 |
| 2 | 0.21 |
| 3 | 0.12 |
| 4 | 0.12 |

7.3.1 Sensitivity analysis

When a decision depends on qualitative assessment it is always necessary to perform sensitivity analysis to see if changes in conditions change the decision. It might also not always be apparent why the value seven is chosen from the scale instead of nine and a seven might fit as well as nine. Therefore a small sensitivity analysis was done by altering the numbers of the highest factors in the pair-wise comparison to see if the results would change.

The highest ranking elements are throughput and metal backlog and therefore the overall decision is most sensitive to them. Their values were altered slightly to see if the results changed, both by having them less important to all of the other elements, and more important. This did not change the results. It was also decided to try to put in the individual comparisons to see if the results would change, which they did not. It is therefore possible to conclude that Model 1 fits the criteria best.

7.4 Summary

In this chapter there was a description on how the simulation runs were done, and what trials and process parameters were being monitored. All the results from the simulation are stored in appendix B. The AHP method was then used to systematically narrow the options down to one, best option. There was a detailed description on how the models were compared and how the objectives were compared to the models. The results can be seen in appendix C. Finally, a best model was found and then a sensitivity analysis was done on the model to see if any changes in the comparison would result in a change in the results, which was not the case. In the next chapter this result will be discussed in more detail.

8 CONCLUSION AND DISCUSSION

As stated at the beginning, the modelling and optimization of an aluminium casthouse is a difficult challenge with many things requiring consideration. This thesis has gone some way into detailing the process and has produced some interesting results.

When modelling a casthouse, the management team first needs to decide on a few constraints, such as budget, etc. Then the data gathering can start. The major factors that need to be looked at when gathering the data are the demand for products, metal purity, machine capacity, scrap rate, etc.

The market team found out that best products to produce were coils, foundry ingots, T-bars and sows and the purity needed would be P1020, or better, or alloyed.

The equipment selection team looked at capacity, product flexibility and scrap rate, etc. This resulted in a decision to look more closely at HDCs, rod mills and open mould castings.

The finance team then did a value analysis from those results, which ended with a decision to proceed with an HDC machine, a rod mill and a sow caster. Then a BIP model was constructed and four models were chosen to be analyzed further by simulation.

The models chosen for simulation were as follows:

- Model 1 : Three sow casters
- Model 2 : Two HDC casters and a sow caster
- Model 3 : Two sow casters and a rod mill
- Model 4 : Sow caster, HDC and a rod mill

Before those models could be simulated they had to be validated. In order to validate the results, measurements needed to be collected in a real-life situation, and the distribution found. Data was taken from the Alcoa Fjarðaál casthouse, which is set up like Model 4, but with an extra manual casting line. This means that the model validated was model four with an extra casting capacity. The model was validated through production numbers; both total produced and divided between each casting machine. It was also validated with a management review. When Model 4, with manual casting, had been validated it was assumed that the other three models were valid as well, for the distributions, routings and set-up shown in the validation phase.

The models were then simulated and the results from the simulation used as a basis for the AHP method.

The AHP method was used in order to select the best model. The objective was to find the best model with the criteria of cost, value, metal backlog, throughput, utilization of machines and product mix. Those elements were compared by a few managers at Alcoa Fjarðaál and that comparison was integrated into one comparison table. Then those elements were compared to each of the models, after which the result showed that **Model 1** was the best one and should be chosen. A sensitivity analysis was done to confirm that this was right. The sensitivity analysis showed that even though the biggest elements changed value, Model 1 remained the best one. In table 25 the results of the simulation on Model one with 85% efficiency and metal throughput of 360,000 tons per year can be seen. It is clear that there is almost no metal backlog and there is plenty of extra casting capacity on sow caster 1.

Table 26: Results of the simulation run on Model 1.

| Item | Average |
|------------------------------|-----------------|
| Throughput | 29.562 \pm 65 |
| Metal backlog | 190 \pm 64 |
| Utilization of sow caster #1 | 27% \pm 3% |
| Utilization of sow caster #3 | 81% \pm 1% |
| Utilization of sow caster #4 | 81% \pm 1% |
| Utilization of crane | 73% \pm 1% |

The management team agreed that the model seemed accurate and wanted to work further on it in order to obtain more information and look into more detailed issues at Alcoa Fjarðaál. The further issues that they would like to look at are, for instance:

- Is it possible to clean every crucible and not lose the flow of metal?
- How much can be pushed through the system?
- What does the model look like with another crane?
- What would happen with more evenly distributed arrival times? Would the models perform better or worse?
- What would it mean to have the amount of metal in a crucible closer to the 12.6 ton limit?
- Does the routing of the crucibles work or is there a better way?
- Will the plant have capacity to produce foundry?

It is also apparent that Model 4 will need further analyzing to see if the crane is a bottleneck in the model and, if so, is it a bottleneck in the other models as well? Therefore it would be of value to take another set of data of the crane in order to get a clear picture of the situation. Another thing that needs to be borne in mind is that the data was taken from a very young plant; the operators were still learning, the machines were not fully stable, etc. Therefore the model could be improved by collecting another set of data when the casthouse is “older”, and reanalyzing to see the difference. The results from Model 4 indicate that the casthouse at Alcoa Fjarðaál will always need extra manual lines in order to keep up with metal production unless the casthouse will be changed in some way such as getting another crane or casting machine.

Another big question is whether it will ever be possible to stop a continuous-producing casthouse at the end of a month, and have zero metal backlog, or is it an unrealistic goal? If not, what would be considered significant metal backlog and what not?

In order to achieve better and more accurate results in the future, there are certain things that need to be looked at be more carefully. In the value analysis stage, companies thinking of building a casthouse will get an offer from manufacturers for a machine or a range of machines – their decision would then vary depending on whether they wanted expensive machines with high production rates or cheaper machines with lower production rates. It is also possible that they will be offered a package deal of some sort by the manufacturers. Also, for the value analysis it is crucial to get as accurate information as possible, and, in real life, more accurate results than what have been presented in this thesis, could be obtained.

It is also strange that Model 3 gets higher metal backlog, as seen in table 21, than Model 2 but has theoretically more casting capacity as was seen in table 13. This tells us that Model 3 either has a bottleneck or the routing of metal was not good enough. It is possible to use other simulations to optimize the routing in order to get the most throughput. It might be interesting to try that for the models and compare the results.

The finance team is also supposed to be able to calculate the value in a much more detailed manner and come up with a product mix, not a machine mix, and they would certainly do some engineering economics calculations and analysis, like NPV or IRR analysis.

In the AHP section, it could have been better to use the Delphi approach to get the most accurate comparison from the managers, or at least have a group meeting with them in order to find a joint best solution. When the comparison was obtained from them it was on a one-on-one basis so they could not observe what the other managers thought, therefore some were thinking about the present situation and others about the future. It raises questions about what happens when a decision is not just numeric but also based on people's opinions.

They also felt that some of the elements being compared were too closely linked and it was not possible to select one over another – for instance cost and value. Next time, it might be useful to incorporate NPV, rate of return, benefit cost analysis, and payback period as was done by Mahmoodzadeh, Shahrabi and Zaeri (2007) who recommended using fuzzy AHP and TOPSIS technique. What was also interesting is that the managers suggested that location and labour should be a part of the evaluating criteria. They felt that the same model could not work in rural areas as in more urban ones because getting qualified labour would be more difficult in the rural areas, enforcing a less complex machinery selection. Regarding labour, Alcoa Fjarðaál's management team would like to have the comparison of what each machine needs in terms of labour – both operators and extra technical staff.

The good thing about the AHP method is that this can easily be changed in the spreadsheet and another solution found, if wished.

The BIP can be used to narrow down model selection with whatever constraints the management wants and therefore it is easily adaptable. Simulation is good in a way that the models are ready for use and can be modified with different numbers. The AHP method is also very adaptable to changes in the comparisons. Therefore these tools can be used further, even though the data or project changes.

9 FINAL WORDS

The aluminium manufacturing industry is huge and is here to stay since a material has not yet been found that has its properties, combined with a low price. This means there is a high demand for more functional and operational aluminium smelters and therefore it is very important to open up the discussion on what is important in the modelling and optimization phase of the construction of a smelter. This thesis aims to do exactly that, but does so with some limitations – accurate figures for cost and rate of return on investments are confidential in this highly competitive industry.

Even though there are some simplifications on calculations in the modelling phase, it succeeds in giving the reader an insight into what is important, what numbers need to be obtained and what to do with them.

What was surprising in the simulation phase was that any pre-conceptions about which model to choose were overturned when the trials were run. There is also always the possibility of analyzing them in more detail to uncover more about them.

It is, however, possible to use this thesis as a starting point for further investigation. Possibilities for future analysis could include:

- Reducing scrap rate; see how much the machines yield and calculate how much could be put into the furnaces.
- Connect the model more to finance - for instance cost per kg of produced metal
- Look at resource utilization.
- Look at distributions again when the plant is more stable – should changes be made?
- What would happen if crucibles were cleaned after every use?

So there are numerous possibilities which are only constricted by the imagination of the modeller and the design team. Remember – it is better to simulate 100 models and remove the bugs first, rather than rush into construction and risk having to make costly changes further down the line.

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APPENDIX A

Table A 1: BIP model

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | |
|--------------------------------|------|---------------|---------------|---------------|---------------------|---------------|-------|----------------|----------------|-------|------------|------|
| Model | 3 SC | 2 SC 1 HDC | 2 SC 1 ROD | 2 HDC 1 SC | 1 ROD 1 SC 1 HDC | 2 ROD 1 SC | 3 HDC | 2 HDC 1 ROD | 2 ROD 1 HDC | 3 ROD | | |
| Select model (1=YES) | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | Objective: | |
| Est. of value | | | | | | | | | | | | |
| Constraints: | | | | | | | | | | | | |
| Model capital all over 41 | | | | | | | | 1 | 1 | 1 | 0 | = 0 |
| Max cost 100 operating cost | 1 | | | | | 1 | | 1 | 1 | 1 | 0 | = 0 |
| 1 over 60 | 1 | 1 | 1 | | | | | | | | 1 | => 1 |
| 3 same machines | 1 | | | | | | 1 | | | | 2 | >= 1 |
| choose only 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | = 1 |
| | | | | | | | | | | | 4 | = 4 |
| | | | | | | | | | | LHS | Sign | RHS |

Table A 2: Data used in BIP model

| Machine | Capital cost [million] | operating cost per ton | extra each year | Value per ton | Scrap rate | % of total production |
|------------|------------------------------|---------------------------------|-----------------------|---------------|------------|--------------------------|
| Sow Caster | \$ X | \$ X | \$ X | \$ X | 0.50% | 62% |
| HDC | \$ X | \$ X | \$ X | \$ X | 1% | 35% |
| Rod Mill | \$ X | \$ X | \$ X | \$ X | 6% | 25% |

APPENDIX B

Table B 1: Results from simulation run for model 1 with 75% efficiency

| Model 1 - 75% efficiency on machines | | | | | | | |
|---|---------------------------------|--------------------------------|-----------------------------|---------------|---------------|--------|---------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] 75% | Metal backlog [tons per month] | Sow caster #1 | Sow caster #2 | Sow caster #3 | Cran e | Haule r |
| 180.000 | 14821.09 | 45.96 | 3.38 | 22.57 | 68.89 | 36.83 | NA |
| 270.000 | 22200.06 | 113.21 | 56.89 | 63.35 | 61.93 | 55.28 | NA |
| 360.000 | 29450.24 | 302.09 | 46.50 | 71.08 | 71.64 | 72.97 | NA |
| 450.000 | 32457.50 | 4745.88 | 65.27 | 71.17 | 71.99 | 80.92 | NA |

Table B 2: Results from simulation run for model 1 with 85% efficiency

| Model 1 - 85% efficiency on machines | | | | | | | |
|---|-----------------------------|--------------------------------|-----------------------------|---------------|---------------|-------|---------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] | Metal backlog [tons per month] | Sow caster #1 | Sow caster #2 | Sow caster #3 | crane | haule r |
| 180.000 | 14812.89 | 54.16 | 1.38 | 15.15 | 78.01 | 36.37 | NA |
| 270.000 | 22202.23 | 111.04 | 8.24 | 67.08 | 66.48 | 54.06 | NA |
| 360.000 | 29561.81 | 190.52 | 27.43 | 80.70 | 81.12 | 72.77 | NA |
| 450.000 | 35986.96 | 1216.42 | 67.62 | 81.08 | 82.25 | 88.96 | NA |

Table B 3:: Results from simulation run for model 1 with 95% efficiency

| Model 1 - 95% efficiency on machines | | | | | | | |
|---|---------------------------------|--------------------------------|-----------------------------|---------------|---------------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] 95% | Metal backlog [tons per month] | Sow caster #1 | Sow caster #2 | Sow caster #3 | crane | hauler |
| 180.000 | 14833.02 | 34.03 | 0.45 | 8.22 | 86.02 | 36.41 | NA |
| 270.000 | 22231.52 | 81.74 | 3.31 | 69.13 | 69.47 | 54.10 | NA |
| 360.000 | 30103.07 | 138.79 | 12.79 | 90.15 | 89.39 | 73.87 | NA |
| 450.000 | 36853.12 | 350.26 | 53.04 | 91.20 | 91.65 | 91.20 | NA |

Table B 4: Results from simulation run for model 2 with 75% efficiency

| Model 2 - 75% efficiency on machines | | | | | | | |
|---|---------------------------------|--------------------------------|-----------------------------|-------|------------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] 75% | Metal backlog [tons per month] | HDC 1 | HDC 2 | Sow caster | Crane | Hauler |
| 180.000 | 14.623.05 | 252.41 | 9.01 | 71.05 | 36.48 | 43.23 | 0.40 |
| 270.000 | 21.953.36 | 359.68 | 54.55 | 72.66 | 49.73 | 64.92 | 0.62 |
| 360.000 | 27.237.62 | 2.520.09 | 74.63 | 74.61 | 71.78 | 77.20 | 9.25 |
| 450.000 | 26.165.81 | 11.031.72 | 75.78 | 75.28 | 72.24 | 54.66 | 54.32 |

Table B 5: Results from simulation run for model 2 with 85% efficiency

| Model 2 - 85% efficiency on machines | | | | | | | |
|---|-----------------------------|--------------------------------|-----------------------------|-------|------------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] | Metal backlog [tons per month] | HDC 1 | HDC 2 | Sow caster | crane | hauler |
| 180.000 | 14.658.02 | 218.56 | 5.36 | 78.09 | 33.94 | 43.58 | 0.42 |
| 270.000 | 22.010.57 | 302.86 | 41.38 | 83.09 | 51.76 | 64.88 | 0.64 |
| 360.000 | 29.174.34 | 576.94 | 81.46 | 83.75 | 69.27 | 86.11 | 0.99 |
| 450.000 | 31.017.37 | 6.185.70 | 85.35 | 85.96 | 83.57 | 73.08 | 36.20 |

Table B 6: Results from simulation run for model 2 with 95% efficiency

| Model 2 - 95% efficiency on machines | | | | | | | |
|---|-----------------------------|--------------------------------|-----------------------------|-------|------------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] | Metal backlog [tons per month] | HDC 1 | HDC 2 | Sow caster | crane | hauler |
| 180.000 | 14666.94 | 208.94 | 2.19 | 80.97 | 33.98 | 43.77 | 0.30 |
| 270.000 | 22017.78 | 293.90 | 25.54 | 91.10 | 57.32 | 64.16 | 0.57 |
| 360.000 | 29284.44 | 465.60 | 88.03 | 91.41 | 58.48 | 87.83 | 0.67 |
| 450.000 | 33435.45 | 3767.05 | 91.24 | 92.62 | 84.95 | 93.08 | 9.81 |

Table B 7: Results from simulation run for model 3 with 75% efficiency

| Model 3 - 75% efficiency on machines | | | | | | | |
|---|-----------------------------|--------------------------------|-----------------------------|---------------|-------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] | Metal backlog [tons per month] | Sow caster #1 | Sow caster #2 | ROD | Crane | Hauler |
| 180.000 | 14599.32 | 272.53 | 40.52 | 16.34 | 72.95 | 39.00 | 1.30 |
| 270.000 | 21843.98 | 473.83 | 50.97 | 53.37 | 72.78 | 54.71 | 4.10 |
| 360.000 | 26399.93 | 3348.03 | 65.52 | 67.15 | 74.35 | 61.25 | 11.35 |
| 450.000 | 26732.14 | 10469.36 | 65.96 | 67.62 | 74.63 | 60.33 | 11.79 |

Table B 8: Results from simulation run for model 3 with 85% efficiency

| Model 3 - 85% efficiency on machines | | | | | | | |
|---|-----------------------------|--------------------------------|-----------------------------|---------------|-------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] | Metal backlog [tons per month] | Sow caster #1 | Sow caster #2 | ROD | crane | hauler |
| 180.000 | 14623.67 | 248.18 | 41.39 | 11.06 | 81.53 | 39.90 | 1.06 |
| 270.000 | 21936.42 | 381.38 | 50.32 | 49.25 | 81.85 | 56.71 | 2.45 |
| 360.000 | 28344.43 | 1403.53 | 70.70 | 70.38 | 82.46 | 69.73 | 6.61 |
| 450.000 | 29541.73 | 7659.77 | 73.63 | 72.88 | 83.43 | 70.58 | 8.54 |

Table B 9: Results from simulation run for model 3 with 95% efficiency

| Model 3 - 95% efficiency on machines | | | | | | | |
|---|-----------------------------|--------------------------------|-----------------------------|---------------|-------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] | Metal backlog [tons per month] | Sow caster #1 | Sow caster #2 | ROD | crane | hauler |
| 180.000 | 14627.22 | 244.63 | 40.31 | 7.52 | 90.18 | 40.28 | 1.05 |
| 270.000 | 21972.57 | 345.23 | 47.85 | 46.93 | 90.80 | 58.11 | 1.58 |
| 360.000 | 29126.06 | 621.89 | 70.54 | 70.89 | 91.12 | 75.71 | 2.39 |
| 450.000 | 31915.44 | 5286.06 | 78.67 | 79.28 | 91.54 | 82.12 | 2.73 |

Table B 10: Results from simulation run for model 4 with 75% efficiency

| Model 4 - 75% efficiency on machines | | | | | | | |
|---|-----------------------------|--------------------------------|-----------------------------|-------|-------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] | Metal backlog [tons per month] | Sow caster #1 | HDC | ROD | Crane | Hauler |
| 180.000 | 14560.87 | 317.79 | 36.17 | 64.87 | 21.42 | 41.92 | 0.81 |
| 270.000 | 21441.12 | 550.45 | 52.63 | 68.35 | 66.39 | 61.73 | 1.07 |
| 360.000 | 23505.53 | 6251.03 | 62.70 | 71.94 | 71.03 | 67.12 | 1.36 |
| 450.000 | 23522.68 | 13679.49 | 62.58 | 71.99 | 70.69 | 67.17 | 1.79 |

Table B 11: Results from simulation run for model 4 with 85% efficiency

| Model 4 - 85% efficiency on machines | | | | | | | |
|---|-----------------------------|--------------------------------|-----------------------------|-------|-------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] | Metal backlog [tons per month] | Sow caster #1 | HDC | ROD | crane | hauler |
| 180.000 | 14583.17 | 285.90 | 35.83 | 69.11 | 15.97 | 42.15 | 0.76 |
| 270.000 | 21838.43 | 474.90 | 48.38 | 77.30 | 72.71 | 64.08 | 1.21 |
| 360.000 | 25539.38 | 4224.46 | 66.11 | 79.38 | 79.90 | 73.05 | 2.00 |
| 450.000 | 25645.48 | 11559.11 | 66.07 | 79.55 | 80.37 | 73.56 | 1.73 |

Table B 12: Results from simulation run for model 4 with 95% efficiency

| Model 4 - 95% efficiency on machines | | | | | | | |
|---|-----------------------------|--------------------------------|-----------------------------|-------|-------|-------|--------|
| | | | Utilization of machines [%] | | | | |
| Size of smelter [tons per year] | Throughput [tons per month] | Metal backlog [tons per month] | Sow caster #1 | HDC | ROD | crane | hauler |
| 180.000 | 14587.42 | 282.56 | 36.18 | 73.33 | 8.91 | 42.00 | 0.68 |
| 270.000 | 21873.51 | 441.41 | 45.48 | 84.36 | 67.92 | 64.48 | 1.04 |
| 360.000 | 27107.31 | 2642.08 | 68.48 | 86.47 | 85.22 | 78.53 | 1.42 |
| 450.000 | 27268.19 | 9929.58 | 68.59 | 86.94 | 84.86 | 78.43 | 1.55 |

Table B 13: Input parameters for arrival times

| | Month | Day | hour | Crucible weight | Parameter |
|---------|-------|---------|-------|-----------------|-----------|
| | 12 | 30 | 24 | 11.00 | 60 |
| 180.000 | 15000 | 500.00 | 20.83 | 1.89 | 31.68 |
| 270.000 | 22500 | 750.00 | 31.25 | 2.84 | 21.12 |
| 360.000 | 30000 | 1000.00 | 41.67 | 3.79 | 15.84 |
| 450.000 | 37500 | 1250.00 | 52.08 | 4.73 | 12.67 |

APPENDIX C

Table C 1: AHP model for the criteria comparison

| | Estm. Cost | Estm. Value | Metal back log | Utilization of machines | Throughput | Product mix |
|--------------------------------|-------------------|--------------------|-----------------------|--------------------------------|-------------------|--------------------|
| Estm. Cost | 1.00 | 3.00 | 0.11 | 1.00 | 0.33 | 0.33 |
| Estm. Value | 0.33 | 1.00 | 0.11 | 5.00 | 0.33 | 3.00 |
| Metal backlog | 9.00 | 9.00 | 1.00 | 9.00 | 9.00 | 9.00 |
| Utilization of machines | 1.00 | 0.20 | 0.11 | 1.00 | 0.20 | 1.00 |
| Throughput | 3.00 | 3.00 | 0.11 | 5.00 | 1.00 | 1.00 |
| Product mix | 3.00 | 0.33 | 0.11 | 1.00 | 1.00 | 1.00 |

Table C 2: Models compared on cost

| Estm Cost | Model 1 | Model 2 | Model 3 | Model 4 |
|------------------|----------------|----------------|----------------|----------------|
| Model 1 | 1.00 | 6.00 | 7.00 | 9.00 |
| Model 2 | 0.17 | 1.00 | 1.00 | 5.00 |
| Model 3 | 0.14 | 1.00 | 1.00 | 5.00 |
| Model 4 | 0.11 | 0.20 | 0.20 | 1.00 |

Table C 3: Models compared on value

| Estm Value | Model 1 | Model 2 | Model 3 | Model 4 |
|-------------------|----------------|----------------|----------------|----------------|
| Model 1 | 1.00 | 0.17 | 0.20 | 0.11 |
| Model 2 | 6.00 | 1.00 | 1.00 | 0.33 |
| Model 3 | 5.00 | 1.00 | 1.00 | 0.25 |
| Model 4 | 9.00 | 3.00 | 4.00 | 1.00 |

Table C 4: Models compared on Metal backlog

| Metal backlog | Model 1 | Model 2 | Model 3 | Model 4 |
|----------------------|----------------|----------------|----------------|----------------|
| Model 1 | 1.00 | 3.00 | 5.00 | 9.00 |
| Model 2 | 0.33 | 1.00 | 3.00 | 5.00 |
| Model 3 | 0.20 | 0.33 | 1.00 | 5.00 |
| Model 4 | 0.11 | 0.20 | 0.20 | 1.00 |

Table C 5: Models compared on utilization

| Utilization of machines | Model 1 | Model 2 | Model 3 | Model 4 |
|--------------------------------|----------------|----------------|----------------|----------------|
| Model 1 | 1.00 | 0.20 | 0.33 | 3.00 |
| Model 2 | 5.00 | 1.00 | 3.00 | 7.00 |
| Model 3 | 3.00 | 0.33 | 1.00 | 5.00 |
| Model 4 | 0.33 | 0.14 | 0.20 | 1.00 |

Table C 6: Models compared on throughput

| Throughput | Model | | | |
|-------------------|--------------|------|---------|---------|
| | Model 1 | 2 | Model 3 | Model 4 |
| Model 1 | 1.00 | 5.00 | 7.00 | 9.00 |
| Model 2 | 0.20 | 1.00 | 3.00 | 5.00 |
| Model 3 | 0.14 | 0.33 | 1.00 | 3.00 |
| Model 4 | 0.11 | 0.20 | 0.33 | 1.00 |

Table C 7: Models compared on product mix

| Product mix | Model | | | |
|--------------------|--------------|------|---------|---------|
| | Model 1 | 2 | Model 3 | Model 4 |
| Model 1 | 1.00 | 0.20 | 0.33 | 0.11 |
| Model 2 | 5.00 | 1.00 | 3.00 | 0.33 |
| Model 3 | 3.00 | 0.33 | 1.00 | 0.17 |
| Model 4 | 9.00 | 3.00 | 6.00 | 1.00 |

Table C 8: Matrices of scores

| Matrix of scores | Est. Cost | Est. Value | Metal backlog | Utilization of machines | throughput | Product mix |
|-------------------------|-------------|-------------|---------------|-------------------------|-------------|-------------|
| Model 1 | 0.661621874 | 0.044427237 | 0.565837769 | 0.121872613 | 0.642681527 | 0.050224196 |
| Model 2 | 0.149491327 | 0.209318577 | 0.249844474 | 0.557892475 | 0.208274867 | 0.248896286 |
| Model 3 | 0.145301383 | 0.185118733 | 0.138461671 | 0.263345111 | 0.101043911 | 0.110104637 |
| Model 4 | 0.043585416 | 0.561135454 | 0.045856086 | 0.056889801 | 0.047999695 | 0.590774881 |

Table C 9: The weighted score of the criteria elements

| Element | Value |
|-------------------------|--------------|
| Estm. Cost | 0.058 |
| Estm. Value | 0.086 |
| Metal backlog | 0.494 |
| Utilization of machines | 0.038 |
| Throughput | 0.115 |
| Product mix | 0.066 |

Table C 10: Comparison of elements from individual manager

| A | B | More important | Intensity | More important | Intensity | More important | Intensity | More important | Intensity |
|----------|----------|-------------------|-----------|-------------------|-----------|-------------------|-----------|-------------------|-----------|
| Cost | Value | A and B | 1 | B | 7 | B | 5 | A and B | 1 |
| Cost | Metal b. | B | 9 | B | 9 | B | 9 | B | 9 |
| Cost | Utiliz. | A | 7 | B | 5 | B | 7 | A | 5 |
| Cost | Through. | B | 7 | B | 7 | B | 5 | B | 3 |
| Cost | P.mix | B | 7 | B | 7 | B | 7 | A | 5 |
| Value | Metal b. | B | 9 | B | 9 | B | 9 | B | 9 |
| Value | Utiliz. | A | 8 | A | 6 | A | 5 | A | 5 |
| Value | Through. | A | 7 | B | 6 | B | 7 | B | 3 |
| Value | P.mix | A | 7 | B | 7 | A and B | 1 | A | 3 |
| Metal b. | Utiliz. | A | 9 | A | 9 | A | 9 | A | 7 |
| Metal b. | Through. | A | 9 | A | 9 | A | 9 | A | 9 |
| Metal b. | P.mix | A | 9 | A | 9 | A | 9 | A | 9 |
| Utiliz. | Through. | B | 7 | B | 6 | B | 5 | B | 5 |
| Utiliz. | P.mix | A | 8 | B | 6 | A | 7 | B | 3 |
| Throu. | P.mix | B | 6 | B | 6 | A | 7 | A | 5 |