Concept Development to Control Non-value Added Logistical Costs in a Primary Aluminium Casthouse by Interfacing Linear Optimization and Simulation

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Gökay Ilgin
aus
Kirklareli, der Türkei

Gutachter: Univ.-Prof. Dr.-Ing. Bernd Noche
Univ.-Prof. Dr.-Ing. Thomas Steinhäuser

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Abstract

After the financial crisis in 2008, demand reduction especially from the automotive industry and changes in CO_2 tax regulations which increased the energy prices the aluminium industry forced to review and reduce its operational expenditure. High energy consumption in the production of primary aluminium dedicates most of the efforts on technological development onto the electrolysis unit. However, other units of a smelter also have the potential to improve their operational efficiency. In this thesis, the focus is on the casthouse unit of the smelter. The aim of this research is to quantify and reduce the non-value added logistical costs in the aluminium industry's supply chain. This research attempts to simulate the internal supply chain of a primary aluminium casthouse and identify the wastes by implementing a lean thinking approach. After highlighting the possible improvements, optimization models attempt to reduce these wastes which create non-value added costs to the system. This concept is further developed by interfacing the simulation model with the optimization model to validate the improvements. The success of the concept is tested by measuring the reduction in redundant logistical costs of a case study founded on the real casthouse specifications. Scenarios are defined to analyze the casthouse supply chain under different perspectives. The potential gain of the new concept is verified by applying it to these scenarios. In conclusion, the results analysis of the scenarios indicates the success of the main objective of this research; to develop a new concept that controls the non-value added logistical costs in the primary aluminium casthouse supply chain.

Keyword: Primary aluminium casthouse, supply chain analysis, lean thinking, logistics simulation, linear optimization

This thesis is dedicated to

My Daughter

&

My Wife

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1 Introduction

Before the financial crisis in 2008, the ultimate goal of industry was to increase the sales and also the production amount. Nowadays, the direction of the storm changes to reduce the operational expenditure to find a place in the shrinkage of the market share with lower sales price.

The aluminium industry has also been influenced from this unstable economic situation. Tremendous decrease of demand in the automotive industry increased the stock levels of aluminium in the last four years. And also the gap between high supply and low demand reduced the sales price of aluminium.

In addition to effects of the financial crisis, CO_2 tax regulations due to its environmental impact increased the energy prices day by day. Besides that, inevitable growth of aluminium production in China creates big challenges in the aluminium industry, especially in Europe.

The technological developments in aluminium industry focus on how to reduce the production costs. Energy consumption forms the main part of these costs due to high energy prices. Therefore, the production process is tried to be optimized so that it consumes less energy. However it is also recognized that logistical activities in the facilities have a potential for improvement.

The main focus of this research is the development of a concept that controls the logistical activities creating extra unpredictable costs in a part of the primary aluminium supply chain. In a smelter concept, the electrolysis first comes into the mind because the actual production process takes place in this sub facility. However, the selected unit of smelter for this research is the casthouse area due to its potential for improvement in logistical perspective and its direct contact to the external customer which brings more challenge for the investigation.

In this chapter, at the first, the fundamental concepts of the thesis are discussed, then, the research motivation and the objective of the research are described. Finally, the outline of the thesis is presented.

1.1 Introduction to Fundamental Concepts of the Thesis

The fundamental concepts of the thesis contain

- supply chain as a focus area,
- primary aluminium casthouse as a core concept,
- discrete event simulation as an analyzing tool and
- linear optimization as an improvement method.

Definitions and introduction to these basic concepts are given in this subchapter.

1.1.1 Supply Chain in General

Business interest has been aroused toward supply chain concept since the 1980's after recognizing its benefits on the company performance according to Braziotis [Bra10]. The term was ill-defined before 1990's. Academic researchers and the companies have approached to supply chain delicately since 20 years. It has become a crucial concept for industry to survive in the competitive environment [ARA10].

Beamon [Bea98] defined supply chain *as "an integrated process wherein a number of various business entities work together in an effort to acquire raw materials, convert these raw materials into specified final products, and deliver these final products to retailers"*.

Mentzer et.al. [MDKMNSZ01] enlarged the definition by adding service, finance and information in addition to product flow. They defined supply chain as *"a set of three or more entities (organizations or individuals) directly involved in the upstream and down-*

stream flows of products, services, finances, and/or information from a source to a customer."

The term "supply chain" has still various definitions depending on its boundary. Figure 1 shows different supply chain definitions and their boundaries. Direct supply chain contains organization with its direct customers and suppliers. In this thesis, the supply chain concept refers to material and information flow of the center facility. Both of the flows start from the direct supplier and end with the direct customer. This kind of supply chain is also called internal supply chain by Harland [Har99].

Extended version of the supply chain enlarges the boundary with supplier's supplier and customer's customer. Financial provider supplying financial support and evaluating the possible financial risks, market search firm providing detailed analysis about ultimate customers and third party logistics (3PL) handling the logistical activities between organization and its customer are included in the ultimate supply chain boundary by Mentzer et.al. [MDKMNSZ01].

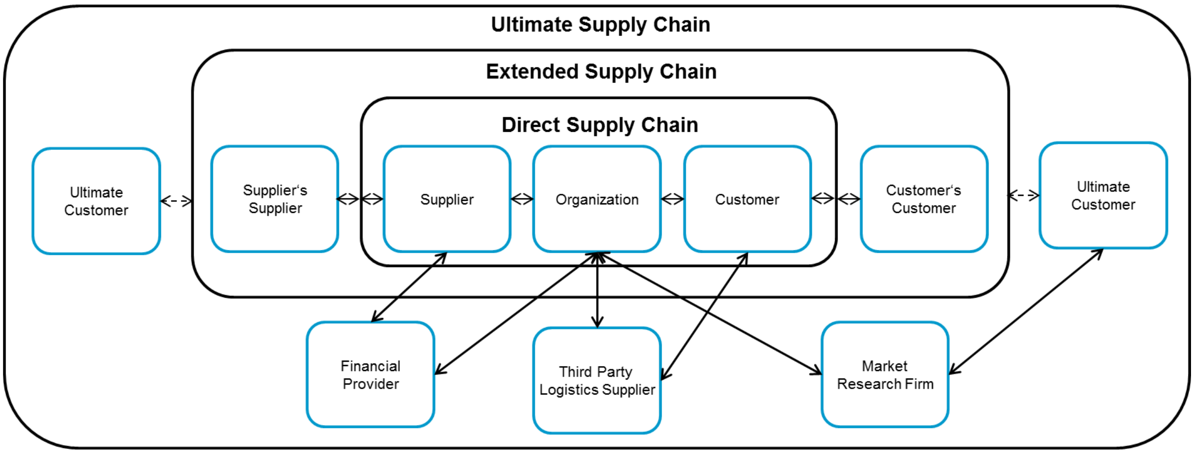

Figure 1 Different supply chain definitions and their boundaries [MDKMNSZ01]

According to Buxmann et. al [BADW04] the major objectives of supply chain studies are listed in Table 1. Most of these objectives, such as reduction in lead time, in inventory, transportation costs and improvement in service levels, create the focus area of supply chain optimization concept of the research.

Major Objectives	Authors and Year of the Study
Reduction in production costs	Heizer & Render (1999), Morton (1999), Shim & Siegel (1999), Waller (1999), Stevenson (2002)
Reduction in lead time	Markland et al . (1998)
Reduction in inventory	Baganha & Cohen (1998), Ho (1999), Waller (1999), Helms et al . (2000), Simchi-Levi et al . (2000), Toomey (2000)
Reduction in transportation costs	Ballou (1999), Toomey (2000)
Reduction in purchase costs	Simchi-Levi et al . (2000), Monczka et al . (2001)
Improvement in supplier evaluation and selection	Christopher & Jüttner (2000), Monczka et al . (2001)
Improvement in service levels	Simchi-Levi et al . (2000), Knolmayer et al . (2002), Tan (2002)
Improvement in cooperation	Lee et al . (1997)

Table 1 The major objectives of supply chain studies [BADW04]

1.1.2 Aluminium Smelter Casthouse

Aluminium cannot be found as an element in nature due to its chemical characteristics. Its raw material alumina is refined from bauxite which is extracted from the earth. Aluminium has been produced since the beginning of 1900's in industrial range. However, the total demand of the industry is increasing continuously. Figure 2 shows the primary aluminum production capacity per country and the capacity increase in the last 10 years which is around "15 Mt/a".

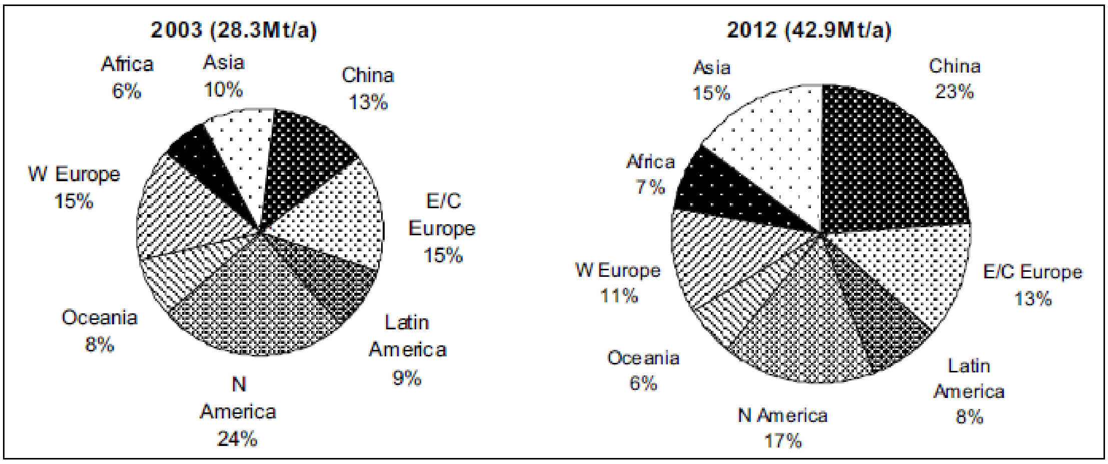

Figure 2 Primary aluminium production capacity in the last 10 years [HKK07]

Aluminium is mostly used in industrial fields such as construction, transportation, packaging etc. The increase in aluminium demand is driven by its advantageous properties some of which are listed as:

- Strong and light
- Highly corrosion resistant
- Good conductive
- Easy to form and process
- Recyclable

Aluminium production can be categorized into primary and secondary smelting. Secondary aluminium production is also called recycling. The steps in aluminium production and its life cycle are shown on Figure 3. In this thesis, the focus is on primary smelting part in which aluminium is produced by processing alumina.

The facility called smelter is normally composed of three sub facilities:

- Carbon plant; supplies anodes to the electrolysis unit
- Electrolysis (pot room); contains reduction cells where the primary aluminium is produced

- Casthouse; casts the hot metal transported from the electrolysis as ingots for further processing.

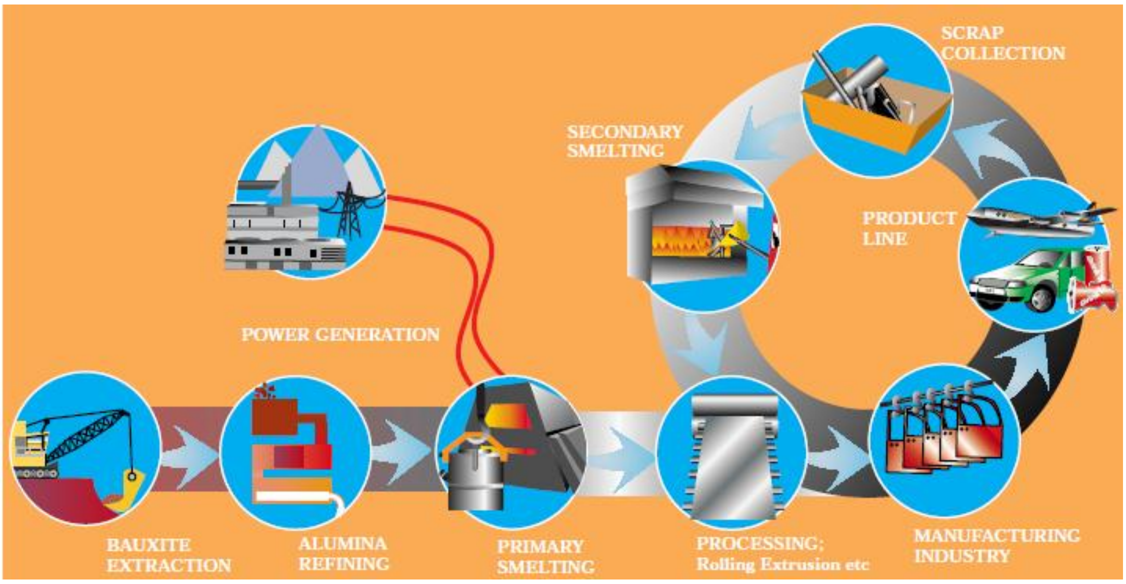

Figure 3 Aluminium production and life cycle [IAI03]

The casthouse facility contains casting furnaces which enable mixing the metal with various alloys to meet the customer specifications. Casting furnaces may also melt the aluminium scrap depending on the quality requirements. The casthouse stands at the last chain of the primary aluminium production. It supplies primary hot metal from electrolysis, alloy and cold metal (pure aluminium ingots and scrap metal) from the suppliers. Possible customers of the casthouse are rolling or extrusion plants which process the aluminium ingots or slabs for further manufacturing industries.

1.1.3 Discrete Event Simulation

Simulation is imitating a real-world process or system by analyzing its behavior asking “what-if” questions [Ban04]. In this research, the system represents a group of entities such as vehicles, resources, materials etc. The dynamic simulation model concept is split into two sub groups which are called continuous flow simulation and discrete event simulation.

A discrete event simulation differs from continuous flow simulation by sequencing the events according to their occurrence time which requires having discrete simulated time points. According to Schriber et. al. [SB10] these event happening times may overlap at the same time, and then these "simultaneous" movements of traffic are simulated by manipulating this train of events serially at that instant. Continuous flow simulation in that context represents the cases mapping the flow of liquid materials. It is possible to approach continuous flow problems with discrete event concept which brings some limitations described by Damiron et. al. [DN08] as:

- Execution speed of the model slows down due to the many events created to map the level of flow discretely
- Model becomes more complicated than necessary due to the definition of many events
- The accuracy of the system never reaches 100% due to the prediction of continuous flow change over time

Mason et. al. [MRFK03] discussed the possibility of information flow mapping next to the flow of goods in the models, which increases the range of discrete event simulation usage. Babulak et. al. [BW10] (quoted from Wang, Sun and Nooh (1995)) listed the application fields of discrete event simulation as:

- New manufacturing processes, at the design and evaluation phase
- Existing processes, to improve the performance
- Operational area, to establish optimum policies
- Production field, to support planning and scheduling

In this research, the discrete event simulation method is selected to analyze the cast-house supply chain.

1.1.4 Linear Optimization

Linear optimization is a mathematical method which specifies the optimum solution of the problem that is formulated in linear equation. The aim of the linear optimization is to find the maximum or the minimum value of the equation in the defined feasible region. The elements in the linear optimization are defined by Chinneck [Chi01] as:

- Variables: represent the items that can be adjusted to find the optimum solution of the linear problem
- Objective function: sets the goal of problem by combining the variables. Its mathematical equation must be in linear form.
- Constraints: draw the limits of the feasible region. These mathematical expressions have to be linear.
- Variable bounds: represents the range of values of the variables

Standard representation of linear optimization is [Fer12]:

$$\max \quad c_1x_1 + c_2x_2 + \ldots + c_nx_n \tag{1.1}$$

$$\begin{aligned} \text{subject to} \quad & a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n \le b_1 \\ & \ldots \\ & a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n \le b_m \end{aligned} \tag{1.2}$$

$$\text{and} \quad x_1 \ge 0, \ldots, x_n \ge 0 \tag{1.3}$$

The objective function is represented as maximization problem in Equation (1.1). This is the primal definition of the problem. Each linear programing problem has duality. In this case the dual problem is expressed as minimization of Equation (1.1) by changing the coefficients of the constraints, the inequalities of which are shown in Equation (1.2). The variables of the objective function and their bounds are formulated in Equation (1.3).

Several methods are developed to solve the linear programming problem. The algorithms developed for linear programming (such as the simplex algorithm, the ellipsoid algorithm, interior-point method etc.) are defined, compared and examined in detail in the literature [DD09], [Tod01], [HMSW53] and [Meg91]. In this research, the integer linear method is selected as a solution algorithm for the linear programming in which all of the variables must have integer values.

1.2 Research Motivation

During more than four years of professional experience in one of the world's three leading integrated aluminium companies, it is recognized that the technological focus in the aluminium industry is on the electrolysis unit. There are several valid reasons for that, such as:

- Electrolysis has still potential in its production division for improvement
- Energy consumption in electrolysis unit forms ~ 25 % of the production cost
- Complex operation techniques

The author has been working as a project engineer in the technology department and is responsible for development of simulation models. These studies enable him to analyze each operational field in aluminium smelter. Possible improvement in the casthouse from the logistical point of view aroused his interest.

As mentioned, the trend in aluminium industry is to reduce the production costs rather than increase the production amount due to actual market conditions. Therefore, the focus of the research should have been to reduce the redundant logistical costs in aluminium casthouse facility. Lack of literature on this concept and the potential on improvement of logistical activities in casthouse have generated strong motivation.

1.3 Research Objectives

The main objective of this research is to develop a new concept that controls the non-value added logistical costs in primary aluminium casthouse supply chain. The following objectives have to be accomplished in this research to reach this goal:

- Identification of material and information flow in the primary aluminium casthouse internal supply chain.
- Drawing of the supply chain boundary by considering the close interaction with the possible suppliers and customers.
- Development of flexible discrete event simulation model which can be implemented to most casthouses easily by modifying some parameters.
- Analysis of casthouse supply chain with the simulation model and identification of non-value added logistical costs.
- Discovering the reasons of the non-value added logistical costs by approaching to the concept with the lean thinking method.
- Development of linear optimization model reducing these redundant logistical costs by planning the production and scheduling the processes in the casthouse.
- Interfacing the simulation model with the optimization model to increase the accuracy of the optimization part.
- Verifying the gain from the new concept by implementing it to the case study founded on the real casthouse specifications

1.4 Outline of the Thesis

The outline of the thesis follows a similar path like the sequence of steps in a simulation model programming. Firstly, previous studies are examined to define the problem in a better way, secondly the data about the studied system is collected, and then the programming phase is executed. As a next step, a case study to test the models is prepared for verification and then the evaluation phase takes place. Finally, the conclusion of the results is discussed and the further follow-ups are defined.

Chapter 1 starts with giving a short description of the fundamental concepts of the thesis. The motivation for the concept is described and the objective of the thesis is set. At the end of the chapter the roadmap of the thesis is drawn and the content of each chapter is shortly explained.

Chapter 2 contains the literature survey on the main concepts of the thesis. The research topics are supply chain simulation, optimization and possible interface between these two models. Lean thinking approach and lot sizing problem definition can also be found in this chapter.

Chapter 3 provides extensive knowledge about the primary aluminium production. The smelter concept and its units are introduced. This chapter also contains the description of a primary casthouse and its internal supply chain which is the core concept of the research.

Chapter 4 explains the simulation model mapping of the material flow in primary aluminium casthouse. The strategies behind the control logic and the main parts of the simulation model are elaborated. The programming approach enabling to handle the problem in the simulation environment is explained in detail.

Chapter 5 highlights the logistical wastes of the casthouse supply chain by evaluating the results gathered from the simulation model. The lean thinking approach application to the primary aluminium casthouse and its possible outcomes are explained in this chapter.

Chapter 6 contains the optimization part of the thesis. The optimization models created to reduce the non-value added costs in the casthouse internal supply chain are presented. The interface between the simulation model and the optimization tools are also explained in this chapter.

Chapter 7 expresses the case study created to verify and test the models and their interfacing. All of the required details of the case are highlighted and also assumptions for the models are listed.

Chapter 8 evaluates the results of both the simulation and the optimization models. Scenarios analyzing the casthouse supply chain in different perspectives are described and the results obtained for each scenario are compared. Possible conclusion is drawn for each case that is created to reduce the non-value added costs occurring due to logistical activities in the casthouse.

Chapter 9 concludes the study by reminding the problem and presenting the outcome of the evaluations. Additionally, recommendations for further development alternatives are also listed in this chapter.

2 Literature Review

In this chapter, literature about main concepts of this thesis is reviewed. This includes simulation studies done for different material flow principles, supply chain optimization, possible approaches for the improvement phase and interfacing methods of simulation and optimization models.

2.1 Introduction

A plenty of literature exist where simulation and optimization concepts are integrated into supply chain investigation. Nowadays, simulation tools provide opportunities to make parameter variations during the simulation run. These investigations are mostly based on sensitivity analysis of the selected variable or variables of the system. Existing approaches combining simulation and optimization are reviewed in the thesis.

Environmental aspects and challenges in technological development force the metal industry to optimize its supply chain to stay competitive. Therefore, as an application field not only aluminium but also other metal production industries (like steel foundry) are investigated during this review. Casthouse has a common concern in the metal production because the casting process and the furnace show similarities in different industrial fields. A specific literature review of simulation and optimization applications to casthouse field is discussed at the beginning of their corresponding chapters (Chapter 4 and 6).

2.2 Literature about Supply Chain Simulation

Supply chain simulation is an analyzing method that experimentally shows the system characteristics of supply chain. The possible objectives of supply chain simulation are defined by Campuzano et. al. [CM11] as:

- Providing supply chain knowledge
- Giving ideas to improve the system
- Creating and verifying the alternative strategies
- Quantifying improvements of supply chain management

Ganeshan et. al. [GH95] integrated comprehensive supply chain in the application fields of simulation by paying attention to strategic and operational elements. Within the context of analyzing complex supply chains via simulation approach, the following advantages were summarized by Tompkins et.al [TS98]:

- Simulation helps to design and analyze the complex internal interactions of specified or existing systems.
- Before implementing the material handling equipment on the actual system, the effects of the changes can then be tested via simulation.
- By creating different scenarios, simulation is used to answer the “what if” questions in analysis and design.
- There are risks to make experiments on the real system; thus the simulation model can help to prepare decision rules and policies about how to operate the real system.
- The time frame can be changed in the simulation approach, by compressing or expanding.
- The bottleneck of the production facility can be seen identified by the help of the simulation model.
- The statistical analysis of introducing new machines to the system or changing the current production line can be obtained.

- With some simulation software the 3D view of the model environment can be presented.

After recognizing the benefits of simulation in supply chain analysis, a lot of research and study were done. Banks et. al. [BBJLM02] discussed the opportunities of simulation in supply chain analysis and the possible application fields in detail. Zeigler et. al. [ZKB99] described the benefit of supply chain simulation as helping companies to determine which strategies will provide the most flexible and profitable operating environment. Capability of capturing uncertainty and complexity [JWCEL01] enables to analyze any kind of system with simulation. Kovacs et. al. [KVKMP03] listed the possible types of uncertainties mapped in simulation environment as:

- Start time uncertainty
- Downtimes
- Processing time
- Re-work and adjustment
- Quality uncertainty

Kleijnen [Kle05] described the characteristics of the simulation models as; quantitative, mathematical and dynamic computer models having at least one equation with one variable.

Commercial simulation tools with different features and application areas have been released in recent years. They have been used widely in the supply chain research. Some examples of these software and studies done by using them are; SimFlex [WG03], Arena [SB99], e-SCOR [BM00], ProModel [Ben97], LOGSIM [Hie98], Witness [WHP98], SISCO [CHH06]. In this thesis the simulation tool Automod, the detailed information of which is shown in Figure 4, is used to analyze the internal supply chain of aluminium casthouse. The type of the simulation model in this study can be considered as a production and distribution based simulation approach as one of the simulation approaches classified by Tumay [Tum96].

Figure 4 Automod simulation software

2.3 Literature about Supply Chain Optimization

Optimal supply chain becomes challenging and demanding for nearly each industry which is under pressure to stay competitive in the global markets. In optimization task, the aim is to find the best solution and decision among several alternatives. Voss et.al. [VW03] analyzed the supply chain optimization in detail and described possible methods to overcome the planning problems occurred in the production phase.

Beamon [Bea98] made a literature survey about the tools and their criteria to evaluate and improve the supply chain, which can be seen on Figure 5. Lakhal et. al. [LMKO01] described a supply chain strategy which maximizes the value added in internal activities.

Author(s)	Model Types				Performance Measures			Decision Variables		
	Deterministic Analytical	Stochastic Analytical	Economic	Simulation	Cost	Activitiy Time	Flexibility	Production/Distribution Scheduling	Inventory Levels	Plant- Product Assignment
Altiok and Ranjan (1995)		X			X				X	
Amtzen, et. al. (1995)	X				X	X		X	X	X
Camm, et. al. (1997)	X				X					
Cohen and Lee (1988)		X			X				X	
Cohen and Lee (1989)	X				X			X	X	
Cohen and Moon (1990)	X				X			X		
Ishii, et. al. (1988)	X				X			X	X	
Lee and Billington (1993)		X							X	
Lee and Feitzinger (1995)		X			X					
Lee, et. al. (1993)		X			X				X	
Lee, et. al. (1997)		X			X				X	
Pyke ynd Cohen (1993)		X			X				X	
Pyke ynd Cohen (1994)		X			X				X	
Newhart, et. al. (1993)	X				X				X	
Svoronos and Zipkin (1991)		X			X				X	
Towill (1991)				X	X				X	
Towill, et. al. (1992)				X	X				X	
Towill and Del Vecchio (1994)	X								X	
Tzafestas and Kapsiotis (1994)	X				X				X	
Voudouris (1996)	X						X	X	X	
Williams (1981)	X				X			X		
Williams (1983)	X				X			X		
Wikner, et. al. (1991)				X	X				X	

Figure 5 Literature review on supply chain optimization (extracted from [Bea98])

Ten Hompel et.al. [HS07] classified the optimization problem as;

- Maximization problem; the best result with the defined expenditure
- Minimization problem; the defined result with the minimum expenditure
- Dual problem; the optimal result with the possible expenditure

In this study the aim of optimization is to create an optimal schedule for an aluminium casthouse by minimizing the non-value added logistical costs. Planning is handled as a lot sizing problem while distributing customer orders to the batches. This dispatching process is done by combining the methods of order- and resource based dispatching which is classified by Sauer [Sau02]. Additionally the lean thinking approach (discussed in Chapter 2.3.2) is used to eliminate or to minimize the non-value added logistical costs in the internal aluminium casthouse supply chain by scheduling the operations to the casting furnaces.

2.3.1 Lot Sizing Problem Approach

A lot-sizing problem was formulated by Wagner et.al. [WW58] as a dynamic single item economic problem determining minimum cost production to satisfy the demand [GAN06]. Summerauer [Sum08] identified the costs as inventory, setup and production costs which have direct impact on a company's efficiency and competitiveness in the market. Peres et.al. [PBNN02] described the lot-sizing problem as a planning problem which aims to determine the production time and the amount. The lot-sizing problem has aroused the interest for the production planning. Drexl et.al. [DK97] made a comprehensive literature survey about the lot-sizing and also scheduling problem.

Potts et.al. [PW92] referred the benefit of lot–sizing problem on splitting the lot of identical items into sub-lots. Duda et.al. [DO05] applied the lot-sizing problem to production planning of steel foundry and Karmarkar et.al. [KKKF85] analyzed the analytical solution approach to the lot-sizing problem with simulation model.

In this research, the lot-sizing problem stays as the backbone of the planning. Its approach on cost reduction and batch creation from customer orders plays an important role at the optimization part of this study.

2.3.2 Lean Thinking Approach

Lean thinking approach can be seen as a main part of the Toyota Production System which firstly appeared in 1950's. To understand the complete Toyota production approach, literature [Ohn88] and [Shi89] are recommended. The Industrial Technology Center [ITC04] described lean thinking as a method aiming to improve productivity, efficiency and quality of the system.

In the lean thinking principle, activities are separated into two categories; "value-added" and "non-value added". These terms are introduced, well defined and distinguished from each other in lean thinking approach which is highlighted by Womack et.al. [WJR91]. Koning et. al. [KVHBD06] identified the distinction between value added and non-value added activities as value added activities contributing to what the customer requests from a product or service. All other processes are defined as non-value added activities.

The main focus of lean thinking is "to eliminate the waste" from the system. Ohno [Ohn88] classified the waste (or Japanese word for waste "muda") in the production system as:

- *Waste of overproduction*
- *Waste of time on hand (waiting)*
- *Waste in transportation*
- *Waste of processing itself*
- *Waste of stock on hand (inventory)*
- *Waste of movement*
- *Waste of making defective products*

This approach is implemented to different sectors (like health care [UAKEN07]) and concepts (like supply chain management). Lean thinking in supply chain management described in detail by Wisner [Wis11] and Rother et.al. [RS03] provides an understanding of the benefits of mapping the material and information flow to reduce wastes in the system.

Value stream mapping, process mapping, spaghetti diagrams, and simulation are well known tools that analyze the flow and help to implement the lean approach to the facilities. Among these tools, according to Detty et.al. [DY00], simulation is capable of showing the benefits of lean manufacturing including:

- Stock levels
- Transportation requirements
- The utility of production scheduling system
- Detailed delivery analysis from suppliers
- Detailed shipment analysis to customers

In this thesis, reduction of non-value added logistical costs is the goal of the optimization part.

2.4 Literature about the Interfacing Simulation and Optimization Approaches

A simulation model is imitating the real system by using defined logic without making any attempt to find the best option or choice. It provides the results according to the predefined strategies and control logic. On the other hand, optimization identifies the best decisions without paying attention to the dynamic interaction between the circumstances. A new approach in the industry is to combine these two beneficial tools to get one package. Fu [Fu01] listed some commercial simulation and optimization packages which are shown on Table 2. Also according to Fu [Fu02], these tools are capable of searching the optimum parameters selected by user with respect to the performance indicators. They use mathematical programming to find the best combination but the user does not have any control on this part of the software. It can be concluded that these tools perform sensitivity analysis on the selected variables in the applied field.

Optimization Part	Simulation Software
AutoStat	AutoMod
OptQuest	Arena, Crystal Ball, et.al.
OPTIMIZ	SIMUL8
SimRunner	ProModel
Optimizer	WITNESS

Table 2 Some commercial software packages [Fu01]

Simulation and scheduling system have also studied to be interfaced with each other. A new wording has appeared in recent days, the "simulation-based scheduling" which has these two approaches in focus. Miller et.al. [MP00] defined the term simulation-based scheduling and the selection rules behind it. They classified the selection rules as:

- Operation selection rule: Applicable when there is an available resource for several operations at an instant time
- Resource selection rule: Applicable when there is an operation which can be processed by several available resources at an instant time

However this approach deals with dispatching of tasks to resources. The problem of production planning and scheduling contains several constraints and parameters, so it is not only an allocation problem. Ganapathy et. al. [GNS03] described another approach to combine production planning and scheduling with simulation. This approach is to create an emulation platform with interfacing decision support system and simulation model. Kadar et.al. [KPM04] sketched the process flow in such a platform which is shown on Figure 6. Gupta et.al. [GS02] compared the typical simulation and simulation with production planning control studies. In this comparison they focused on scope, model, experiment and output of both platforms.

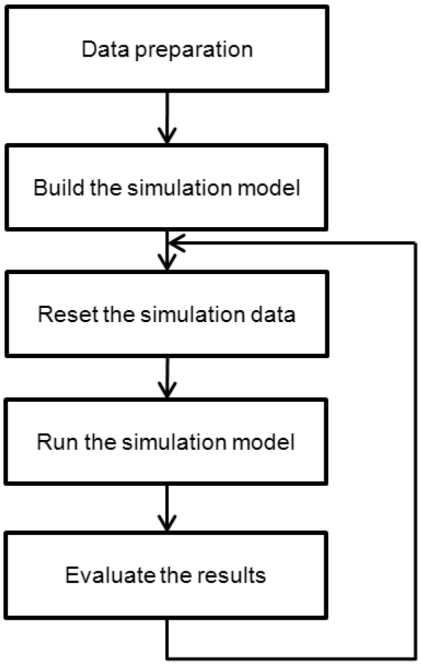

Figure 6 Architecture and the main process flow in the verified simulation platform [KPM04]

Lendermann et. al.[LPM01] focused on interfacing the simulation model and optimization tool which has an objective of cost minimization. However like other recently discussed studies the information flow occurred in one direction from optimization to simulation. Glover et.al. [GKL99] defined another approach for the combination of simulation and optimization models. They created two directions of information flow in between two models (like [TA03]). The sketch of this information flow is shown on Figure 7.

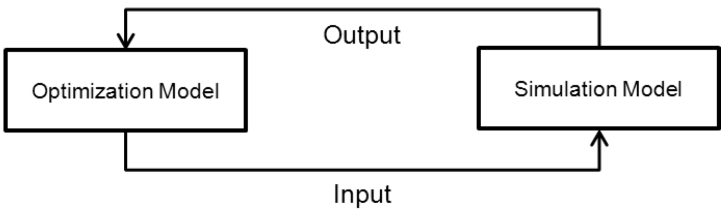

Figure 7 Coordination between simulation and optimization [GKL99]

The objective in the interfacing phase of this study is to create a platform and methodology to share the information which is one's output and becomes other's input. The software used for the optimization part is called "OpenSolver" shown on Figure 8 which contains macros written in MS Excel environment. These macros enable to eliminate the limitation of MS Excel Solver platform on the numbers of variable and constraints. The simulation software Automod has a feature to read and to write the data from the external sources like MS Excel or “txt” file. With the help of this characteristic the communication bridge between simulation and optimization can be easily built. Therefore, it is not needed to have another tool to perform the data flow.

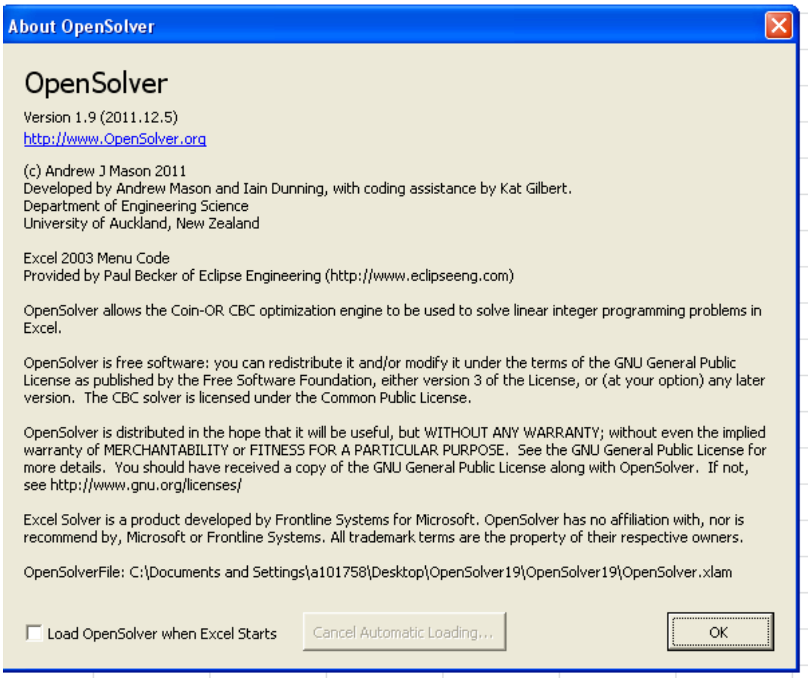

Figure 8 OpenSolver optimization engine

3 Casthouses in Primary Aluminium Smelter

In this chapter, aluminium production is introduced and general information about the steps from bauxite to aluminium and their global production is explained. Additionally, production in primary smelters and their sub facilities are described. Finally a deep analysis is done on primary aluminium casthouse supply chain by considering material and information flow, activities and their interaction, casting process and product range.

3.1 Introduction to Aluminium Production

In aluminium life cycle (shown on Figure 3 in Chapter 1) there are two important processing steps which are called primary aluminium and secondary aluminium production. Primary aluminium production is the reduction of aluminium oxide to aluminium. Secondary aluminium production is re-melting of scrap aluminium recycled after usage.

After the development of Hall-Héroult process [GK93] which is an electrochemical process used to produce primary aluminium from alumina, production of aluminium increased continuously. Figure 9 shows the global production of primary aluminium until 2010. The effect of financial crisis in 2008 on production and the growth of primary aluminium industry in China can be observed. The percentage of primary aluminium production in Europe compared to other continents decreased in the last four years after the financial crisis.

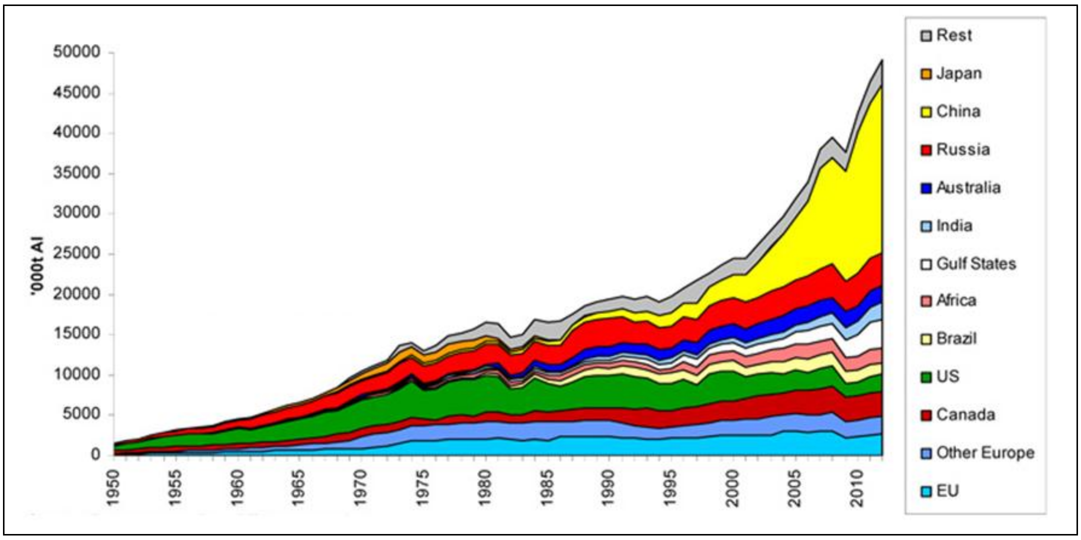

Figure 9 Global production of primary aluminium until 2010 [EAA12]

Aluminium cannot be found on the earth as an element. The ore bauxite is processed to have aluminium oxide (also named as alumina) which is the raw material of primary aluminium production. The Bayer process, cycle of which consists of processes such as digestion, clarification, precipitation, evaporation and calcination, is used to purify bauxite to aluminium oxide [GW88]. Figure 10 shows the intermediate material forms in the steps of aluminium production from bauxite. For production of approximately one kg aluminium, two kg alumina is needed. For two kg of alumina four kg bauxite has to be used.

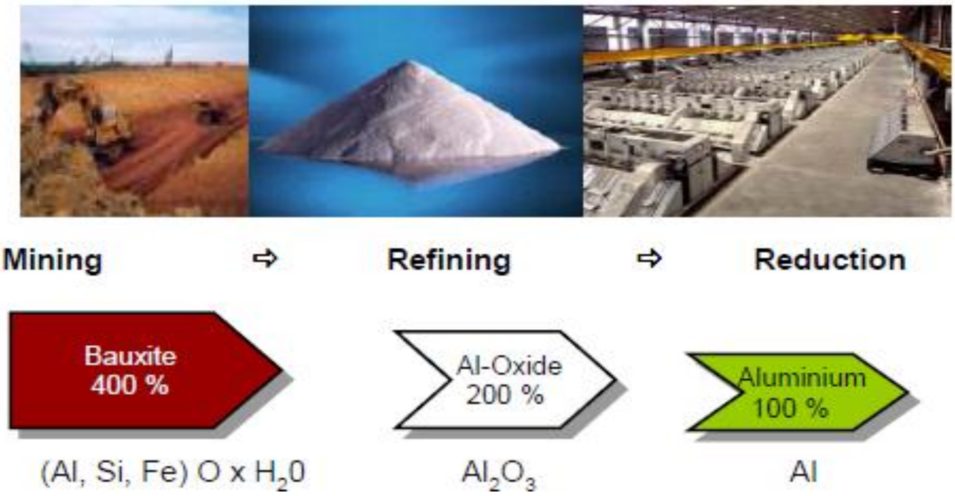

Figure 10 Steps of aluminium production from bauxite to aluminium [Hoe04]

Bauxite contains not only aluminum (Al_2O_3) which has around 50 % of the mass but also ferric oxide (Fe2O3), titanium dioxide (TiO_2), silicon dioxide (SiO_2) and other impurities. Figure 11 shows the global production of bauxite in 2000 in “%”split to countries. Figure 12 shows the global production of aluminium oxide by the Bayer process in 2003 (in unit Mt) split to continents.

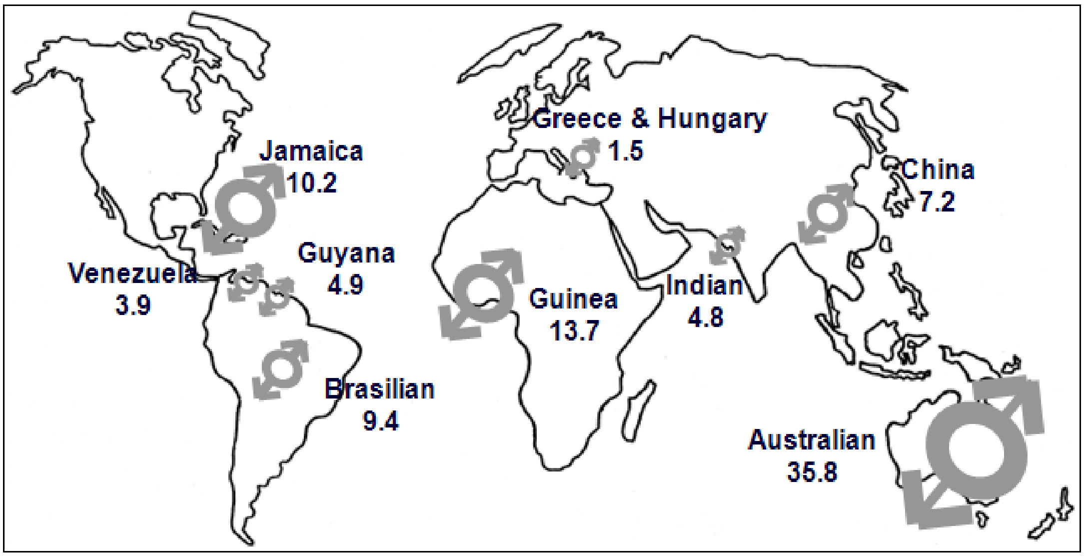

Figure 11 Global production of bauxite in 2000 (%) [Fri04]

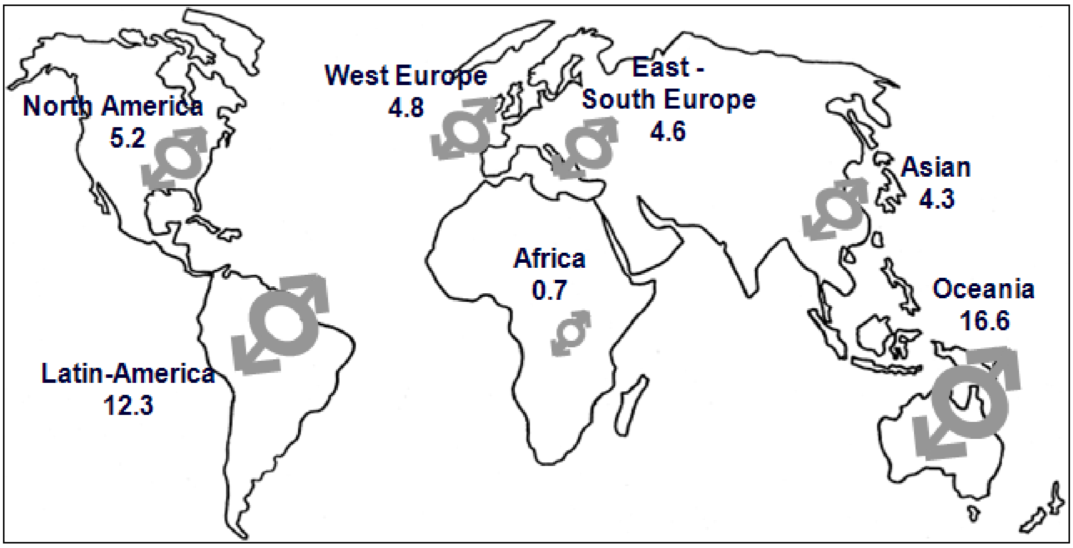

Figure 12 Global production of aluminium oxide in 2003 (Mt) [Hoe04]

Energy consumption expenditure in primary aluminium production cost is around 25 % which forces aluminium smelters to be located in the fields serving cheaper energy. The other important criterion in selection of smelter location is the closeness to customers and aluminum oxide suppliers. These criteria explain the inevitable growth of aluminium production in China. Figure 13 shows the location of aluminium smelters in the world.

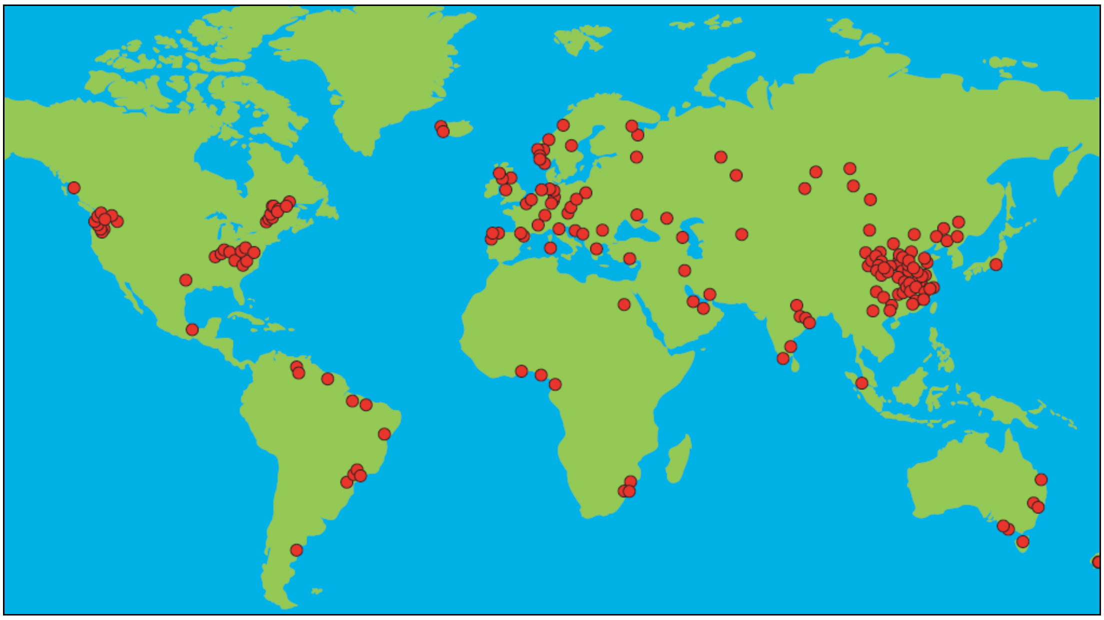

Figure 13 Location of aluminium smelters [IAI03]

The increase in global aluminium demand and production occurs due to its material properties (such as light weight, cast ability, machinability, surface finish etc.) compared to other metals. Table 3 shows the comparative evaluation of commonly used metals in industry. Although aluminium has higher cost compared to the others, its properties such as light weight, high resistance to corrosion, easy to form and recyclability increase its use percentage by the industry. The main industries which have high demand to aluminium are automotive, construction, electronics, packaging etc.

	Aluminium	Steel	Grey cast iron	Brass
Availability	Good	Good	Good	Good
Castability	Less difficult	Difficult	Good	Good
Machinability	Very good	Good	Good	Very good
Surface finish	Very good	Good	Good	Very good
Lending to modification	Good	Good	Good	Very good
Weight	Very light	Very heavy	Very heavy	Heavy
Brittleness	Low	Low	High	Low
Tendency to oxidation	No	Yes	Yes	No
Requiring machining	Not much	Less	Yes	Not much
Cost	Medium	Low	Low	High

Table 3 A comparative evaluation of commonly used metals [Jai03]

3.2 Primary Aluminium Production

The production of primary aluminium is based on Hall-Héroult process which was invented in 1886. The basic of this process is reduction of alumina in a molten salt bath. The process takes place in a cell which is shown on Figure 14. The cell (also called pot) is formed by a cathode block made of carbon, carbon anodes and electrolytic bath where alumina is dissolved. Electric current flows from anode to cathode heats up the bath to a temperature around 950 °C, well above the melting point of the aluminium and electrolyte.

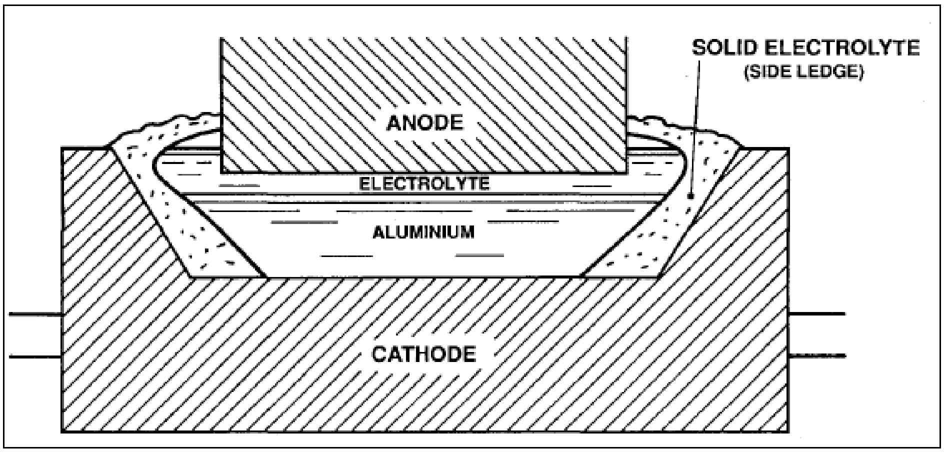

Figure 14 Schematic drawing of an alumina reduction cell [GK93]

The electrolysis unit in an aluminium smelter facility contains many cells where the aluminium is produced. A modern smelter having production capacity around 500000 "tons/year" contains approximately 700 cells connected in series.

Smelter may have two other main units except electrolysis. The first one is the carbon plant where the anodes are produced from coke and pitch. And the second one is cast-house where the liquid aluminium is casted as an end product to be delivered to custom-er. There are some other auxiliary plants such as fume treatment plant, bath treatment plant etc. Figure 15 shows the material flow and the boundaries of the sub-facilities in an aluminium smelter.

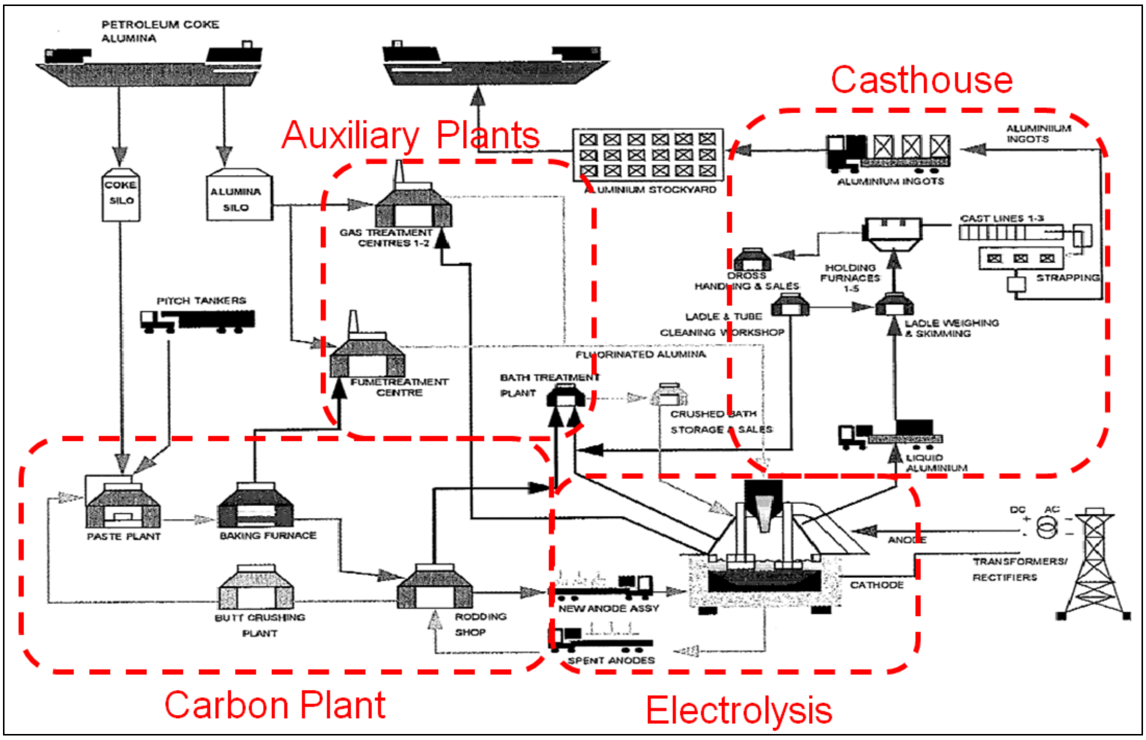

Figure 15 Material flow and sub facility boundaries in primary aluminium supply chain [HKK07]

The material flow from carbon plant to electrolysis contains the fresh anodes, and in reverse direction transportation of used anodes. As raw material coke and pitch enter to the carbon plant supply chain. Carbon plant contains paste plant where the coke and pitch form the green anode, baking furnace where the anodes are baked and rodding shop where the anodes are rodded and ready to be used in electrolysis.

The electrolysis is at the center of a smelter in the production point of view and from the material flow perspective. It has direct contact to the carbon plant and casthouse units. Fresh anodes and alumina are the main incoming materials and hot liquid metal is the outgoing material to casthouse unit. Alumina is transported into electrolysis continuously but on the other hand, anode and hot metal transportation form the main part of the logistical activities in electrolysis.

3.3 Primary Aluminium Casthouse Supply Chain

The casthouse is the last unit in the process flow of an aluminium smelter and has a direct interface with electrolysis by receiving hot metal from this unit. However, there is not any material flow between carbon plant and casthouse. Figure 16 shows the internal supply chain of a primary aluminum casthouse. The boundary of this supply chain starts with delivery of hot and cold metal and ends with shipment of end products to customer.

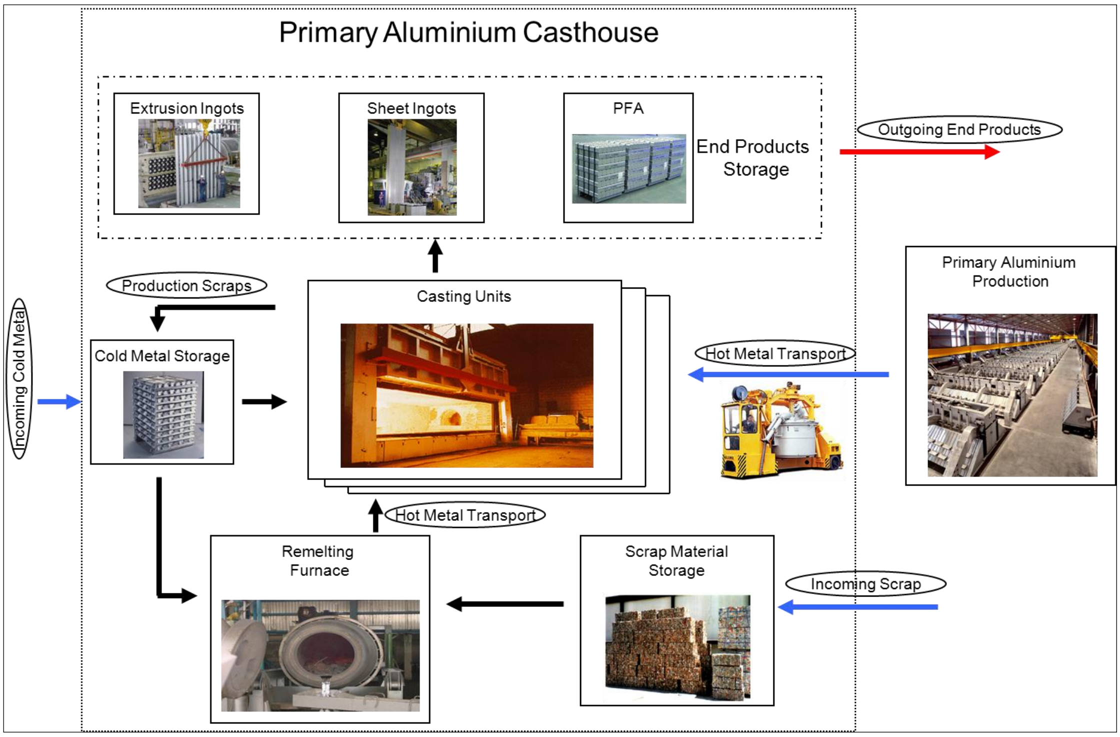

Figure 16 Internal supply chain of primary aluminum casthouse

The main resources in a casthouse are the casting units including the casting furnaces. These furnaces are filled with hot and cold metal to melt and mix them by considering the quality of the metal. It supplies this metal to casting line to cast the end product as requested by customer.

Hot metal filled in the casting furnaces may have two sources, one is the electrolysis unit where aluminium is produced from alumina and the other is the remelting furnaces where the recycled scrap material is melted. In most cases the remelting furnaces belong to the casthouse layout. In this case, high amount of scrap material supply for re-melters is included in the casthouse supply chain.

Cold metal as an incoming material contains aluminium ingots like bundle, T-bar, sow etc. Alloys like silicon, mangan, magnesium etc. follow the same route in the supply chain like cold metal as an incoming material. In addition to cold metal and alloys, scrap materials can also be added to inbound materials of casthouse supply chain. Scrap materials are required not only by re-melters but also by casting furnaces. They can be added to the batch of casting furnaces depending on the customer quality specifications and the melting capacity of the furnace. The amount of scrap melted in casting furnaces are very low compared to the amount melted in re-melters.

The layout of furnaces and casting lines has big influence on the logistical activities in casthouse. It has direct impact on the concepts like storage strategy, traffic, safety, parking location of vehicles etc. Berlioux et. al. [BBB11] focused on optimizing layout of aluminium casthouse by arranging the configuration of casting furnaces per casting line. The casthouse production and the furnace batch planning also depend on the layout configuration. Batch start time and distribution of orders to the furnaces are the main impacts of layout on planning activities.

3.3.1 Material and Information Flow in the Casthouse Supply Chain

A casthouse unit differs from other smelter sub-facilities due to its direct contact to customer and also its relations with internal and external metal suppliers. In addition to that, the hot metal flow from electrolysis forces the production in the casthouse to follow the planned schedule. The challenge is that it is impossible to buffer hot metal without significant heat loss. These circumstances conduce to map information flow, material flow and their correlation in detail. Figure 17 shows the material and information flow in casthouse internal supply chain.

The information flow in Figure 17 may differ from casthouse to casthouse depending on the characteristics of the casthouse supply chain. One of the levels from production plan to batch plan may disappear or steps of data flow may differ. However, the backbone of the flow including time frame, approach and transferred data do not vary so much.

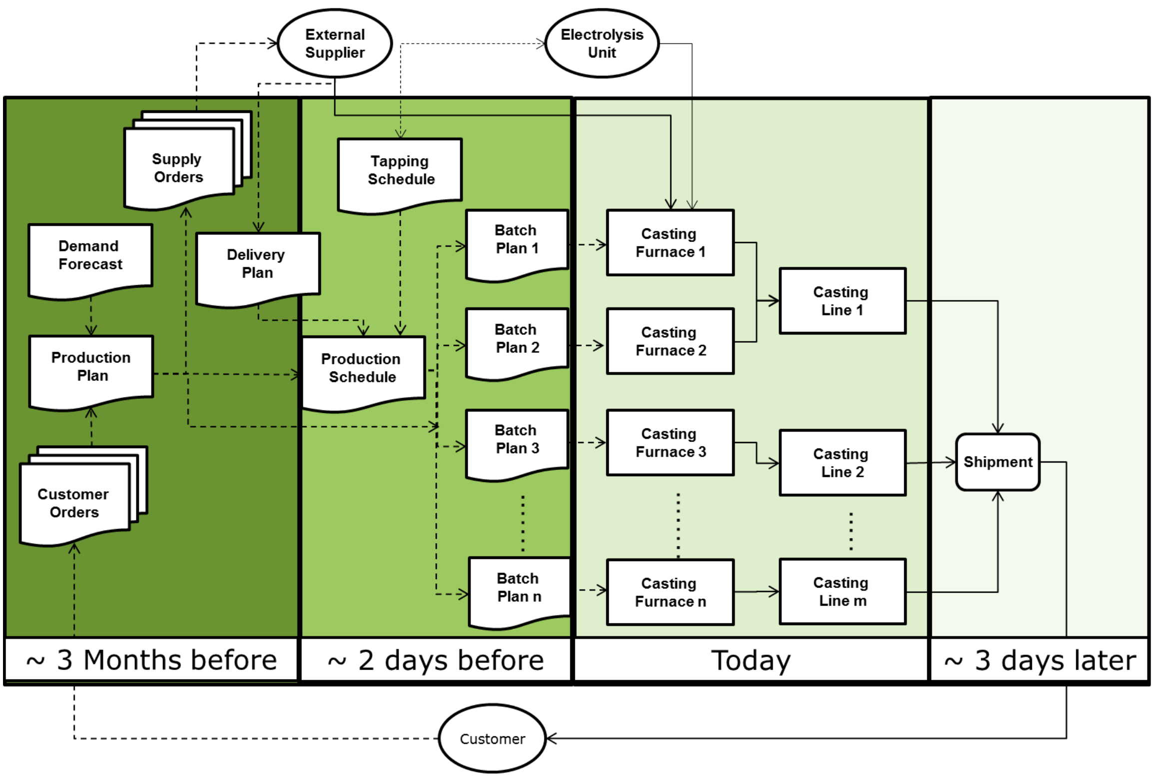

Figure 17 Material and information flow in casthouse internal supply chain

The arrows with dashed lines show the information flow and solid lines show the material flow between the units of casthouse internal supply chain in Figure 17. The time frame of the figure starts with three months before production and ends with the next three days after production. The production plan has two input sources. The first source is the demand forecast according to analysis of historical data and the current situation of the market. The second one is the customer orders that have already been received.

The orders generated according to demand forecast are replaced with the received customer orders.

The production plan contains information such as customer identification number, product type, product specifications (such as dimension, alloying etc.), production amount, assigned casting furnace, assigned casting line, packaging mode, SKU (stock keeping unit) specifications, delivery location and latest shipping date. The production plan also supplies data for external suppliers by preparing supply orders according to the customer order specifications. This planning operation may be updated up to two days before the production when the production schedule is prepared.

External suppliers hand in delivery plans which provide information about the delivery of incoming material to the production schedule. The delivery plan contains data such as supplier definition, material type, material specifications, delivery amount, SKU of delivery, date of delivery and transportation type etc. The material flow from the external suppliers takes place latest one day earlier than the production date. The reason behind this limitation is that some extra processes (such as drying, quality check etc.) may be applied to incoming material before filling into a furnace.

The last data is received from tapping schedule to create the production schedule of the casthouse. The operational management of the casthouse and the electrolysis units has impact on the tapping schedule. Larrivée [Lar09] listed the factors that have to be taken into account during preparation of tapping schedule as:

- Amount of hot metal required by casthouse
- Operation cycle of electrolysis
- Quantity of hot metal that can be obtained from one pot
- Chemical analysis of the hot metal
- Tapping process and operation characteristics (such as, tapped pot per transportation, direction of tapping in pot line etc.)

- Transportation and resource specifications (such as capacity of crucible, distance between electrolysis and casthouse etc.)

The production schedule organizes the operations in the casthouse. It is valid for the whole casthouse and contains the information about start time of each process and operation, their durations, assigned casting furnace and line of each batch, amount of required material and its location, next steps that product follows after production etc. The production schedule has to be updated periodically (like shift wise) to highlight the current situation and possible modifications on the tapping schedule and process organization in the casthouse.

The production schedules distribute the information to batch (charging) plans. Each furnace has its own batch plan which contains the data for the production in the next one or two days according to the casthouse organization. The batch plan also matches the batches with customer identification obtained from production plans. The batch plan controls the production in casting furnace by providing information about the batch start time, duration of production, batch composition, required hot metal quality, end product properties and cold metal specifications (such as storage location, amount, allocated transportation unit etc.). The information flow in the reverse direction occurs after production to verify the customer order before shipment.

The material flow contains cold and hot metal as inbound materials. Cold metal has intermediate storages between supplier and casting furnace (final destination). On the other hand, hot metal is filled into a furnace directly after it is tapped from the electrolysis. The equipment used to transport hot metal from electrolysis to casthouse is called crucible. It is designed to keep heat loss at minimum during the transportation.

The molten metal in the casting furnace is transferred into the casting unit. The next production steps after casting process differ according to the product type. In most cases, approximately two or three days are required to ship the material from the casthouse to customer after it is stored in the end product storage. The duration of preparation for shipment depends on the shipment type, international or domestic customer and required paperwork etc.

3.3.2 Activities and Their Interaction in the Casthouse Supply Chain

The process flow in casting furnaces drives the activities in the casthouse supply chain. A casthouse operation management system triggers the material flow, allocates the resources, controls the traffic and organizes the processes in its supply chain according to batch plan of casting furnaces. Figure 18 shows the activities and their interactions in the casthouse internal supply chain. As it can also be seen on the figure, the casting furnace stays in the center of the process flow.

The process flow of casting furnace may vary depending on:

- the furnace specifications (such as inaptitude of furnace to stirring process)
- end product type and properties (such as pure ingot does not require any alloying process)
- operational strategy (such as sampling or one of the holding processes may disappear in the sequence).

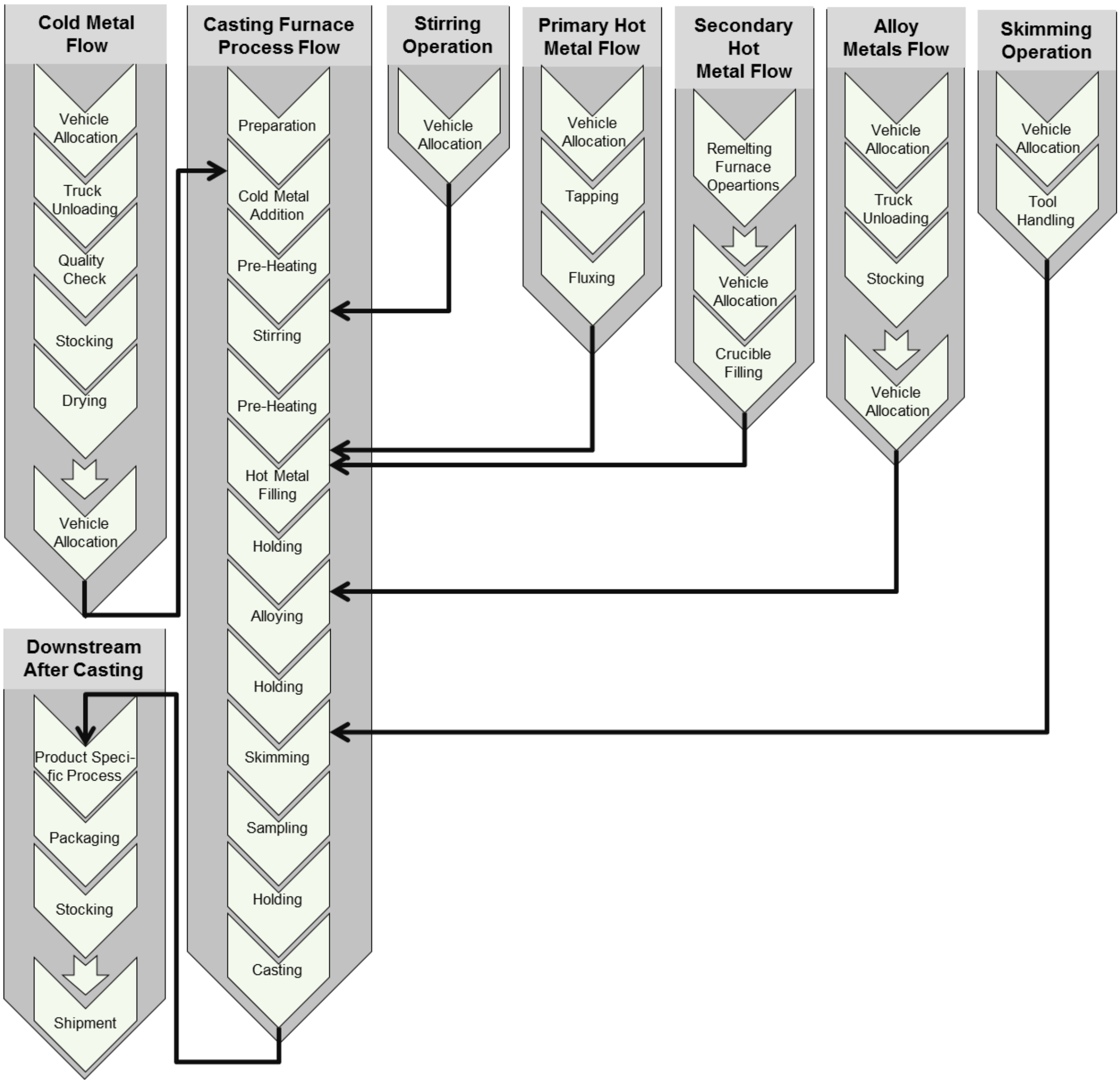

Figure 18 Activities and their interactions in casthouse supply chain

The process flow in casting furnaces may start with a preparation phase depending on the relation between the last and the next batches. If the alloy type differs and requires any wash-up process, cleaning will be done in this step by removing all of the metal from furnace and adding some alloys. Even though there is not any production, furnaces cannot be turned off. During this idle period, a furnace still contains a little amount of metal which is called sump.

The cold metal addition process normally takes place after the preparation phase, but in some cases when the temperature is higher than planned, cold metal is added to the furnace in the next steps of process flow. It cools down the furnace and regulates the temperature. In this concept, cold metal represents pure aluminium ingots supplied from external sources. Depending on the furnace melting rate and customer order specifications, a little amount of scrap can also be added to the furnace.

Cold metal and scrap follow the same process flow before being filled into furnace. They are unloaded from external transportation unit (trucks or boats) by forklifts or shovel depending on their transportation type. A quality check is done to identify their chemical contents. They have to be dried to remove water particles before being melted in a furnace. While furnace melts the added cold metal, the stirring process helps to mix the bath of metal to decrease the dissolution duration [BC02]. A special vehicle and equipment are used to stir the furnace.

After melting the cold metal, hot metal can be added to furnace. The source of the hot metal can be the electrolysis unit or re-melting furnaces depending on the casthouse system. Primary hot metal flow is triggered by tapping schedule. It organizes tapping time, identification of pots to be tapped and allocation of tapping vehicles. After the tapping operation, the fluxing operation takes place depending on the smelter specification. The reason of the fluxing process is to purify the metal.

The routing of tapping vehicles between electrolysis, fluxing station and casting furnace differs from smelter to smelter. The whole transportation can be done by the same tapping vehicle or it can be split in two loops at the fluxing station. Tapping vehicles do the tapping operation and transport the crucible to the fluxing station and another crucible carrying truck handles the fluxed crucible and transports it to casthouse. This operational strategy depends on the vehicle fleet and specifications of hot metal flow management in the smelters.

Another possible source for the hot metal is a re-melting furnace which supplies secondary hot metal to casting furnaces. The process flow in a re-melting furnace has similarities to the process flow in casting furnaces. However, it does not contain hot metal filling, alloying and casting operations.

The holding process in the flow represents the heating process to keep the metal at desired temperature for the casting process. During the holding process alloying metals can be added to the bath according to the customer specifications. Kaufman et. al. [KR04] listed seven basic families for the alloys in aluminium casthouses. They are; aluminium-copper, aluminium-silicon-copper, aluminium-silicon, aluminium-silicon-magnesium, aluminium-magnesium, aluminium-zinc-magnesium and aluminium-tin. Sampling operation in the process flow, checks the chemical composition of metal if it satisfies the requirements or not. If it is not in the defined specification, other alloying processes will take place until the customer requirements are reached.

The skimming process is used to remove the dross over the surface of the metal in the furnace. Dross is the residual material occurred during melting process [CWD09]. It is not a waste product, after a recycling process it can be used as a scrap material in secondary aluminium production. For the skimming process, a skimming beam is used to remove dross over the surface. In the industry special furnace tending vehicles are designed to simplify the skimming process. After skimming process, the gathered dross product is kept in cooling boxes. Transportation of these boxes is done by forklifts in the casthouse. After cooling down, this residual material is shipped to other facilities to be processed for recycling.

The metal in the furnace is held until the casting unit is available for the casting process. Normally a casting unit is linked to more than one casting furnace. However, the mixture of the metal from different furnaces is not possible due to their chemical composition. After emptying the furnace to the casting unit, it will be ready for the next batch cycle.

3.3.3 Casting Process and Possible Product Range

European aluminium association [EAA12] separates the casting techniques used in aluminium industry into two groups according to the final product. Primary and secondary aluminium casthouses which produce semi-finished products use the ingot casting technique and the other foundries cast aluminium with mould casting technique. However some casthouses in primary aluminium smelters also use the mould technique to cast semi-finished products such as T-bars. Literature contains detailed studies (Some of them are [BB99], [KU07], [TM03], [Bee01]) about casting process and different casting techniques.

The quality check of the final goods is done after the casting process. Failed products are sent back to casthouse production area to be used as cold metal for the next batches. Schmitz [Sch07] called these products “new scrap” which are received from own production of the casthouse. In this study, this material is called production scrap to prevent confusion with external scrap which has high contamination.

After casting and quality check, some further processes (such as homogenization, stacking etc.) take place. These processes are often fully automated in today’s aluminium industry. So after packaging, the material is transported to the storage area to be shipped to customer. According to the transportation type some extra handling are done in the end product storage operations (like container filling).

End products of primary aluminium casthouses are semi-finished products which are used as raw material in foundries, in rolling mills or in extrusion facility. The specifications such as alloy content, dimension, level of impurities, surface quality, cast ability and conductivity form the possible product range of primary casthouse. Figure 19 shows some end product types produced by Hydro Aluminium. In addition to the types shown on the figure, T-bars, standard ingot and sows are also produced in the smelters as an end product.

Figure 19 End products of primary aluminium casthouse [Kva11]

The usage fields of end products differ according to their types. For example, wire rods due to its conductivity are used in cable production area. Extrusion ingots (also called billets) are the raw material for the extrusion facilities which have automotive, construction and transportation industries as a client. On the other hand, sheet ingots are used in rolling industry to serve the customers from the fields packaging, construction and transportation. Foundry alloys are re-casted in foundries to be used in manufacturing of wheel rims, suspension parts and engine cradles in automotive industry.

4 Simulation Model Development for Aluminium Casthouse

The focus of the simulation part of the thesis is to map the whole material flow in aluminium casthouse, and the aim of the model is to create a universal platform which is applicable to any casthouse. As mentioned, Automod is used as the simulation tool for this study. In this chapter, after giving brief information about the literature review of simulation usage in aluminium industry, the model concept and logistical control approaches behind the model will be described in detail. The strategies behind the control of the model increase flexibility of the model implementation.

4.1 Introduction and Literature Review

Logistics simulation studies performed in metal industry have become challenging in the recent years. The reason is that attitude toward simulation models are changing. According to Guo [Guo03], in the past expectations were "quick and dirty" simulation models with "Know-how" approach, but today it is expected to model the system as accurate as possible to find the answer to the question "Why". Additional to that, due to safety reasons in the heavy metal industry, detailed analysis of the human behaviors is also intended to be in the main focus of logistical studies done for the metal industry.

Several simulation studies have been done to analyze the material and information flow in the aluminium production. The focuses of simulation studies were to reduce the fixed costs and eliminate the risks from the safety perspective. As mentioned, in aluminium industry the electrolysis part of the smelter has the highest priority due to high energy cost. Casthouse arouses the interest in logistical analysis due to the hot metal transport.

Eick et al. [EVB01] and Meijer [Mei10] focused mainly on material flow of the electrolysis and made some investigations only for the pot room part of the smelter. Harton [Har10] simulated the hot metal flow between electrolysis and casthouse. Baxter et al.

[BBTM09] built a simulation model focusing on the anode production plant area which has not a correlation with the hot metal transport. Tikasz et al. [TBPM10] and Pires et al. [PBTM11] investigated the full smelter logistics with the objective to improve the system from the safety perspective. Jaouen [Jao11] made a simulation study for the downstream part of aluminium casthouse. This simulation study differs from others by aiming to map the whole material flow taking place in the casthouse of an aluminium smelter.

4.2 Boundary of the Simulation Model

The system boundary for the casthouse simulation model has to take into account the close interaction with the electrolysis part of the smelter. Electrolysis has an ongoing process cycle of continuous aluminium production. The liquid aluminium is tapped batch-wise and the tapped aluminium is transported to the casthouse in crucibles. Therefore, in the casthouse supply chain analysis, the hot metal transported from the electrolysis should be considered in detail to get accurate results.

The tapping cycle may shift with short delays when a disturbance occurs but long delays cannot be tolerated due to the system restriction (such as hot metal characteristics). However the transported load in between the pot room and casthouse cannot be buffered longer and also cannot be reserved as scrap. Winkelmann et al. [WEDS09] defined a full smelter simulation approach to map the system in more accurate way and also to eliminate the risks (e.g. inaccuracy in hot metal flow) occurring due to some simplifications in the system interactions.

Having a flexible model, which can be applied to different casthouses, brings the challenge to consider many possible control approaches that can be used in the material flow field. For that reason, various casthouses were studied to have wide eligible logistical perspectives in the model. The model boundary of the simulation study contains not only the primary casting furnaces but also re-melting furnaces. Extrusion billets, foundry alloys, sheet ingot slabs and wiring rods are considered as the possible end products of the casthouse.

4.3 Concept of the Simulation Model

Structure of the casthouse simulation model contains four layers which are shown on Figure 20. These layers are classified according to their attributes and file format. Arrows show the direction of information flow occurs in between these layers in the simulation model structure. The first layer is input data definition which is done in MS Excel, the second and the third parts, control logic and model elements, are defined in Automod simulation software. The last part is determined in Automod and converted to “txt” format.

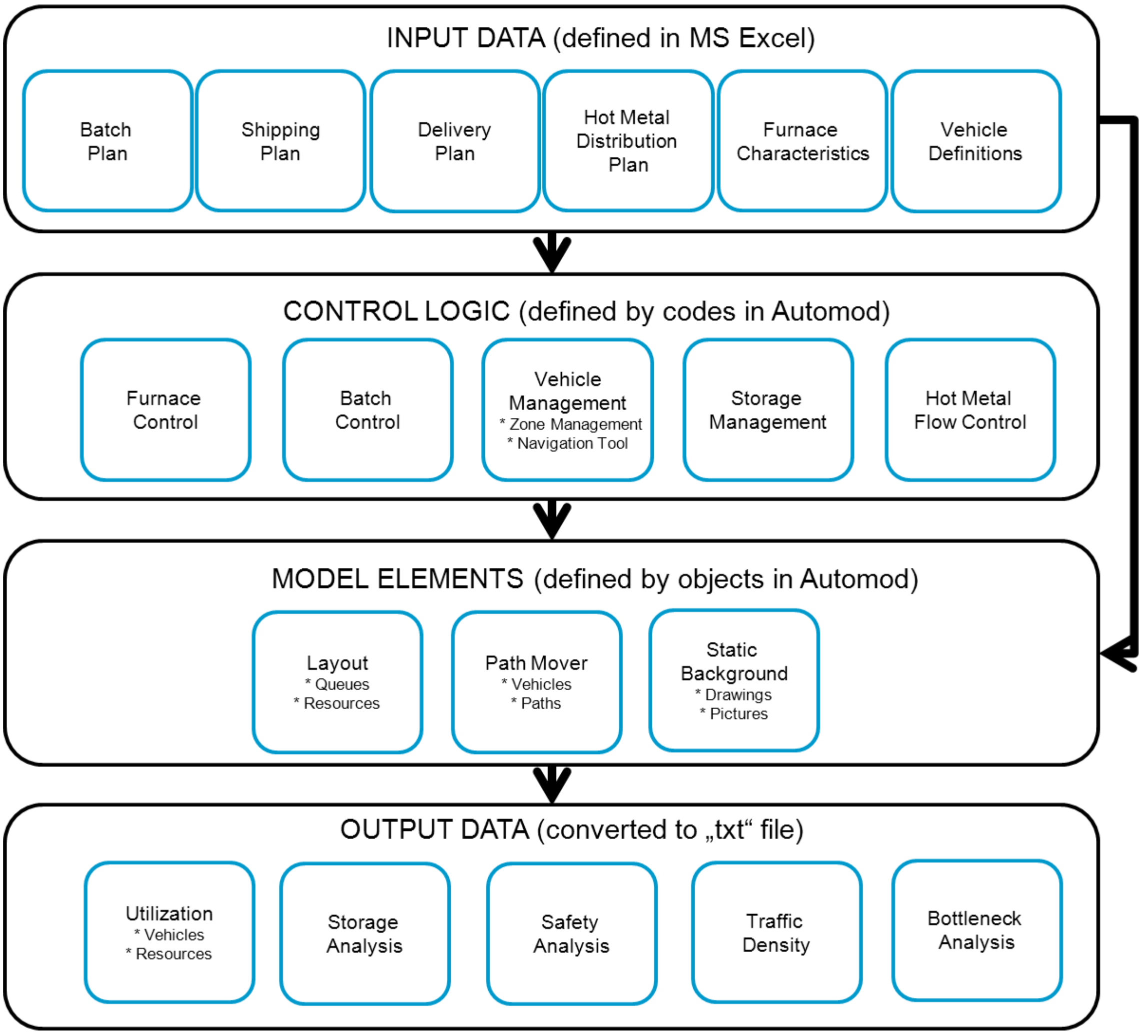

Figure 20 Casthouse simulation model structure

Input Data

This part of the model concept contains planning data and the characteristics and components of the system which are defined in MS Excel. The data explored in this section in most cases is received from the other departments of the smelter like planning and operational departments. All of the data defined in MS Excel environment inserted to the simulation environment with the help of functions written in Automod and macros defined in MS Excel. Information flow occurs from this layer to second and third layers of the model structure. Items defined in this part of the concept are;

- Batch plan; is defined for each furnace in the system. It contains the information like; identification and the recipe of batches, final product specifications, average durations (filling, melting, holding) etc.

- Delivery plan; is prepared for the incoming material. Information defined in delivery plan is described in the subchapter 4.5.4.

- Shipping plan; is prepared for the outgoing materials. It contains the information like; customer identification, product specifications, date of delivery, packing type, transportation type etc.

- Hot metal distribution plan; contains the information about electrolysis part of the smelter, hot metal transportation specifications, average driving duration in between casthouse and electrolysis etc.

- Furnace characteristics; contains the information about furnaces like; furnace design specifications (identification, capacity, melting rates), responsible casting line, selected strategies for metal filling etc.

- Vehicle definitions; contains the design data of each vehicle in the system boundary, vehicle fleet, possible task allocation groups etc.

Control Logic

Control logic behind the simulation model is programmed in Automod simulation software with the help of its functions. The tool enables to build the logic, not only with its predefined functions but also user defined functions written in C or C++ programming language. Control logic segment controls the all other parts of the simulation model. The parts integrated into control logic concept are discussed in detail in the subchapter 4.5. In the development phase of the casthouse simulation model, some parts of the software programming in Automod were done in cooperation with IdeCraft, Norway.

Model Elements

All of the items enabling to visualize the system are integrated in this layer. Automod defined objects and their attributes are used to visualize the system. Some object oriented simulation tools (such as Enterprise Dynamics, Simul8) attach its own control logic to each element in the model. In Automod, only the characteristics of item are linked to it, all of the control logic has to be defined separately. This has disadvantages such as requirement for a skilled programmer. On the other hand, defining the logic separately has many advantages like user defined strategies and needs, advanced logic control and flexible models to be modified easily. Items in the model element segment are;

- Process layout; contains the queues, resources and loads defined to visualize the real system. All of these Automod defined objects are placed in the model to identify furnaces, storage locations, materials etc.

- Movement system ; contains the paths, vehicles and vehicle segments defined in the model

- Static background; Automod enables to import some drawings at the background of the model to improve the visualization. This may be a drawing or bird view picture to describe the layout of the system in a better way.

Output Data

Result gained from the simulation model depends on the objective and the demand from the user, but there are some standard statistics that are valid in the casthouse model for example bottleneck analysis, resource utilization, traffic density safety and storage analysis. In this thesis, the required output data from the simulation model is defined to interface with the optimization model in detail in Chapter 6.

4.4 Main Components of the Simulation Model

The simulation model contains the components classified into sub-models with respect to their properties. These sub-models are primary hot metal flow, secondary metal flow, cold metal flow, furnace operations and material flow after the casting process. Each of these components can be examined independently. If only the partial material flow analysis is required then only the needed part of the model can be used for further investigations.

4.4.1 Primary Hot Metal Distribution

Hot metal flow from electrolysis constitutes the crucial part of the casthouse material flow. Hot metal flow without detailed electrolysis concept makes the casthouse supply chain so complex to design in the simulation environment. For that reason, the logic of the flow trigger system in the model should have been designed in detail to allow mapping of various strategies. The solution applied at the simulation model is to create a distribution of the crucible numbers according to time [Des110]. The distribution may vary depending on the possible strategies applied in the real environment.

The starting point is to calculate the amount of metal produced in the electrolysis on the shift based system. The equation (4.1) shows how the average amount of metal produced per shift is calculated in the model logic.

$$AvgMPS = \frac{\sum_{potline=1}^{k} (NP_{potline} * TMTC_{potline}) * DD}{SD * TC}$$

(4.1)

where;

AvgMPS = Average metal produced per shift (ton)

NP = Number of pots for each pot line

TMTC= Total metal tapped from one pot per tapping cycle of the pot line (ton)

DD= Day duration (24 hours)

SD = Number of the shifts per day

TC = Tapping cycle duration of the pot line (hr)

k = Total number of pot lines in the system

Average metal produced per shift helps to calculate the average number of crucibles transported per shift from the electrolysis to the casthouse. The equation (4.2) shows the basic calculation of the average number of crucible transported per shift.

$$AvgNCS = \frac{AvgMPS}{AvgTMC}$$

(4.2)

where;

AvgNCS = Average number of crucibles transported per shift

AvgMPS = Average metal produced per shift (ton)

AvgTMC = Average tapped metal per crucible per transport (ton)

After calculating the crucible number transported per shift, the tapping operation cycle duration is needed to distribute the crucibles in time perspective. To calculate the average tapping operation and transportation duration, four main constraints should be taken into account. First one is the transportation duration, the second is the tapping operation duration, the third is the time spent at the fluxing station and the last one is the crucible tilting process duration. The equation (4.3) shows the correlation of these constraints to find the average tapping operation and transportation cycle duration.

$$AvgTCD = TDP * NPTC + AvgDRT + AvgFOD + AvgTPD \tag{4.3}$$

where;

AvgTCD = Average tapping operation and transportation cycle duration (min)

TDP = Tapping duration per pot (min)

NPTC = Number of pots per crucible

AvgDRT= Average driving duration of round trip outside of the casthouse (min)

AvgFOD= Average fluxing operation duration (min)

AvgTPD= Average tilting operation duration (min)

The hot metal from electrolysis transported in a shift is defined as hour based distribution. The maximum number of crucible transport per hour is determined. However it is not allowed to park the crucible transporting vehicle at the electrolysis and casthouse area due to the safety reasons. Therefore, at most of the smelters, tapping vehicles are parking at the special parking locations or maintenance area. Due to that reason, during the first hour of the shift the crucible transport may not reach the maximum number. In the model logic, the crucible distribution in the first hour of the shift is calculated by equation (4.4), while the maximum crucible transportation number is determined from equation (4.5).

$$FNCT = \frac{NTV * (60 - AvgTCD)}{AvgTCD}$$

(4.4)

where;

FNCT= Number of crucible transport for the first hour of the shift

NTV= Number of tapping vehicles operating in the system

AvgTCD = Average tapping operation and transportation cycle duration (min)

$$MaxNCT = \frac{NTV * HD}{AvgTCD}$$

(4.5)

where;

MaxNCT= Maximum number of crucible transport that can be performed in one hour

NTV= Number of tapping vehicles operating in the system

HD= Hour duration (min)

AvgTCD = Average tapping operation and transportation cycle duration (min)

After the calculation of the hot metal transportation in the first hour of the shift and the next hours, it has to be determined the amount left for the last transportation hour. Equation (4.6) is used to calculate the number of crucible transport for the last hour of the planned hot metal transportation frame for one shift.

$$LNCT = AvgNCS - (FNCT + MaxNCT * (PTS - 2))$$

(4.6)

where;

LNCT= Number of crucible transport for the last hour of the planned hot metal transportation frame for one shift

AvgNCS = Average number of crucibles transported per shift

FNCT= Number of crucible transport for the first hour of the shift

MaxNCT= Maximum number of crucible transport that can be performed in one hour

PTS= Planned hot metal transportation frame for one shift

After calculating the first, last and maximum number of crucible transport, the trigger system can use the distribution approach which is shown in the Figure 21.

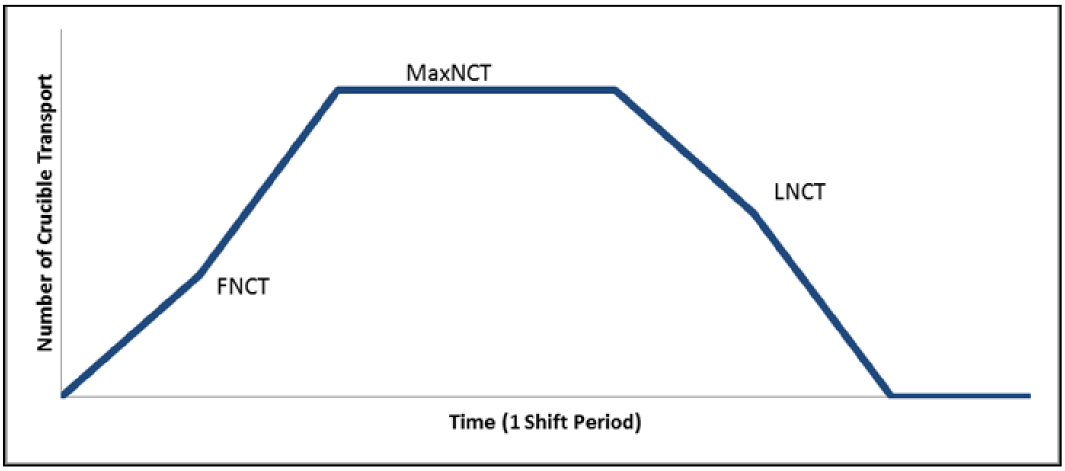

Figure 21 Distribution of the crucible transport in one shift

4.4.2 Secondary Hot Metal Transport

Secondary hot metal transport has to be taken into account for the casthouse supply chain when there is a re-melting furnace in the system. Normally re-melting furnace or furnaces are located inside the casthouse. Therefore, material flow to and from the re-melting furnace has to be considered in the interim casthouse supply chain concept.

A re-melting furnace is used to melt external scrap, internal pure scrap and cold metal. The operations and material flow of the re-melting furnace is similar to the casting furnace except the primary hot metal filling and the final process. In the simulation model concept, furnace management of the re-melting furnace and casting furnace are mapped in the same way. For the final process, if the re-melting furnace has the batch-wise production then a "Push" concept will be applied to transport the metal from the re-melting furnace to the casting furnace. Alternatively, if the system contains a continuous re-melting furnace then the transportation logic control will turn to a "Pull" system.

In both cases, due to the uncertainties in the system, small buffers should be considered. To place the buffers between re-melting furnace and casting furnace mostly the empty vehicles or crucible filling area are occupied. Casthouses with re-melting furnaces need an optimum planning concept to distribute not only the primary metal from electrolysis but also the secondary hot metal from the re-melting furnaces.

4.4.3 Scrap and Cold Metal Transport

Hot metal transport is the core part of the casthouse external supply chain but also the internal material flow scrap and cold metal transport requires detailed consideration. It is not possible to charge the cold metal directly coming from the supplier. Some processes like sampling, drying and warming should be applied beforehand. For each process, new storage location and also reshuffling possibilities in between the storages have to be taken into consideration. In addition, surplus, pure scrap from the own production, is also added to the cold metal inventory. From the logistical perspective, detailed inventory and storage management should be determined for the cold metal material flow.

In the simulation model, a classification approach [Des210] is implemented to identify the materials. Firstly, the material category, which is the upper level of the classification, contains the piles such as ingot, scrap, pure metal, alloy etc. In the second level of the classification, the material type is identified according to the transportation type or properties of material such as top bottom pieces, T-bar, bale scrap etc. Figure 22 shows one example for the category and type classification of additive metals. In the last part of the classification has the quality level which is linked to the supplier of the metal.

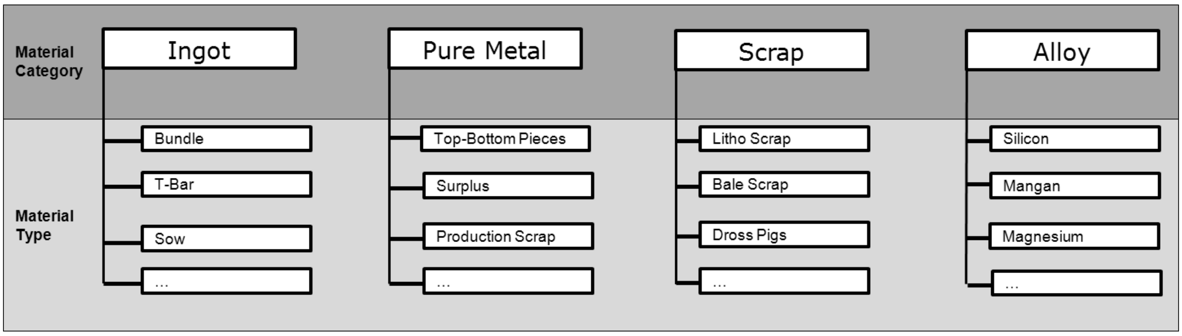

Figure 22 Category and type classification example

In the model, this classification approach is also linked to the storage location. The pre-defined storage locations contain the information about the classification data coming from the material specifications. Therefore, it is enough to define the storage location in the batch plan if the specifications are known for the simulation period. To define the material type, it is sufficient to identify the location of the required material.

4.4.4 Furnace Operations

In the simulation model, all of the decisions taken in the internal casthouse supply chain are based on casting furnaces and their operations. Processes handled in a casting furnace are logically lined up and mapped as duration in the system. The uncertainties in this duration mapping influence the decisions taken by the system. Therefore, some processes may be repeated due to delays or the lack of material at current state.

Figure 23 shows the flow diagram of processes in the production cycle of a usual casting furnace. The simulation model follows this sequence of processes which can be modified according to the system characteristics. Re-melting furnace also follows the same process order except the hot metal filling process. The process durations of the re-melting furnace are based on the furnace specifications such as casting furnaces, and the final process of the re-melting furnace is also named as casting in the simulation model despite the process is not the usual casting operation.

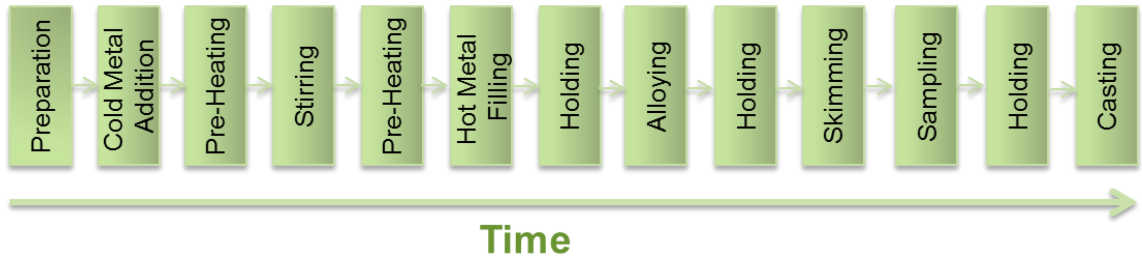

Figure 23 Process cycle of casting furnace in the simulation model

Preparation

Due to alloy usage, in some cases wash-up process is needed in between two batches. In the model concept, the predefined correlation in between alloy types determines the length of the process duration.

Cold Metal Addition

Before hot metal filling due to the cost factors and need for cooling the furnace, cold metal is filled into the furnace. This process contains also pure scrap metal additions. The duration of this process depends on handling and the transportation duration of the metal from storage into the furnace.

Pre-Heating

After cold metal addition, the duration used to melt the metal is named as “Pre-Heating” process. The duration of this process depends on furnace specifications. Melting rate for cold metal may differ from the melting rate for scrap. Therefore, the specifications should be well determined at the beginning of simulation.

Stirring

After cold metal addition, the stirring process increases the efficiency of the system by mixing the bath which decreases the dissolution duration. Special equipment is used to stir the metal, so in the model, equipment handling and travelling time are considered in the stirring process duration.

Hot Metal Filling

This process starts with the claim for the first crucible and ends with the tilting of the last crucible into the furnace. In this process not only the primary hot metal, if the system contains, secondary hot metal flow is also integrated. The process depends on the handling strategy of the crucible from vehicle to the furnace. Handling by crane, siphoning by special equipment and tapping system on the vehicle are possible alternatives that are considered in the model logic. Handling procedure has big influence on the process duration. Additionally, equipment availability and resource idleness cause the system being behind the schedule.

Holding, Alloying

The duration from hot metal filling until the casting process is named as “Holding” in the simulation model. Alloying process is also integrated as duration in the model logic. Aim of the holding process is to keep the temperature constant in the furnace. The planned holding process duration is calculated statically at the beginning of the simulation based on the furnace specifications, and it is kept constant during the simulation run.

Skimming, Sampling

Skimming process contains the dross handling process and its transportation. Skimming has an influence on the process duration due to special tool usage to skim the furnace. The vehicle transportation and tool handling are mapped in detail in the model logic. Also the dross box availability, handling and transportation may cause some delays in the system. Sampling process occurs just after skimming and has constant duration in the model. Only uncertainty may occur due to the skimming process. In the real life, sampling process may cause some process repetitions (e.g. alloying), but in the model effects of the chemical composition are ignored.

4.4.5 Down Stream Processes after Casting

The downstream part of casthouse supply chain contains the processes after casting and also the handling operations until shipment of orders. Casthouse specific processes, for example cooling, homogenization etc., and also general packing processes such as strapping, cutting, stacking etc. are considered in the simulation model logic.

All of these processes are mapped as duration in the model. Possible activities and interactions of the processes are not taken into consideration. In other words, the average processing time is applied to the system from the first product of the batch entering the sub-model until the last product of the batch leaving the system. The process lead time planned for each process is kept constant during the simulation, so in this part of the system disturbances may only occur due to the resource availability.

4.5 Logistical Control Strategies in the Simulation Model

The core point of logistics simulation models is the analysis of reality with the different logistical control approaches. In some cases two or more of these approaches can be mixed and simulated system may have its own control logic. Therefore, selecting and implementing correct logistical strategy to the simulation model should be well structured at the beginning of the study. In this sub-chapter, some of the logistical control strategies considered in the simulation model are described.

4.5.1 Possible Scenarios for Primary Crucible Allocation

Under subchapter 4.4.1 the primary hot metal trigger system, its distribution and the logic behind it were discussed in detail. As mentioned in casthouse supply chain hot metal flow plays an important role due to its characteristics. For the production scheduling, crucible-carrying primary hot metal- and casting furnace allocation becomes very crucial. This allocation strategy may differ from casthouse to casthouse. Therefore, the logistical approach behind this allocation should be mapped with alternative scenarios in the model to match with the reality.

In some smelter organizations, the tapping schedule of the electrolysis manages the hot metal flow. In the others, allocated pots and the tapping schedule are decided by the casthouse operation management. As a third alternative, there is a hot metal coordinator in the system and tries to balance hot metal flow between pot room production and casthouse requirement. In this simulation study, four possible alternatives were modeled.

Push System

In this alternative, the logic is based on the push strategy from electrolysis to the casthouse. Electrolysis unit decides the hot metal flow scheduling and casthouse reacts to this schedule. If uncertainties (delays, resource unavailability etc.) occur and hot metal needs to be buffered, this will take place in front of the furnace. System in the model approaches to the reality by arranging the production plan according to the data coming from electrolysis unit. With this concept the production schedule of the casthouse should be rearranged periodically to respond to uncertainties.

Pull System

In this alternative, the logic is based on the casthouse hot metal filling schedule. This schedule may contain a pot selection depending on quality of the metal, time of operation and the amount of tapped metal. The crucible buffer area is either the fluxing station or the gate in front of the casthouse. Safety reasons prohibit buffering the crucibles in the electrolysis area.

Combination of Push and Pull Systems

This concept can be used when the real system has a metal manager on the top who organizes the hot metal schedule. In this concept, vehicles buffer at the push-pull boundary [SKS03] of the system and are allocated to the casting furnaces according to a FIFO rule. In a crucible furnace matching, only arriving times of the vehicles play a role. Each crucible can be allocated to each furnace without any restriction.

Combination of Push and Pull Systems with Limitations

The logic of this alternative has one advanced step compared to "*Combination of Push and Pull Systems".* The aim of this strategy is to create a link in between the pots and furnaces, based on metal quality specifications. If the preferred furnaces do not require hot metal in predefined waiting duration then the crucible is allocated to the other available furnaces. This advanced logic is mostly selected if the casthouse has different product types or if the system boundary contains more than one casthouse.

4.5.2 Traffic Management in the Simulation Model

The simulation tool has its own traffic management approach based on the predefined interactions between the paths. It is possible to change the navigation factor which is defined for the whole path at the beginning of the simulation. According to these factors, the system calculates the possible shortest path during the simulation. These factors are defined at the beginning of the simulation so it is not possible to change their values during the simulation. It is required to control the course of the vehicles in a sophisticated way. A navigation tool was developed to solve this problem. And also the restrictions (like layout perspective) coming from the simulated system specifications need to be applied in a flexible way in the model, for that reason the zone management approach is determined.

Vehicle Navigation

It is possible to route the vehicles according to strict traffic rules by programming sophisticated logic, which may restrict the flexibility of the model. For that, all of the possible alternatives should be written in the logic and user should design all decision possibilities and selections at the beginning. When it is needed during the simulation, the system selects the correct path according to this predefined logic.

The required navigation concept in simulation models needs more sophisticated logic than the vehicle control systems provided by the simulation tools. First and probably the most important requirement is the dynamic approach ([EKP96], [BMND05]) which cannot be managed by the current vehicle control system of Automod simulation tool.

Automod has its own navigation system which also allows defining static weighing factors through the paths, but it is not possible to change these factors during the running simulation. It is a big challenge for simulation tools to change these factors and make a decision according to the new factors at an instant time which introduces dynamics to the model.

The second demand is related to the flexibility of the system configuration. Path definition in Automod has the option where the navigation factor can also be attached as an attribute, but this factor is valid for the whole path. It is not possible to differentiate the navigation factor for all path connections. The challenge for this issue is to have different weighing factors between the decision points along the path. In principal, it can be solved by defining separate paths between each control points but then the model becomes slower due to the high number of defined identities.

The third lack of Automod is that it is not able to differentiate the weighing factors according to the different vehicle types. This feature is needed because each vehicle type has its own restrictions. For example, in some cases one vehicle type cannot have access to one part of the layout. It is not possible to model it with the vehicle control system of Automod. Logic has to be written to define that kind of features in the model. After recognizing the requirements the approach defined in Figure 24 was developed to accomplish the lacks of the navigation system of Automod.

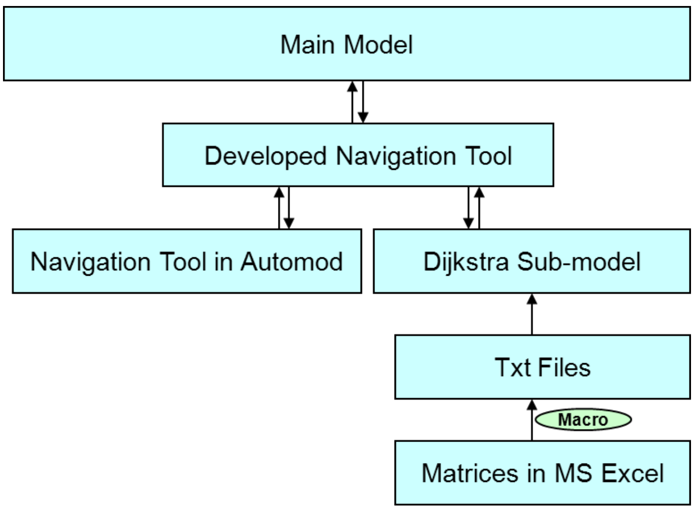

Figure 24 The new navigation tool implementation to guide vehicles

The logic of the navigation tool is based on the modified Dijkstra's Algorithm ([Dij59], [GT96]). The interface between Automod and Dijkstra acts as a decision maker for path selection according to the output from Dijkstra and the restrictions coming from simulation model. A modified Dijkstra's Algorithm with neighborhood approach ([ISW09], [Pri04]) for the vehicle routing problem ([SWW00], [SF96], [Mey03]) finds the optimized node connection by passing the layers in between source and sink points. Figure 25 shows possible two layers connection problem for the navigation tool. The abbreviations and their explanations on Figure 25 are:

i=	Nodes from 1 to n
L_i =	Decision locations along the path
$W_{Li\text{-}L(i+1)}$ =	Weighing factor from L_i to $L_{(i+1)}$

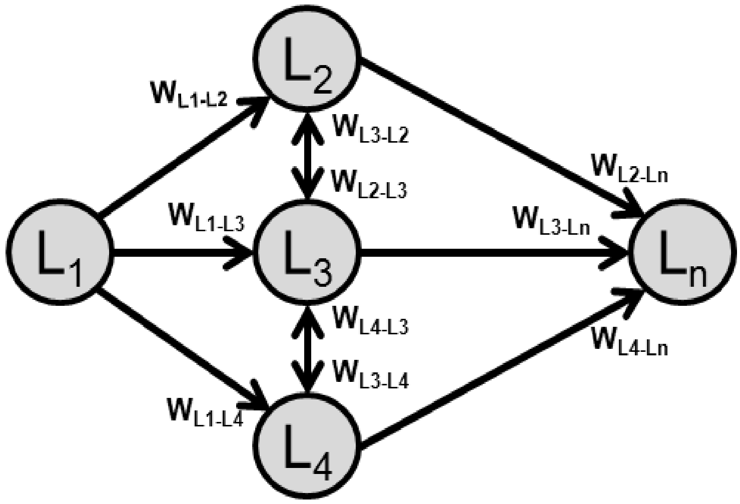

Figure 25 Possible two layers node connection

Aim of the system is to reach from L_1 to L_n and the steps followed by the navigation tool are;

1. Check the first possible connection according to the neighborhood sequence approach;

   $L_i \rightarrow L_{i+1} \qquad \forall\ i$

2. Calculate total weight of the possibilities by;

$$W_{total} = \sum_{i=1}^{n}\left(\sum_{j=1}^{n}(W_{ij})\right) \qquad \forall_i, \forall_j \quad (\text{if } W_{ij} <= 0 \text{ then break})$$

(4.7)

3. Check all of the possible alternative connections in between;

   $L_1 \rightarrow L_n$ if W_{total} > "The breaking parameter" then break

4. Select the option having smallest W_{total} as the preferred path.

Example to show the logic behind navigation tool:

According to the example shown in Figure 26, the task is defined to travel from point A to point E on the layout by using the navigation tool. If the points are read by the system according to the alphabetical sequence, the navigation check will start from A to B. After calculating all the possibilities with this starting arrangement, the model will start to check other possible alternatives from A to C, then from A to D and finally from A to E. At the end all the possibilities from A to E are determined and the most optimized path according to step 5 will be selected.

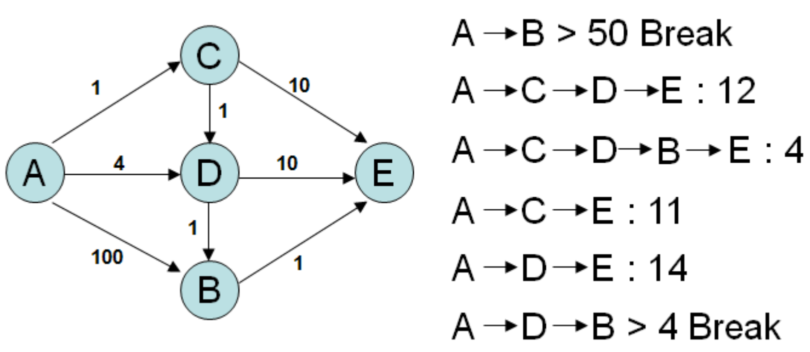

Figure 26 An example to show the selection logic

The sequence of the calculation is started with A to B, but the defined weighing factor is greater than "50" (the default breaking parameter) so the connection is broken, and the system skips this initial arrangement and passes from A to C. With this new arrangement, the system can reach the destination through the connection ACDE according to the neighborhood approach. The total weighing factor is reset from “50” (as predefined) to “12”. The tool continues to find the other possible alternatives with the breaking parameter “12” and in the next alternative, it reaches the destination with the arrangement of ACDBE and the total weighing factors are stored as “4”. It continues with the other possibilities but after that alternative (ACDBE), the breaking parameter of the calculation is set to “4”. It is obviously seen at the last check that the system terminates the calculation without reaching to the destination because the ADB arrangement has “5” as a weighing factor after reaching to the point B. By the help of this terminating logic, the speed of calculation is tremendously increased without changing the result.

At the end of this example, the system decides ACDBE as most optimized one and routes the vehicle through this path. For the next possible demand from A to E, the system will again recalculate all these alternatives. Pre-calculated connections are not stored in the memory, because the connections between the paths are changing during the simulation dynamically. For example, if one obstacle is located between B to E and increase the weighing factor, then system can choose the ACE connection or any other one according to the modified factors for the next travels.

As mentioned, the logic behind the navigation tool is based on quantitative optimization between possible alternatives found according to a predefined matrix. The system at the beginning stores all connections and their weights between the decision points. And also during defining period, neighborhood priority criteria between the connections is created. The decision path is shown in Figure 27.

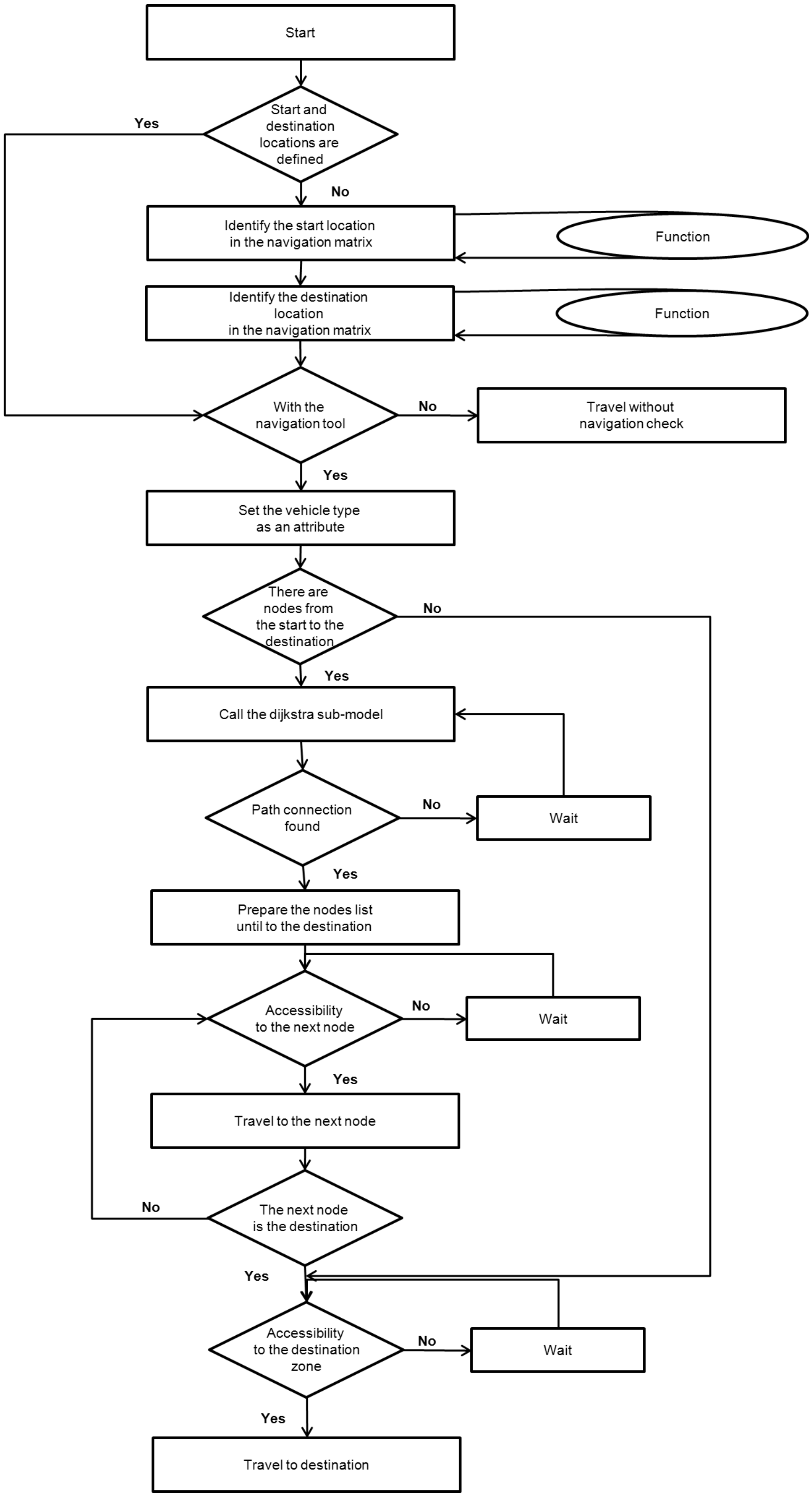

Figure 27 Information flow in the decision logic behind the navigation tool

Zone Management Concept

In the model for vehicle management, the navigation tool is used to control the traffic inside and outside of the casthouse. In addition, a zone management approach was developed and implemented to the vehicle routing control of the model due to safety rules in the casthouse. The zone management approach has three layers of control. The logic behind is similar to the work zone approach used in highway's roadway management [KA03] which is applied when there is a reconstruction, maintenance or any factor disturbing the traffic on a highway. Mirchandani et al. [MSL03] and Yadlapati et al. [YP04] performed simulation studies to analyze the decision alternatives taken after coming across with a work-zone. In the casthouse model, the decision is taken by the navigation tool when there is a blocked zone along the path. The difference from the normal work zone management is a multi-stage control of the zones depending on the layout and system restrictions.

Figure 28 shows the zone layers in front of the casting furnace. The first zone controls the resource availability. When there is a vehicle based process at the furnace at an instant, this zone prevents the furnace to be claimed by another vehicle. The upcoming vehicle process is queued until availability of the furnace.

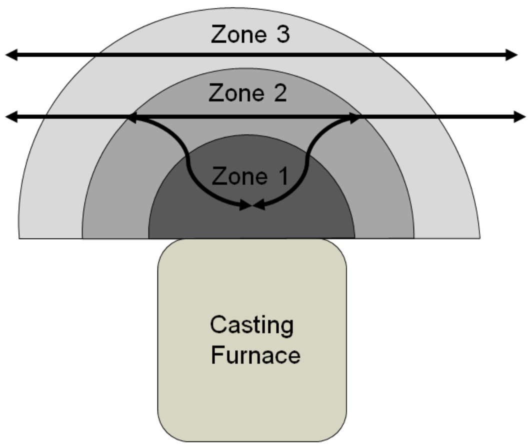

Figure 28 Layers of the zone management approach in front of the casting furnace

The second zone controls the traffic just in front of the furnace by obeying the safety regulations. When there is a vehicle standing in front of the furnace for any reason, this zone blocks the traffic on the lane in front of the furnace. Depending on the system characteristics, vehicles may queue at the zone boundary or find another alternative way to the destination.

The third zone is responsible for traffic of the aisle in front of the furnace. In some casthouses, in front of the furnace special traffic rules (such as, overtaking an operating vehicle is forbidden) are executed due to the layout restrictions. This stage is applicable when there is a two lane way in front of the furnace which can be used by two vehicles if none of them is in operation. With this zone level the whole access to the furnace area can be blocked when needed.

4.5.3 Furnace Management

Furnace management is the main decision maker in the process triggering part of the simulation model. The process cycle (Figure 23) defined in the logic sequences the processes and arranges their start time. In the simulation model, the furnace cycle starts with the warm-up period which helps to create a production schedule for the casthouse operations. After the warm-up period in the simulation the first process “preparation” begins to set the batch properties when necessary.

The second process “cold metal addition” depends on the transportation logic in the model. When the target amount of cold metal is loaded into the furnace then the burners turn on to melt the metal. Duration of the pre-heating process, excluded the duration of stirring process, is calculated as shown in equation (4.8). In the middle of the pre-heating, the stirring process is activated if it is included in the furnace operation cycle. The stirring process duration is not included in the pre-heating duration because it is simulated as a discrete event.

$$MD = \frac{TScA + TCMA}{AvgMR}$$

(4.8)

where;

MD= Melting duration (min)

TScA= Total amount of scrap metal addition (ton)

TCMA= Total amount of cold metal addition (ton)

AvgMR= Average melting rate of the furnace (ton/min)

After reaching the end of the melting duration, the hot metal filling process is triggered. The hot metal filling process is ended with the last crucible transport that accomplishes the required hot metal amount. With this event the holding process is triggered in the furnace cycle. The duration of the holding process, which also contains the alloying process duration, is pre-defined in the system depending on the operation and furnace characteristics. Skimming and sampling are excluded from the holding operation. They are mapped as discrete event processes.

The start time of the casting process which has a constant duration depends on two criteria, one is the termination of holding process and the other is the availability of the casting unit. If the casting unit is not ready at the end of the holding process, then the system continues with the holding process by changing the state of the furnace to „Waiting for Casting". When both of these criteria are satisfied then the casting process is triggered. At the end of the casting process if the start time of the next batch is not reached then the furnace turns its state to "Idle". Figure 29 shows the flow of control logic behind the furnace management concept after the furnace process "holding".

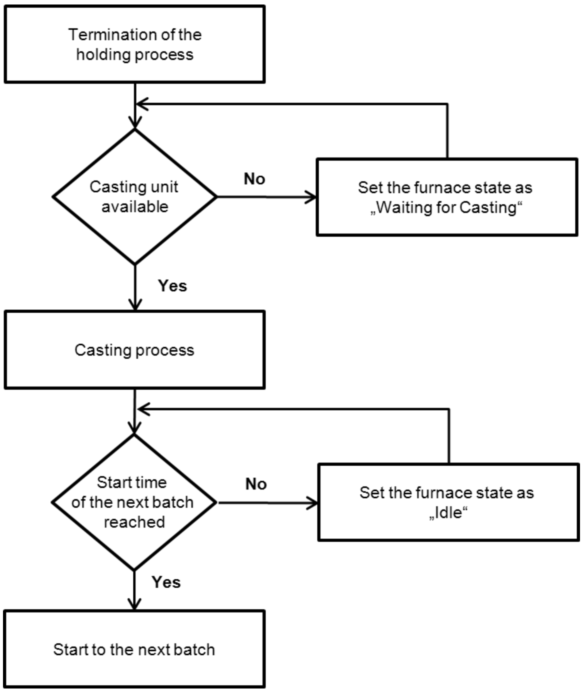

Figure 29 Control logic of the furnace management after the holding process

4.5.4 Storage Management Concepts

The strategies behind storage management used by the facilities depend on criteria such as material flow characteristics, material type, transportation unit, and storage properties etc. Logistical simulation studies were performed to analyze some of these strategies in different industry fields ([DD07], [BPS08], [LJI02], [SER06]). A practical usage of the storage strategies in aluminium casthouse supply chain can be seen on stocking of scrap, cold metal and final goods storage concept.

The handling operation for the cold metal may be duplicated due to the drying process and storage space restrictions. To control this replenishment process in between the intermediate storages makes the model complicated. Another important issue for the storage management concept drives from the “door buffering” strategy applied in some casthouses. This “door buffering”, which is defined in subchapter 4.5.5, enables to fill the cold metal to the furnace in one step to minimize the hatch opening duration. The other benefit of door buffering is that it is applicable for special cases like automatic pusher concept.

The replenishment of intermediate storages is triggered by the material sources having defined capacity, which brings the opportunity to push the material from the source to the intermediate storages or another source if the amount of storage reaches its limit. This concept increases the flexibility of material turn over between the storages in the casthouse. Figure 30 shows the strategy behind the storage management concept.

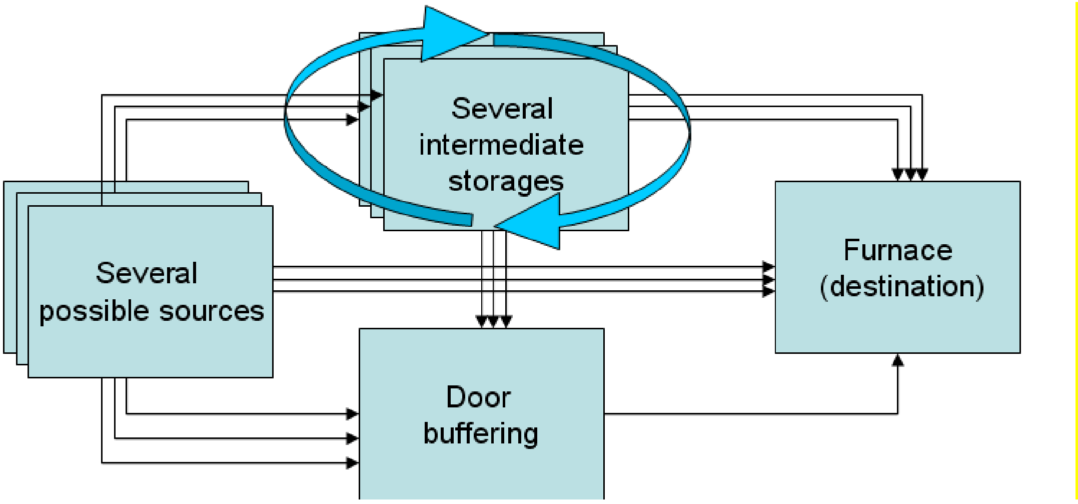

Figure 30 Strategy behind the storage management concept

The delivery plan, which contains the information like supplier identification, material category, material type, SKU specifications, amount, delivery date, delivery type etc., triggers the incoming material flow. All of the data, specifying the material, is carried with the material load until the furnace filling. Therefore, system enables the traceability of incoming materials to support at the decision gates in the concept.

Incoming Material Stocking Strategies

In the simulation model, several strategies are prepared for the material unloading process [Des210], because this process differs from plant to plant depending on the transportation type, plant location, safety regulations, supplier contract etc.

Two main steps require more attention during the incoming material stocking. One is the unloading from the transportation unit and the other one is the bay selection for the material in the internal storage.

Two concepts are considered for the material unloading process:

1. Always unload at first to a temporary area to enable quality check and create a decision point for bay selection at the next step.

2. Direct unloading to the internal storage, at which the quality check and bay selection are done before the unloading process. In this concept incoming material stays on the transportation unit during the acceptance process which causes long waiting time for the transportation unit.

For the bay selection decision four alternatives are prepared:

1. According to the type of material, to the first available storage based on the index (sequence of definition) is selected.

2. According to the type of the material, to an available storage selection of which based on the defined selection criteria; such as supplier identification, quality etc.

3. To the predefined bay if there are strict storage rules in the system

4. Always to an empty storage, the first available storage from the storage definition sequence is selected.

Storage Control Alternatives

Three storage control alternatives are established according to the characteristics and complexity of the system. These alternatives can be seen as the complexity stages of the control mechanism. Each alternative has its own principles concerning the stocking, filling and emptying practices [Des110].

- *<u>Default:</u>* If no details are specified, this concept generates simplified material flow. The only stocking criterion is the amount of the storage. This concept pulls material when the amount of the storage reaches its predefined minimum level. The source of the system has infinite capacity and a delivery plan is not needed for this concept. Basic FIFO principle is applied to remove material from the storage.

- *Intermediate:* Enables to control the system better than the default concept by identifying details about storage management and the system layout. The stocking criterion depends on the material category. The filling strategy is still a pull concept which does not require detailed delivery plan. For the emptying principle, a FIFO concept, paying attention to the storage replenishment application, is applied.

- *Advanced:* Compared to the intermediate concept the material type is in focus for the stocking. A detailed delivery plan manages the filling process. With this principle, the storage areas have to be mapped in detail on the system layout to be able to define the boundaries. If there is not enough storage places compared to the material type than system obeys the material category rules (defined in subchapter 4.4.3.

All of these concepts are prepared to analyze the casthouse supply chain in the simulation environment as close as possible to the reality. Additionally these alternative approaches enable the user to implement the simulation model to different casthouses. Flexibility and complexity of the model are increased by providing alternative control strategies in the forehand.

4.5.5 Scrap & Cold Metal Filling Strategies

Strategies applied for the scrap and cold metal filling into the furnace depends not only on the buffering concept but also on the transportation type. In most cases the characteristics of the casting furnace decide for the filling strategy. From the logistical perspective the material flow in between the main material storage and the casting furnace depends on the material SKU type, distance in between source and sink, availability of the transportation resources and the filling specifications of the casting unit. Figure 31 shows the common approaches for the furnace filling strategy. The strategy enables to generate simple transportation in between storage and the unit without “door buffering”. Although the door-buffering concept doubles the transportation, it eases the resource allocation. Another advantage of the door buffering concept is the heat loss reduction during the filling operation. The door buffering concept reduces the iterative filling process time which forces each time opening the lid of the furnace.

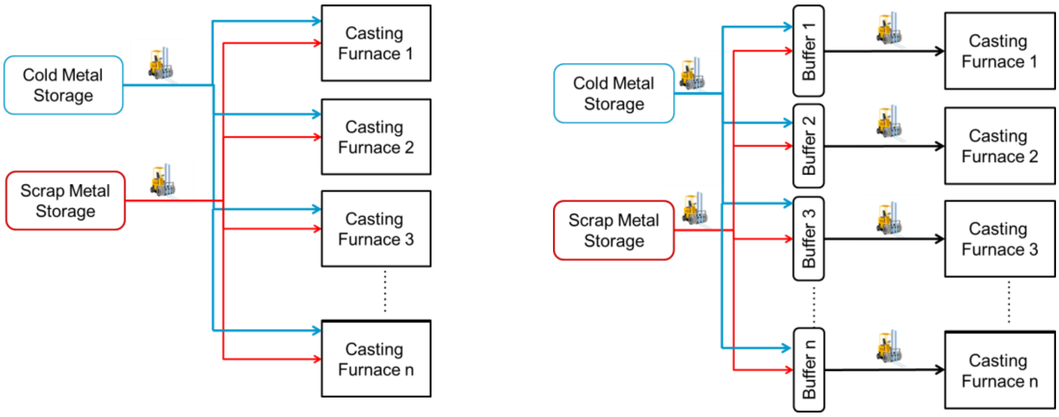

Figure 31 Furnace filling strategy (left) without and (right) with door buffering

Specified by the furnace and material characteristics, in some cases similar to the door buffering concept, all of the required material are firstly filled into a box. The transportation equipment can be a front loader with shovel or a simple forklift. Depending on the system, the box is emptied into the furnace by front loaders or automatic pushers. This concept is common for the re-melting furnaces or the casting furnaces having burners with higher heating power. Compared to the other concepts, the filling process into the furnace is handled in one step. Figure 32 describes the transportation process in between storage and furnace.

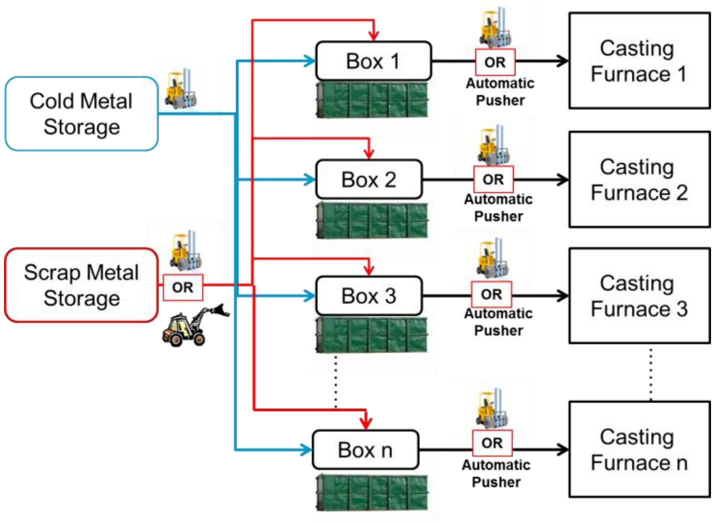

Figure 32 Furnace filling strategy with a box

5 Lean Thinking Approach in the Primary Aluminium Casthouse Supply Chain

After preparing the simulation model for the primary aluminium casthouse supply chain, in this step of the research the results of the model are analyzed. Possible wastes from logistical point of view are defined and reasons behind these non-value added activities are specified. The waste categorization in the lean thinking approach is the main driver of the analysis. Additionally, possible improvements are highlighted to reduce the non-value added costs in the supply chain.

5.1 Introduction and Literature Review

The aim of the lean thinking approach is to increase the efficiency in an application field. It was developed for the automotive industry which has batch-wise production. The implementation of lean thinking comprises of three steps. At first, the material and information flow are mapped to analyze the system which was done in the previous chapter. Then according to the results of the simulation model, wastes are identified and finally potential improvements are defined to eliminate these wastes. The improvements are discussed in the next chapter where the aim of the optimization models is defined.

Wastes are identified in the supply chain by differentiating between value added activities and non-value added activities in the flow. Wastes or non-value added activities in this context contain the processes which do not create any value in the production cycle of the product. There are seven groups of wastes categorized in the lean thinking approach [Ohn88]. These groups are: Overproduction, waiting time, unnecessary transportation, poor processing, inventory, extra movements and defective products.

According to Abdullah [Abd03], the application of the lean thinking approach to continuous processes is not that common compared to discrete manufacturing. It was created for the automotive industry which has discrete assembly operations instead continuous processes. Therefore, the number of publications concerning lean thinking in metal industry is restricted (e.g. steel production [Abd03], steel mill facility [AR07] and chemical process industry [Mel05]). The casthouse supply chain can be defined as a mixed system which combines continuous and batch-wise production. The continuous process in electrolysis has an impact on the batch-wise production of casting furnaces.

In the primary aluminium production, cost reduction was studied in different fields of the smelters. However, the focus of these studies was mostly on process improvement of the production. A few of the studies in the literature have the aim to improve efficiency of the system by focusing on the non-value added activities. Meier [Mei11] did a study for an Electrolysis area by focusing logistical activity flow.

Studies done in the casthouse area were mostly focused on a single concept in the supply chain. For example, Peterson et. al. [PN02] studied to minimize gross melt loss during skimming process. Jensson et. al. [JKG05] and Yuan et. al. [YKSBT04] examined the casthouse production in minimizing the setup times. Maiwald et. al. [ML06] focused on finding optimum temperature regime in casting furnace which has impact on productivity and efficiency. Gravel et. al. [GPG02] followed a closer approach to analyze the scheduling problem by aiming to reduce hot metal waiting time, tardiness and early production. However, they did the optimization for each waste separately without combining them.

In this thesis, the lean thinking approach is applied to all possible non-value added costs occurred due to logistical activities.

5.2 Waste Analysis in the Casthouse from a Logistical Point of View

In this subchapter, the results of the simulation model are analyzed from a logistical point of view and the wastes are identified. The analysis contains the non-value added costs depending on logistical activities such as traffic, transportation, buffering, stocking, production planning and scheduling etc. Additionally, it is also described how these items are quantified and measured in the simulation model.

5.2.1 Overproduction in the Casthouse Supply Chain

Overproduction means in lean thinking producing more than demanded. In a primary aluminium casthouse, there is a considerable surplus production. There are several reasons for the surplus. The first one is the campaign production principle. In this strategy, uninterrupted production of the same material type is done in the same casting furnaces and unit. For example, this principle is preferred in casthouses to prevent the wash-up process due to different alloy usage.

The second reason of surplus production is the continuous hot metal supply from the electrolysis unit which cannot be stored without casting. Therefore, it is not possible to stop the casting in casthouse even if there is not any customer order for a batch.

The solution for such inconsistencies is found by matching the surplus with a customer order after the production. Therefore, surplus material is stored in the casthouse for a while to be demanded by customers. The difference between customer orders is based on specifications of product such as dimension of the material and its alloy type. Therefore, the surplus material is produced with the most common alloy types and in common dimensions.

There is another reason of overproduction which also causes to produce surplus material. After splitting customer orders to batches, the amount of the last remaining part of the customer order can be lower than the production capacity of the casting furnace. The energy consumption during the furnace holding process does not vary so much with the amount of material in the furnace. In other words, the energy used to heat up the furnace and to hold it with a constant temperature does not depend on the amount of material in the furnace. Therefore, the casthouse unit follows the strategy to produce a batch the amount of which is closer to the capacity of the furnace. This strategy may cause to produce more metal than the customer order. A solution for this problem is to split the customer orders in an optimized way to the casting furnaces to get less amount of surplus material. However, this cannot be a hundred percent solution of the problem, it only reduces the overproduction.

As mentioned, surplus materials are stored until a customer order matches the specifications. If the surplus does not satisfy any customer requirement within a certain time frame then it will be re-melted in a casting furnace as cold metal.

In the simulation model, the surplus materials are transported to surplus storages according to the data flow from the batch plan. If the customer identification column in the batch plan is empty or specified as "surplus", than the type of material is also considered in the simulation model as "surplus". The material amount in the surplus storage is updated periodically and shows the current status of the storage.

5.2.2 Waiting Time in the Casthouse Supply Chain

Waiting time of resources such as transportation units, casting furnaces and casting units creates not only direct non-value added costs but also inconsistency in the production planning and scheduling. Logistical activities in the casthouse have direct impact on waiting time. Possible reasons of waiting time in casthouse supply chain are discussed after describing how these waiting durations are measured in the model.

The casting furnaces are the production units in the casthouse, so the analysis on waiting duration has these units on focus. Two reasons of waiting time are specified in the simulation model after analyzing the status of casting furnaces. The first reason is the relation between processes such as hot metal flow and furnace charging. And the second one is the resource unavailability such as waiting for the casting unit or waiting for a special tool (e.g. skimming, stirring, packaging processes).

Hot metal waiting time is caused by delays in the tapping schedule which can also create disturbances in the production schedule of casthouse. On the other way around, poor scheduling in casthouse may cause also tardiness in hot metal transportation. This waiting duration of casting furnaces is specified in the simulation model by considering the hot metal filling process duration and the state of casting furnace resource in "Hot Metal Filling".

Resource unavailability can also cause the casting furnace to wait for processing. Two examples in the simulation model are observed for this case casting furnaces wait either for a skimming machine or for the assigned casting unit. The waiting duration of a skimming machine can be ignored because the process duration of skimming is not that long. However, the waiting duration for a casting unit cause considerable amount of delay in the batch production. This waiting duration increases the batch lead time considerably.

Simulation time(min)	Furnace ID	Batch ID	Process Definition	Process Duration (min)
630.0	Furnace 1	10001	0_Preparation	0.0
630.0	Furnace 1	10001	1_Cold Metal Addition	21.0
651.0	Furnace 1	10001	2_Pre-heating	52.0
703.0	Furnace 1	10001	3_Hot Metal Filling	42.0
745.0	Furnace 1	10001	4_Holding	20.0
765.0	Furnace 1	10001	5_Alloying	17.0
782.0	Furnace 1	10001	4_Holding	50.0
832.0	Furnace 1	10001	Waiting for Casting	18.0
850.0	Furnace 1	10001	6_Casting	120.0
970.0	Furnace 1		7_Idle	50.0
1020.0	Furnace 1	10002	1_Cold Metal Addition	28.0

Table 4 An example of a furnace status tracing in the simulation model

The batch lead time of casting furnaces is measured in the simulation model by tracing the start time and end time of batches. Start time is captured when the casting furnace is triggered for the first process of the batch. End time is captured when the last metal is transported to the casting unit and the status of the furnace turns to “idle”. In the example presented on Table 4 the start time of the batch was recorded as “630” minutes after simulation was started and end time of the batch is captured as “970” so the batch lead time is calculated as 340 min for this example.

The waiting durations in the simulation model is also measured by highlighting the resource utilization graphically and also by preparing a data table showing the activity of this resource per time. For each resource, a set of states is attached to specify its current activity. Vehicles and production units have their own state definition. In other words, the possible states of the resources are categorized for each resource type.

The figure below (Figure 33) shows an example of resource utilization output from the model of a production facility. This example highlights the percentage of resource states for the casting furnace in a casthouse. The states such as casting, hot metal filling, alloying, skimming, stirring, holding, sampling, waiting for casting, cold metal loading, and scrap loading and burning are some of the possible states of casting furnace. The duration and percentage comparison help to analyze the furnace efficiency and also unexpected high proportion due to delays.

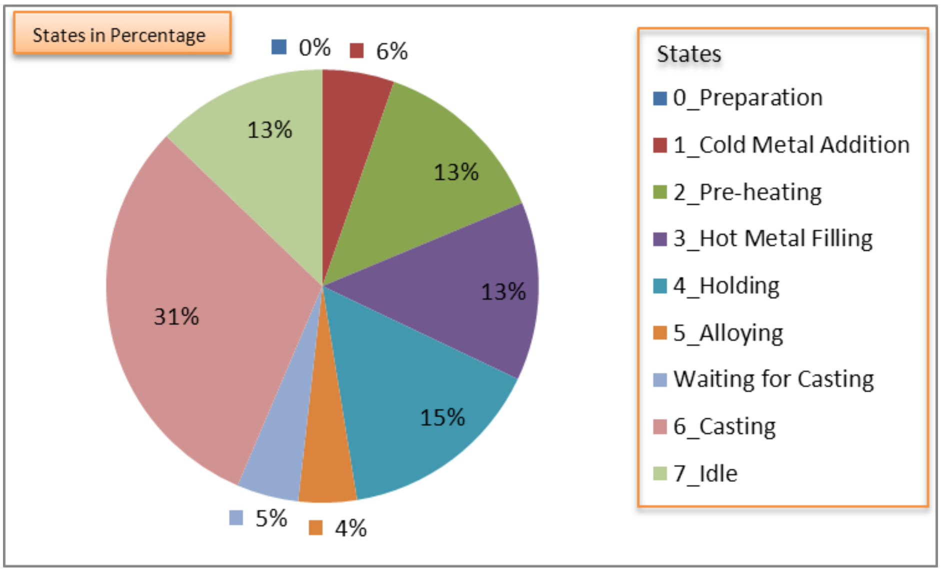

Figure 33 Example utilization graph of a casting furnace in percentage

Vehicle utilization can also be gathered from the simulation model. The states of the vehicles in the system are defined as waiting, retrieving, parking and delivering. “Waiting” represents the duration without any movement occurred while performing a task. It contains for example, possible disturbances due to the traffic or possible delays due to processes or possible bottlenecks due to the resource usage. The second state named as “Retrieving” represents the empty travel duration spent on the way to the next scheduled task. “Parking” shows the time spent at the parking area. The last state “Delivering” represents the travel duration while carrying a load. Figure 34 shows one example of forklift performing tasks such as furnace filling, storage reshuffling etc.

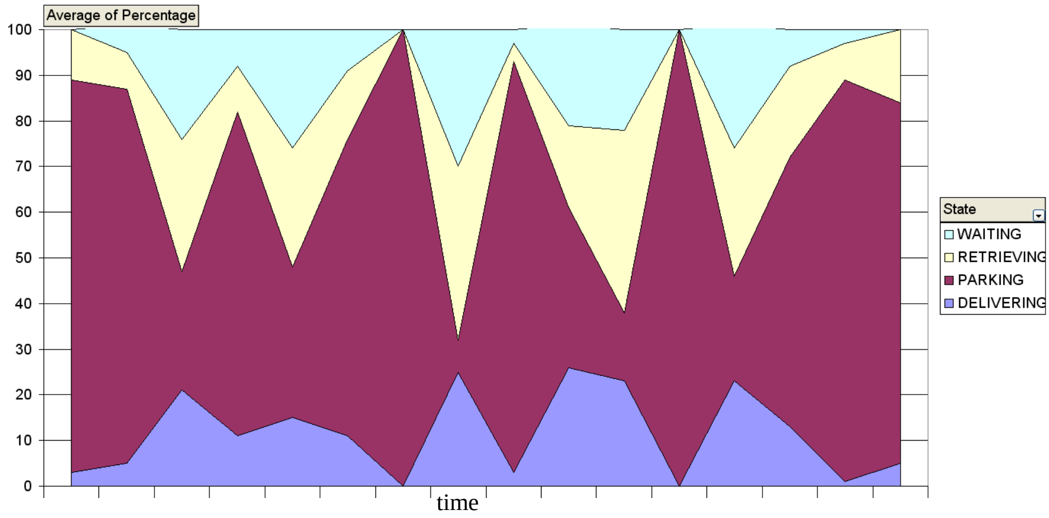

Figure 34 An example utilization graph of a transportation unit in percentage

5.2.3 Unnecessary Transportation in the Casthouse Supply Chain

Waste in transportation contains the relocation of materials which does not add value to the analyzed system. Other waste groups of the lean thinking approach (such as waste in processing, waste in inventory etc.) have direct impact on the concept "waste in transportation". However, storage reshuffling brings extra cost which is not included into any group of waste.

The storage reshuffling depends on the capacity of storages and inventory strategy of a casthouse. One reason of reshuffling is that the amount of the assigned product extends the stock capacity. Then the materials are transported to another stock area. Another reason is that some storage areas are assigned for specific processes such as drying due to their location (for example closeness to the furnace). Therefore, incoming materials transported from outside of the casthouse are firstly stored in this area then distributed to another storage place.

It is possible to quantify the transportation cost of storage reshuffling in the simulation model. And also alternative strategies can be selected in the model to map advanced storage concept. However in this waste, the root of the problem is the operational strategy of the casthouse. The possible improvement forces to change the operational strategy in the casthouse.

5.2.4 Inefficient Processing in the Casthouse Supply Chain

In this part of the lean thinking concept, the logistical activities such as production planning and process scheduling can be included. These activity coordination processes may cause waste in the supply chain such as longer idle time in furnaces or late delivery of order. For example, poor production planning in combination with unexpected delays in the casthouse may cause to ship the material later than the planned delivery date. This waste is measured in the simulation model in a way that after leaving the last production station, the delivery date is checked for the material. If the delivery date has already passed then the late delivery penalty is added to the non-value added costs depending on the delay and the penalty rate.

Another waste in processing can be the idle time of casting furnaces between two batches due to unavailability of assigned casting line. This waste can occur when two or more casting furnaces are assigned to the same casting unit. In this case, scheduling has to be done by considering the availability of casting unit. If the schedule is not carefully prepared then the casting furnaces wait longer than planned. The idle time of the furnace is calculated by capturing the trigger time of the last processes of the previous batch and the first process of the next batch. The duration in between is recorded as an idle time. For the example presented on Table 4, the idle time is measured as 50 min for the batch “10001”.

In this research, the focus is only on the discrete logistical events occurring in a casthouse. Therefore, metallurgical processes are not in the scope of the study. Processes in the casting furnace are mapped as duration in the simulation model. If a process is not affected by the traffic in the casthouse or any resource availability then this duration does not vary during the simulation run.

5.2.5 Inventory of the Casthouse Supply Chain

A poor inventory management in a supply chain requires extra space, extra handling and extra costs [ITC04]. Therefore, the waste due to inventory management is determined in the simulation model by two different methods. The first one is highlighting the storage status by measuring the amount in the storage and the total retention time of the products spent in the storage periodically. The second one is focusing on a specific product to analyze resulting costs for inventory, handling etc. in the casthouse.

There are three groups of materials that are stored in casthouse. They are:

- Incoming materials containing cold metal, external scrap and alloys
- Internal scrap and surplus materials which are supplied from the production
- Finished goods which are ready for the shipment to customer

Incoming materials enter the supply chain according to a delivery plan provided by a supplier. In the simulation model, the external truck transport is triggered by these delivery plans, which are defined statically at the beginning of the simulation run. Unloading the truck has an effect on the activities in the supply chain due to the resource allocation and the traffic. However, mostly individual resources like forklifts are dedicated for external truck unloading. In this study, a static delivery plan and a particular resource allocation makes it difficult to find any improvement in the incoming material inventory with the help of the simulation model.

The second group of materials is supplied directly from a casting unit. They are transported to their assigned storage and according to the batch plan allocated to a furnace. Scrap materials are created in the simulation model according to the historical quality deviation of the casthouse which is statically implemented. The inventory cost for the surplus products is measured in the simulation model by highlighting the storage amount and measuring the utilization of the allocated transportation unit. These costs can be reduced by lowering the amount of surplus material.

The last group contains the finished products for shipment to customer. According to the shipping type specified in the customer order, they are stored in the casthouse. Before shipment, in most cases some days are needed to prepare the order for the shipment such as paperwork. However if the product is produced earlier than this time then it creates extra inventory cost for the casthouse. It is possible to measure this inventory and also the transportation cost in the simulation model. This non-value added cost can be eliminated or reduced by optimizing the production plan of a casthouse.

5.2.6 Unnecessary Movement in the Casthouse Supply Chain

Waste of movements contains the motions of resources, tools or people which do not add value to the analyzed system. The furnace charging strategy and the routing strategy of tapping vehicles in a casthouse may cause extra movements of resources which create not only extra handling cost but also possibility to damage the equipment or product during movement. Strategy in furnace filling such as charging box usage adds also extra tool handling.

The simulation model concept is developed to map alternative strategies for the furnace charging. However in this case, the root of the problem is the operational strategy of a casthouse. Although it is possible to quantify the transportation cost for the box usage, potential defect cost cannot be measured in the simulation model. And also any improvement requires changing the strategy of furnace filling concepts.

The routing of tapping vehicles can create non-value added costs which can happen due to one-way rule for tapping vehicles in casthouses in terms of safety. It eases the traffic and helps to prevent tapping vehicles encounter with any other vehicle which may create a danger. It is possible to measure the travelled distance and also the utilization of vehicles in the simulation model. Although finding another routing path for tapping vehicles may improve this situation and reduce the non-value added costs, it is not allowed in casthouses to change one-way rule if it is requested by safety regulations

5.2.7 Defective Products in the Casthouse Supply Chain

In general, a quality check is done after the casting process directly in the casthouse. Surface finish, cracks and dimensions are the main characteristics of the products that are controlled during this process step. The rejected products are called production scrap which has to be differentiated from the external scrap material. It has high purity and can be melted as cold metal in further batches. The internal scrap is transported to the scrap storage and then according to the batch allocation reshuffled to a cold metal storage or directly to the furnace.

In the simulation model, the quality deviation of production scrap is parameterized so it is just defined as a percentage in the logic. However, the percentage does not change during the simulation so it is not required to measure the internal scrap amount in the simulation model. Transportation of the production scrap from the casting line to the storage and to the furnace is mapped as a discrete event in the simulation model.

5.3 Summary of Waste Analysis

Each group of waste in the casthouse supply chain was analyzed and some of them were specified for the improvement. The process of elimination or reduction of wastes contains optimization models which focus on these non-vale added costs. The categorization of wastes depending on improvement potential within the scope of the optimization model is listed on Table 5. Some of them are kept out of the scope of the optimization model. The reasons of the exclusion are also defined in the same table, and the extended explanation for these reasons can be found in the previous subchapter.

	In Scope	**Out of Scope**	**Reason**
Waste of overproduction	Surplus production		
Waste of waiting time	Hot metal waiting time		
	Longer batch lead time		
Waste in transportation		Storage reshuffling	Problem of the operational strategy
Waste in processing	Longer idle time in furnaces		
	Late delivery of an order		
Waste in inventory		Inventory of incoming materials	Improvement approach not suitable
		Inventory of internal scrap and surplus	Integrated into surplus cost
	Inventory of finished goods		
Waste of movement		Furnace charging strategy	Problem of the operational strategy
		One-way rule for tapping vehicles	Safety aspects
Waste of defective products		Rejected products in quality check	Improvement approach not suitable

Table 5 Categorization of wastes depending on improvement possibility in the scope of the optimization model

6 Optimization Model Development

After analyzing the non-value added logistical costs in aluminium supply chain (with the help of the simulation platform and the lean thinking approach), the next step, development of the optimization part, is discussed in detail in this chapter. For the optimization of aluminium casthouse supply chain, two models are developed. The first one is the short-term production planner and the second one is the production scheduler. These models are described in detail with their objective functions, constraints and variables. In addition to those, interfacing platform between simulation and optimization parts is explained in the last section of the chapter.

6.1 Introduction and Literature Review

The optimization part of this study contains two different models which aim to minimize the non-value added costs due to logistical activities. The aim of the first tool is to create a production plan which is capable of distributing the customer orders to the batches for casting furnaces and also allocate these batches to the appropriate furnaces. Tang et. al. [TLRY01] created a production plan in the same direction for the steel casting plant. Their objective was to increase the productivity and energy saving.

Nonas et. al. [NO05] also focused on production planning of foundry and their objective was to find an efficient plan which minimizes late delivery. Pacciarelli et. al. [PP04] created a production plan with the same objective for steel casting plant. Tan et.al. [TK05] studied rearranging customer orders with the help of computerized method for the casting unit. They succeeded in reducing scrap metal 20% with the new approach.

The aim of the second tool is to schedule the production in aluminium casthouse by arranging the operations at the casting furnaces. This part of the study has a close interaction with the electrolysis part of the smelter due to the impact on the hot metal flow management. According to Freeman et. al. [FKZM05] the basic of casthouse scheduling can be identified as the combination of problems known as:

- Lot-sizing
- Sequencing
- Scheduling

This definition is based on the combination of continuous operations (e.g. aluminium production in electrolysis) and batch–wise processes (e.g. pot tapping, crucible transport and furnace filling). Therefore, batch-optimization formed the main focus of many studies such as: iron and steel enterprise [TW08], small foundry [AAC08] and aluminium foundry [Rya98] and [Pie08].

Maticevic et.al. [MML08] dealt with scheduling issues in aluminium foundry by aiming to minimize the tardiness in production. Gravel et. al. [GPG02] also studied the scheduling problem in an aluminium casting center by aiming to reduce:

- Set-up time
- Hot metal waiting time
- Tardiness
- Early transportation penalty

Tikasz et. al. [TMPB12] highlighted the benefits of testing the production schedule of aluminium casthouse in the simulation platform. However, after detailed literature survey, any published study about interfacing a production plan or schedule with simulation platform for the aluminium casthouse could not be found. Therefore, the methodology for the interfacing is kept in general which is defined by Matta [Mat08]. According to this study, simulation model sends “system performance” to optimization model and receives “system alternatives”.

6.2 Model Structure

As mentioned, the optimization part, containing two models, aims to minimize the non-value added logistical costs in the internal aluminium casthouse supply chain. The first model is named as "Short-term production planner" which is discussed in sub-chapter 6.3. The second model called "Production scheduler" is detailed in sub-chapter 6.4. These two optimization models have the same structure. Both of them were modeled in MS Excel environment and use the "OpenSolver" optimization engine to find the optimum solution.

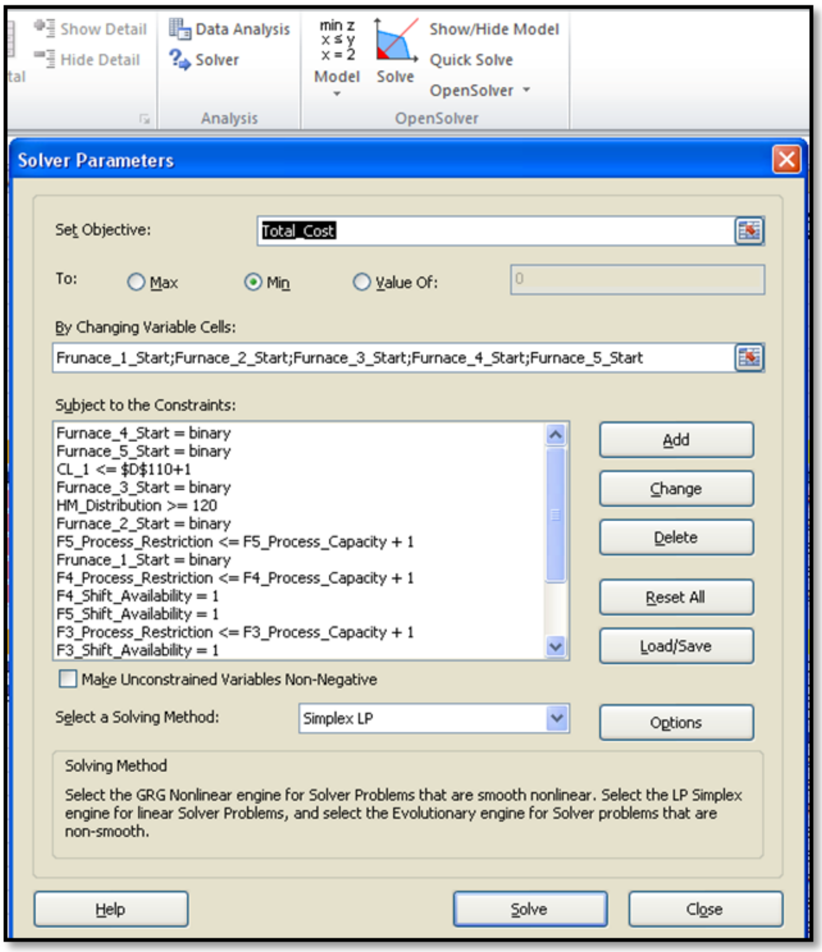

Figure 35 Optimization platform in MS Excel

Figure 35 shows the optimization platform prepared in MS Excel. The objective function, constraints and variable definitions are defined in excel solver platform without paying attention to its limitations. Macros defined in "OpenSolver" are used to solve the optimization models of the study. Integer linear programming method is used to program the logic behind the optimization concept.

Input data is received from customer orders and system specifications, both of which are prepared in MS Excel environment. The first tool distributes the customer orders to the batches and then allocates them to the furnaces. The data provided from customer orders contains the information such as:

- Customer identification number
- Sales document number
- Material type
- Dimension of material
- Alloy type
- Date of delivery
- Total delivery weight
- Priority of order
- Region of order

With this data, the optimization tool tries to find the best combination of batches appropriate casting furnaces. After solving the optimization problem, the data is converted to the batch plans which are read by the simulation model.

The second tool schedules the operations for the casting furnaces in the casthouse. The data gained from system specifications contains the information about:

- Duration of each process
- Process sequence for each furnace
- Furnace characteristics (e.g. capacity, melting rate etc.)

- Relation in between casting furnace and casting line
- Hot metal distribution and transportation strategy
- Needed time between two different alloys based production

With this data, the optimization tool seeks the best production schedule for the whole system.

6.3 Short-term Production Planner

Primary aluminium casthouse which produces the final form of product is the last facility of primary aluminium supply chain. Therefore, it has direct contact to customers. The costs due to this contact (e.g. late delivery) may be high and cannot be easily compensated. For that reason the production has to be well planned and followed by the production unit.

6.3.1 Aim of the Model

The aim of the short-term production planner model is to minimize the non-value added costs occurring due to the production planning. The model handles the problem by focusing on the casting furnaces. The main parameters of the model are number of batches per shift per furnace, capacity of furnace, allocated casting unit and production period. Customer orders are distributed with respect to the possible number of production per furnace in a day. The planning period can be extended by defining more parameters to increase the time frame. In "OpenSolver" optimization engine, there is not any limitation for the number of parameter so the planning period depends on the user.

Figure 36 shows a snapshot of the optimization model which is prepared as an example for five casting furnaces (represented as F_1, F_2, F_3, F_4, and F_5) with two casting lines (represented as CL_1 and CL_2). The example has one batch production per furnace per shift. This figure shows the batch distribution in the matrix as placing "1" under the assigned furnace number and across the sales document number which identifies the customer order. This assignment complies with the constraints:

- Capacity of the casting furnace (batch capacity)
- The relation between casting furnace and casting line
- Casting line availability and utilization
- Capacity of assigned casting line

			Day_1														
			Shift_1					Shift_2					Shift_3				
			CL_1			CL_2		CL_1			CL_2		CL_1			CL_2	
Index	Customer Identification Number	Sales Document Number	F_1	F_2	F_3	F_4	F_5	F_1	F_2	F_3	F_4	F_5	F_1	F_2	F_3	F_4	F_5
1	106	106101	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1
2	117	117101	0	0	0	0	0	0	1	0	1	0	0	1	0	1	0
3	122	122101	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0
4	105	105101	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
5	113	113101	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	125	125101	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	112	112101	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
8	111	111101	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Figure 36 Snapshot of the first optimization tool

6.3.2 Objective Function

The objective of short-term planner tool is to minimize the costs due to;

- late delivery of the order
- early production causing the inventory cost at the storage of final goods
- surplus material because of more production than customer demand

The indices used in the optimization model are:

- furnace Furnaces in the casthouse
- order Customer orders

- batch — Produced unit of a customer order
- timeslot — Slots that shift duration is equally divided in
- shift — Shifts in the optimization period

The parameters used in the optimization model are:

- m — Total number of furnaces in the casthouse
- k — Total number of customer orders
- n — Total number of produced batches
- t — Total number of slots
- s — Total number of shifts
- $FurAv_{furnace\ shift}$ — Number of batches assigned to the furnace per shift
- SmFurCap — Capacity of the smallest furnace in the system (ton)
- $BtAm_{order\ batch}$ — Amount of the batch of the order (ton)
- OAm_{order} — Amount of the order (ton)
- $OPri_{order}$ — Penalty rate of the order depending on the customer
- $LaProT_{order}$ — Latest production time that is planned for this order (day)
- BAm_{batch} — Amount of the batch (SKU)
- $DelT_{order}$ — Delivery date of the order (day)
- SalesPr — Sales price of the product (Euro /ton)
- PenRate — Penalty rate (% per day)
- ManHrC — Man hour and equipment cost (Euro/ SKU / day)

- InvC Inventory cost (Euro/ SKU / day)
- CMC Market price of external cold metal (Euro /ton)

The decision variables of the optimization model:

- $FurCS_{furnace\ timeslot}$ Current status of the furnace per timeslot
- $SurpAm_{order}$ Amount of over production per order (ton)
- $ODel_{order}$ Duration of the delay for the order (day)
- $ProT_{order\ batch}$ Production time of the batch belonging to the related order (day)
- $BRet_{batch}$ Retention time of the batch in the end product storage (day)

The objective function of short-term planner tool*:*

Minimize COST_LD + COST_EPS + COST_SR

(6.1)

subject to;

$$FurCS_{furnace\ timeslot} \in \{0, 1\} \qquad \forall_{furnace}, \forall_{timeslot}$$

(6.2)

$$\sum_{timeslot=1}^{t} (FurCS_{furnace\ timeslot}) = FurAv_{furnace\ shift} \qquad \forall_{furnace}, \forall_{shift}$$

(6.3)

$$SurpAm_{order} = \sum_{batch=1}^{n} (BtAm_{order\ batch}) - OAm_{order} \qquad \forall_{order}$$

(6.4)

$SurpAm_{order} <= SmFurCap \quad \forall_{order}$ **(6.5)**

$SurpAm_{order} >= 0 \quad \forall_{order}$ **(6.6)**

$ODel_{order} = \max[0, (ProT_{order\ batch} - LaProT_{order})] \quad \forall_{order}, \forall_{batch}$ **(6.7)**

$BRet_{batch} = \max[0, (DelT_{order} - ProT_{order\ batch})] \quad \forall_{order}$ **(6.8)**

where;

COST_LD	Punishment cost of late delivery
COST_EPS	Inventory cost for waiting at the end product storage
COST_SR	Cost of surplus products

6.3.3 Equations of Costs in the Objective Function of the Short-term Production Planner

Punishment cost of late delivery

This cost contains the extra payments that have to be paid to customer due to the late delivery. The amount of penalty depends on duration of the delay, amount of the order and priority of the order. The formula of "Cost_LD" can be seen in Equation (6.9).

$$Cost\_LD = CoeffLDtoCost * \sum_{order=1}^{k} (ODel_{order} * OAm_{order} * OPri_{order}) \tag{6.9}$$

where;

CoeffLDtoCost	Coefficient of the equation for the cost conversion

The delay of the order in this frame can be analyzed in detail with respect to production date and delivery date. The reason of this analysis is to create a connection between order and batch which is produced later than planned. Equation (6.7) shows the formula for determination of delay of the order in the optimization model.

End product storage cost:

The inventory cost of early produced batches which depends on waiting duration in the end product storage forms the main part of "Cost_EPS". Early produced batches require not only storage space but also additional handling cost. This extra transportation cost is also taken into account in the coefficient (shown in Equation (6.13)) of Equation (6.10). Equation (6.8) shows the detailed analysis of retention time calculation of batch in the end product storage.

$$Cost\_EPS = CoeffEPStoCost * \sum_{batch=1}^{n} (BRet_{batch} * BAm_{batch}) \qquad \textbf{(6.10)}$$

where,

CoeffEPStoCost Coefficient of the equation for the cost conversion

Surplus cost:

As mentioned in Chapter 5, the amount of the batch, which depends on the casthouse and system characteristics, in most cases is nearly equal to the effective capacity of a furnace due to system efficiency. Therefore, the produced amount is sometimes more than the amount of the customer order. If the overproduced amount is not requested by customer in a defined time frame, the extra production will become production scrap. The coefficient (shown in Equation (6.14)) of Equation (6.11) contains also the extra storage and transportation cost in an average value during this waiting time.

$$Cost\_SR = CoeffSRtoCost * \sum_{order=1}^{k} (SurpAm_{order})$$

(6.11)

where;

CoeffSRtoCost Coefficient of the equation for the cost conversion

6.3.4 Equations of the Conversion Coefficients

Equation (6.9) calculates the penalty cost due to late delivery. Without the coefficient, the formula determines the delay of order in unit “ton * day”, so the formula has to be converted to cost unit “Euro”. For that reason the coefficient which is calculated by Equation (6.12) is used.

$$CoeffLDtoCost = SalesPr * PenRate$$

(6.12)

Equation (6.10) is used to calculate the cost due to early production. Extra handling operation and storage cost is determined in calculating the coefficient which is used to convert the unit of equation from “day * SKU” to cost unit “Euro” with Equation (6.13).

$$CoeffEPStoCost = ManHrC + InvC$$

(6.13)

To calculate the coefficient used in Equation (6.11) the difference between sales cost and external cold metal cost is determined with the formula (6.14). The reason behind is the usage of surplus material as production scrap which can be substituted with required cold metal in the batch plan.

$$CoeffSRtoCost = SalesPr - CMC$$

(6.14)

6.4 Production Scheduler

After creating the batches from customer orders and allocating them to the casting furnaces, the schedule of processes is coordinated by the tool “production scheduler”. This model is capable of deciding the start time of the operations of casting furnaces by aiming to reduce the logistical costs occurring due to resource availability, waiting time in the queue and additional handling operations.

6.4.1 Aim of the Model

Like the first optimization model, this tool also focuses on the casting furnaces. The sequence of operations, their durations and starting time are the main parameters of the tool. The logic of the tool divides the time into intervals the length of which depends on the required sensitivity. The shorter the interval means more sensitive the analysis. The length of processes is also determined with respect to the length of the intervals. Figure 37 shows the snapshot of the example model which has a half an hour time interval. In this example the length of the processes are also defined as multiples of 30 minutes that helps to allocate the process to the interval.

	1st Shift															
Furnace\ Hour	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Fur_1	7	7	7	7	7	7	7	7	1	2	2	3	3	4	5	5
Fur_2	7	7	7	7	1	2	2	3	3	4	5	5	6	6	6	6
Fur_3	1	2	2	3	3	4	5	5	6	6	6	6	7	7	7	7
Fur_4	7	7	7	7	7	7	1	2	2	3	3	4	5	5	6	6
Fur_5	1	2	2	3	3	4	5	5	6	6	6	6	6	6	7	7

Figure 37 Snapshot of the second optimization tool

The processes of each furnace have a sequence, an index and duration definition according to the system characteristics of the casthouse. Figure 38 shows another snapshot of this optimization tool. In this snapshot, the process distribution to time for one furnace can be seen. The time interval is also taken as 30 minutes for this example and each process has duration as multiples of 30 minutes. Index of processes and their sequence are seen on the left hand side of Figure 38. Green circles in the matrix show the time and process intersection. When there is a green circle across the process then this means that process takes place at a time at the specified furnace. The last process, “7” in this example, always signifies the furnace idleness.

				1st Shift															
Furnace\ Hour				0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Fur_1				1	2	2	3	3	4	5	5	6	6	6	6	7	7	7	7
Process	***Index***	***Duration (hr)***	***Sq.***																
Cold Metal Addition	1	0.5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pre-heating	2	0.5	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Pre-heating	2	0.5	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2
Hot Metal Filling	3	0.5	3	3	3	3	4	3	3	3	3	3	3	3	3	3	3	3	3
Hot Metal Filling	3	0.5	4	4	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4
Alloying	4	0.5	5	5	5	5	5	5	6	5	5	5	5	5	5	5	5	5	5
Holding	5	0.5	6	6	6	6	6	6	6	7	6	6	6	6	6	6	6	6	6
Holding	5	0.5	7	7	7	7	7	7	7	7	8	7	7	7	7	7	7	7	7
Casting	6	0.5	8	8	8	8	8	8	8	8	8	9	8	8	8	8	8	8	8
Casting	6	0.5	9	9	9	9	9	9	9	9	9	9	10	9	9	9	9	9	9
Casting	6	0.5	10	10	10	10	10	10	10	10	10	10	10	11	10	10	10	10	10
Casting	6	0.5	11	11	11	11	11	11	11	11	11	11	11	11	12	11	11	11	11

Figure 38 Another snapshot of the second optimization tool

The needed data for the application of this tool is:

- The time interval meeting the requirements of the analysis
- Sequence of processes for each furnace
- Duration of each process
- Casting furnace to casting unit assignment
- Hot metal distribution
- Desired furnace utilization with respect to time (e.g. per shift)

6.4.2 Objective Function

The objective function for the second optimization model is shown in Equation (6.15). The aim is to minimize the costs due to hot metal waiting, idle time of the furnace and longer batch lead time. The duration of processes is determined as constant in the optimization part of the study, so the batch lead time is set as constraint in the optimization model but can be measured in the simulation model. Therefore, it is integrated to the objective function of the model but does not have any impact on the calculation.

The indices used in the optimization model:

- furnace — Furnaces in the casthouse
- castingline — Casting units in the casthouse
- batch — Produced unit of a customer order
- timeslot — Slots that shift duration is equally divided in
- shift — Shifts in the optimization period
- process — Processes take place at the furnace

The parameters used in the optimization model:

- m — Total number of furnaces in the casthouse
- l — Total number of casting units in the casthouse
- n — Total number of produced batches
- t — Total number of slots
- s — Total number of shifts
- p — Total number of processes take place at the furnace
- $FurAv_{furnace\ shift}$ — Number of batches assigned to the furnace per shift
- $CLCap_{castingline}$ — Capacity of the casting line
- $FurProCap_{furnace}$ — Process duration capacity of the casting furnace (min)
- $HMCap_{shift}$ — Total planned hot metal amount for the shift (ton)
- $AmHM_{furnace\ batch\ shift}$ — Amount of hot metal per furnace per batch per shift(ton)
- $Cap_{furnace}$ — Capacity of the furnace (ton)

- $BatAm_{batch}$ Amount of the batch (ton)
- PHTP Planned hot metal transportation period in the casthouse
- $BatDur_{batch}$ Lead time of the batch
- $ProDur_{batch\ process}$ Duration of each process in the batch
- PrNoIdle Process number of “Idle process”
- ReqEn Required energy to cast one ton aluminium (kWh / ton)
- EnCost Energy cost (Euro / kWh)
- TotPro Annual production amount of the casthouse (ton/yr)
- SysCap System capacity (total capacity of the casting furnaces) (ton)
- YrtoHr Unit conversion from year to hour (hr / yr)

The decision variables of the optimization model:

- $FurCS_{furnace\ timeslot}$ Current status of the furnace per timeslot
- $CLUti_{castingline}$ Current usage of the casting line
- $FurProAll_{furnace}$ Total process duration allocated to the casting furnace (min)
- $HMTrans_{shift}$ Amount of hot metal transportation in the shift (ton)
- $WTHM_{furnace\ batch\ shift}$ Waiting time of hot metal per furnace per batch per shift (hr)
- $TrHM_{furnace\ batch\ shift}$ Time of hot metal transportation for the defined batch at the furnace in the shift (hr at the current shift according to the shift begin)

- $IdTFur_{furnace}$ Idle time of the furnace (hr)
- Del_{batch} Delay in the batch lead time (hr)

The objective function of the production scheduler is formulated in Equation (6.15)*:*

Minimize COST_HM + COST_FI + *COST_OLD*

(6.15)

subject to;

$$FurCS_{furnace\ timeslot} \in \{0, 1\} \qquad \forall_{furnace}, \forall_{timeslot}$$

(6.16)

$$\sum_{timeslot=1}^{t} (FurCS_{furnace\ timeslot}) = FurAv_{furnace\ shift} \qquad \forall_{furnace}, \forall_{shift}$$

(6.17)

$$CLUti_{castingline} <= CLCap_{castingline} \qquad \forall_{castingline}$$

(6.18)

$$FurProAll_{furnace} <= FurProCap_{furnace} \qquad \forall_{furnace}$$

(6.19)

$$HMTrans_{shift} = \sum_{furnace=1}^{m} \left(\sum_{batch=1}^{n} (AmHM_{furnace\ batch\ shift}) \right) \qquad \forall_{shift}$$

(6.20)

$$HMTrans_{shift} = HMCap_{shift} \qquad \forall_{shift}$$

(6.21)

$$BatDur_{batch} = \sum_{process=1}^{p} (ProDur_{batch\ process}) \qquad \forall_{batch}$$

(6.22)

$$IdTFur_{furnace} = \sum_{batch=1}^{n} (ProDur_{batch\ process}) \text{ for process} = PrNoIdle \quad \forall_{furnace}, \forall_{batch}$$

(6.23)

$$WTHM_{furnace\ batch\ shift} = \max[0, (TrHM_{furnace\ batch\ shift} - PHTP)] \quad \forall_{furnace}, \forall_{batch}, \forall_{shift}$$

(6.24)

$$Del_{batch} = BatDur_{batch} - \sum_{process=1}^{p} (ProDur_{batch\ process}) \quad \forall_{batch}$$

(6.25)

where;

COST_HM Cost due to the hot metal waiting time of the casting furnace

COST_FI Cost due to the idle time of the furnace in between two batches

COST_OLD Cost of longer batch lead time than planned duration

6.4.3 Equations of Costs in the Objective Function of the Production Scheduler

Hot metal waiting time

The possible strategies behind the hot metal schedule are discussed in detail in Chapter 4. Uncertainties such as resource availability, operational delays may defer the schedule. These delays generate extra waiting time for casting furnaces or full crucibles and cause energy loss and additional logistical activities. This part of the objective function contains the extra cost occurred due to this non-value added waiting time. Equation (6.26) shows the formula of the cost which determines the waiting time of hot metal and its amount.

$$\text{Cost\_HM}=\text{CoeffEnLotoCost} * \sum_{\text{furnace}=1}^{m} \left(\sum_{\text{batch}=1}^{n} \left(\sum_{\text{shift}=1}^{s} \left(\text{WTHM}_{\text{furnace batch shift}} * \text{AmHM}_{\text{furnace batch shift}} \right) \right) \right)$$

(6.26)

where;

CoeffEnLotoCost Coefficient of the equation for the cost conversion

Idle time of casting furnaces

In between two batches the waiting time except the preparation for the next batch is determined in this part of the objective function. Casting furnaces cannot be totally turned off during inactive state. While there is no production in the furnace, it has to operate with low temperature. Therefore, there is heat loss which is compensated with additional energy. Equation (6.27) calculates this non-value added cost occurred due the furnace idleness.

$$\text{Cost\_FI}= \text{CoeffEnLotoCost} * \sum_{\text{furnace}=1}^{m} \left(\text{IdTFur}_{\text{furnace}} * \text{Cap}_{\text{furnace}} \right)$$

(6.27)

where;

CoeffEnLotoCost Coefficient of the equation for the cost conversion

Longer batch lead time

As mentioned above the cost occurred due to longer batch lead time is kept in the objective function but has not any influence on the result. In the optimization model, the duration of processes is assumed to be constant and does not change during the calculation. However, in the simulation model the duration of the operations may change due to the dynamics. This variance can be determined by measuring the length of the batch lead time. The impact of the cost is reflected to the optimization model after interfacing with simulation model. The data flow from the simulation to the optimization contains the duration of processes measured in the simulation model.

The main disturbances causing costs are delays in material handling, traffic in the cast-house, transportation unit availability, waiting for the casting line etc. Equation (6.28) shows the formula to calculate the cost of longer batch lead time.

$$\text{Cost\_OLD} = \text{CoeffEnLotoCost} * \sum_{batch=1}^{n} (\text{Del}_{batch} * \text{BatAm}_{batch}) \tag{6.28}$$

where;

CoeffEnLotoCost — Coefficient of the equation for the cost conversion

6.4.4 Equation of the Conversion Coefficient

The cost calculation for the second tool has the unit “ton * hr” without the coefficient which is tagged as “CoeffEnLotoCost”. The required total energy for the whole production is used to convert this result to real cost. The calculation is done for the whole year with total production and then split into the unit “ton * hr”. The coefficient can also be calculated by considering the profit loss. But then the impact of this loss has to be determined for the whole facility which is not easy to calculate without mapping the internal supply chain of other sub facilities located in an aluminium smelter. In this concept, the focus is more on losses due to waste in the system boundary. Therefore, the energy loss is taken into account to calculate the coefficient shown on the Equation (6.29).

$$\text{CoeffEnLotoCost} = (\text{ReqEn} * \text{EnCost} * \text{TotPro}) / (\text{SysCap} * \text{YrtoHr}) \tag{6.29}$$

6.5 Interfacing with the Simulation Model

Interface between the simulation model and the optimization model performs to share the data via MS Excel. Firstly, the optimization model calculates system alternatives and then sends them to the simulation model. Secondly, the simulation model responds with the system performance by converting its output in an appropriate form which becomes the input for the optimization part.

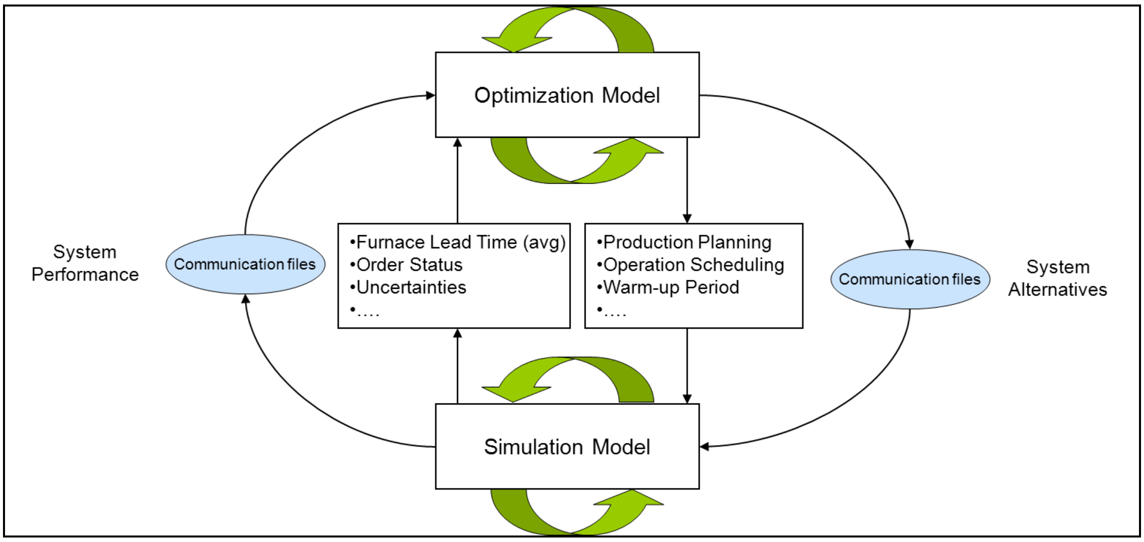

Figure 39 Data transfer between simulation and optimization models

Figure 39 shows the data flow between the simulation and optimization models. The main items flowing from the optimization to the simulation are production planning, operation scheduling and warm-up period for simulation runs. After running the simulation model with this input data, average duration of processes, order status and uncertainties are sent to the optimization part. After each communication, each model reruns itself to analyze the impact of the output received from the other tool.

6.5.1 Methodology of the Interfacing

As described before, the thesis has two optimization models. The interface between optimization models and simulation model is separately set up. Each optimization model has its own communication path and the data flow has not any influence to the other. The interface between simulation and optimization models is done in a static way so the simulation model can receive and transfer data to both models in the same instant. But the output gained from the simulation model depends on the result of both optimization models.

The optimization models do not have any data transfer in between. It is possible to run the simulation model by interfacing with only one of the optimization models. The steps of the methodology of interfacing shown on the Figure 40 are:

1. The optimization model runs with the initial assumed data and determines the required result with respect to its objective function. The output of the optimization model is transferred to MS Excel table which is prepared in the format as an input for the simulation model. This step is valid for both optimization models.

2. The simulation model reads the input data and builds its logic with this data. Simulation duration depends on the required time frame. It also depends on the time interval of the input data received from the optimization model. The calculated time interval of the input data in the optimization model cannot be shorter than the simulation run period.

3. The simulation model creates the output and inserts it into MS Excel platform for the further run of the optimization model.

4. As a last step, the optimization model reads the output data of the simulation model and reruns its logic for the next round of the interface.

The repetition of the communication loop depends on the accuracy expected by the user.

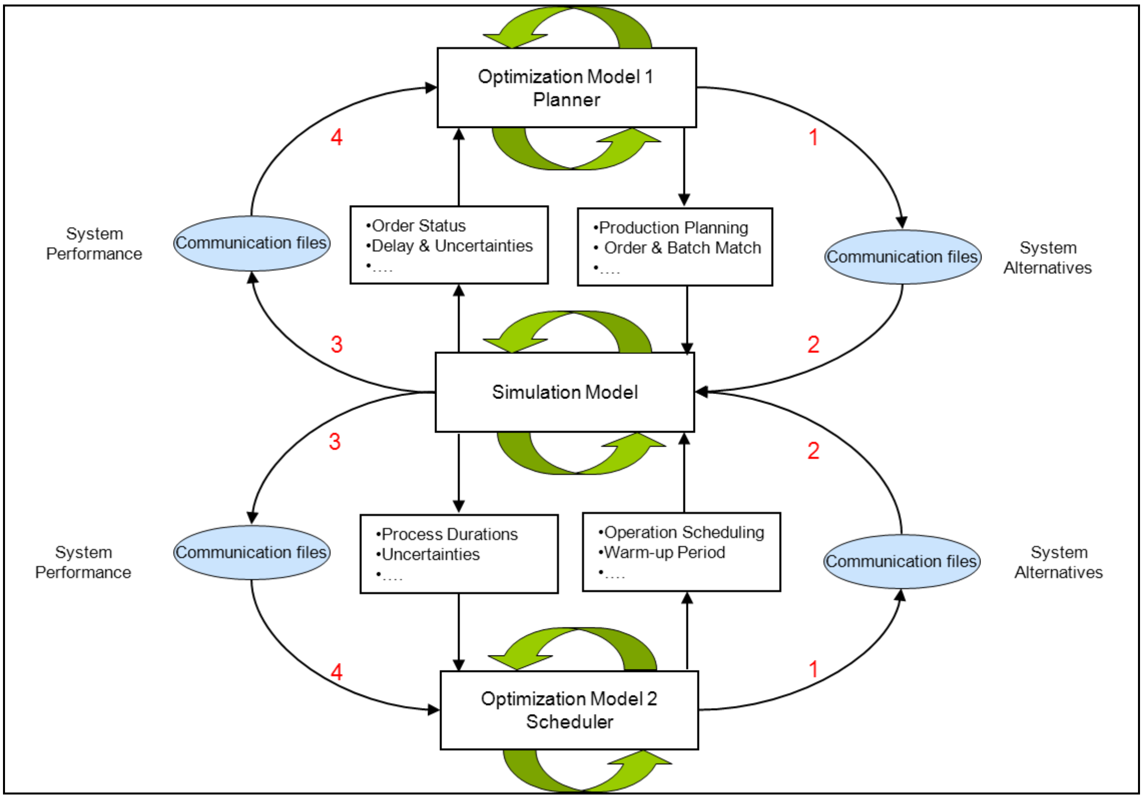

Figure 40 Methodology of the interface between the simulation and optimization models

6.5.2 Architecture of the Interface

After developing the methodology, the structure is built to interface the models. Four layers of application fields are shown on Figure 41. The first layer which is defined in MS Excel consists of the data of customer orders and the casthouse facility specifications. Customer orders contain the information about product properties and delivery information. Specifications comprise operational control issues, resource properties, system characteristics etc. Both data is transmitted to the second layer which includes the optimization model and its macros. This second part is also programmed in MS Excel platform.

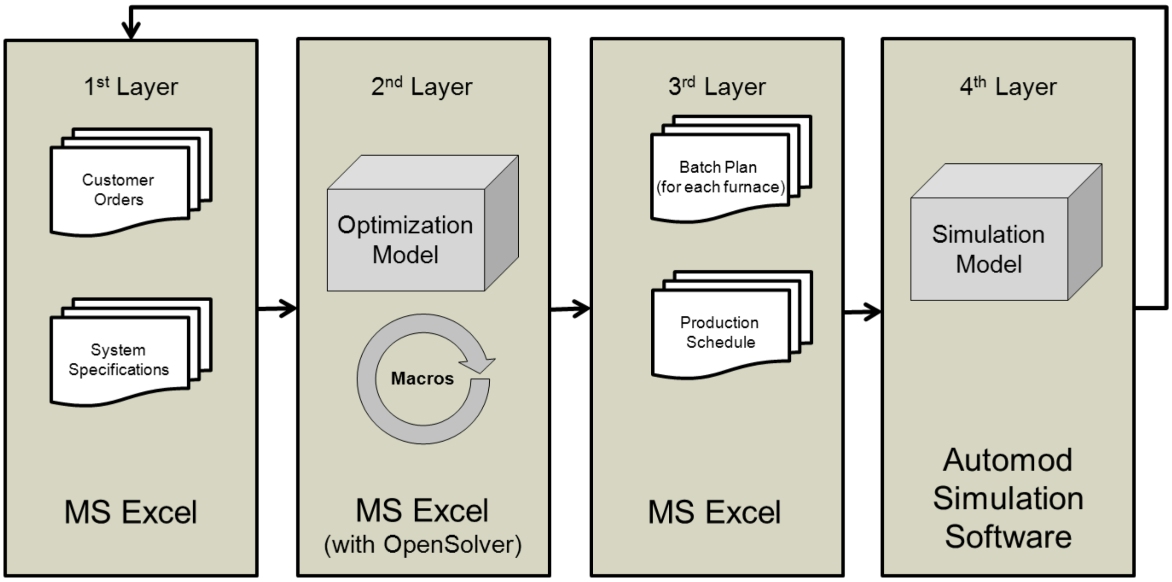

Figure 41 Layers of application fields in the interface structure

The third layer of the interface is the output of the optimization model which is received by the simulation model. This part contains two main MS Excel data, the batch plan of each furnace and the production schedule for the casting furnaces. The batch plan including the data about recipe of the batch, production specifications, and material storage locations gathers information from both optimization tools. On the other hand, the production schedule which contains the start time of processes and the planned duration of the batches is formed only by the second optimization tool. When one of the optimization models is not activated then the presumed specifications are transmitted to the simulation model.

The simulation model stands at the last layer of the interface which reads the input data directly from MS Excel. Automod is capable of interfacing with MS Excel to read and write data. Therefore, the batch plan and the production schedule are prepared in the format which is converted to the simulation environment by Automod. This feature of Automod helps to send the output data to the optimization model by writing them in MS Excel. The simulation model as output changes the status of the customer orders and modifies the system specifications. The data sent from the simulation model to the optimization model is such as;

- The status of the order

- The average duration of each process
- The delays due to resource unavailability
- The distribution of hot metal

In the evaluation phase of this research, after the required runs of the models, the cost values in the objective function are received from both the optimization and the simulation models. The optimization model gives the optimum result according to the parameters defined and modified by the simulation model. The simulation model at the end reaches a conclusion for the value of the objective function with respect to input gained from the optimization model. The final result obtained from the simulation model may differ from the value gained in the optimization model because of the uncertainties. The simulation model maps the flow interactions and the operations in a dynamic way. Therefore, the result obtained from the simulation model illustrates what happens if the batch plan and the production schedule received from the optimization model are applied to the casthouse supply chain.

7 Description of the Case Study

An example case is built to test both the simulation and the optimization models and to verify the interface. In this chapter, the case study with respect to layout and material flow specifications is described. Additionally, parameter set for both model concepts according to assumptions is done. The results gathered from the models are based on the properties of the casthouse and characteristics of the facility described in this chapter.

7.1 Casthouse System Characteristics

The aim of creating a case study is to validate the gain from interfacing the simulation and optimization models. For that reason, during the set up period of the case study, system characteristics of the casthouse are considered to touch each single point in both model concepts. As a final, one type of end product is selected. The high range of differentiation in characteristics of customer orders influences to select Primary Foundry Alloy (PFA) ingots as a final product type.

Both optimization and simulation models have casting furnaces in the center of their concepts, so the example created to verify the study is set up by focusing on the casting furnaces. Two different groups of casting furnaces are considered to see the variances of the furnace specifications on the results. The layout of the casthouse is built by combining different characteristics of casthouses owned by Hydro Aluminium. Before discussing the details of the layout of the system, the production units in the internal supply chain of the casthouse are identified.

	Group 1	Group 2
Number of casting furnaces	3	2
Number of casting line	1	1
Capacity of the furnaces (ton)	30	50
Required hot metal per furnace per batch (ton)	20	30
Filling Frequency per furnace per day	3	3

Table 6 Production units in the casthouse

Production units in the casthouse in terms of group dispersion are shown on Table 6. Number of casting furnaces per group, their capacities, hot metal requirements and filling frequencies per day are highlighted. Detailed explanation of production units in the casthouse and their specifications are:

- The casthouse determined for the case study contains two casting lines and two casting furnace groups with five furnaces in total. The groups are split according to the capacity and the assigned casting lines. Each group transfers the metal to its own casting line.

- The first group has three casting furnaces. Each furnace in this group has capacity of 30 tons. From the planning perspective, two casting furnaces cannot transfer the metal to the casting line at the same time. At a time only one casting furnace fills the casting line, and others have to wait until the end of the process if they are also ready for casting.

- The second group has two casting furnaces. Each furnace in this group has capacity of 50 tons. The same planning rule is also valid for this group that two casting furnaces cannot cast the metal at a same instant.

- The day is split into three shifts which have eight hours duration. This assumption is valid for the simulation and optimization models.

- The filling and casting frequency of each furnace is determined as one time per shift. This implies that the casting line of the first group has nine and the casting line of second group has six times filling operation during a day.

- The hot metal rate to the batch amount is assumed to be constant for each furnace in the case study. For the first group, 20 tons out of 30 tons of a batch and for the second group, 30 tons out of 50 tons of a batch are covered by the hot metal supplied from the electrolysis.

- In addition, the batch contains cold metal, external scrap or internal production scrap material. Amount of alloy addition is ignored.

According to these specifications, annual and daily transported hot metal amount from the electrolysis and the capacity of the casthouse are calculated as shown on Table 7. Total daily capacity of the casthouse is determined as 570 tons which brings annual production around 208000 tons. Electrolysis supplies 131400 tons of hot metal to reach this annual production amount.

	Casting Line 1	**Casting Line 2**	**Total Capacity**
Daily casting capacity (ton)	270	300	570
Annual casting capacity (ton)	98550	109500	208050
Daily required hot metal (ton)	180	180	360
Annual required hot metal (ton)	65700	65700	131400

Table 7 Annual and daily required hot metal and production capacity of the casthouse

7.1.1 Layout Description

The layout of the casthouse established for the case study is shown on Figure 42. Besides the arrangement of the storage locations which are described in detail at subchapter 7.1.2, the figure shows the paths followed by the vehicles which are represented with purple lines. The casting furnaces and the connected casting lines can also be seen on the top-left hand side of the layout.

The fluxing process is integrated to the supply chain before filling the hot metal to the casting furnaces. The location of the fluxing stations is also highlighted on Figure 42. Although the fluxing process is only mapped as duration in the simulation model, tapping vehicles travel to this location to fulfill the process. During the fluxing process duration, both the crucible which carries hot metal and also the vehicle that transports the full crucible are occupied.

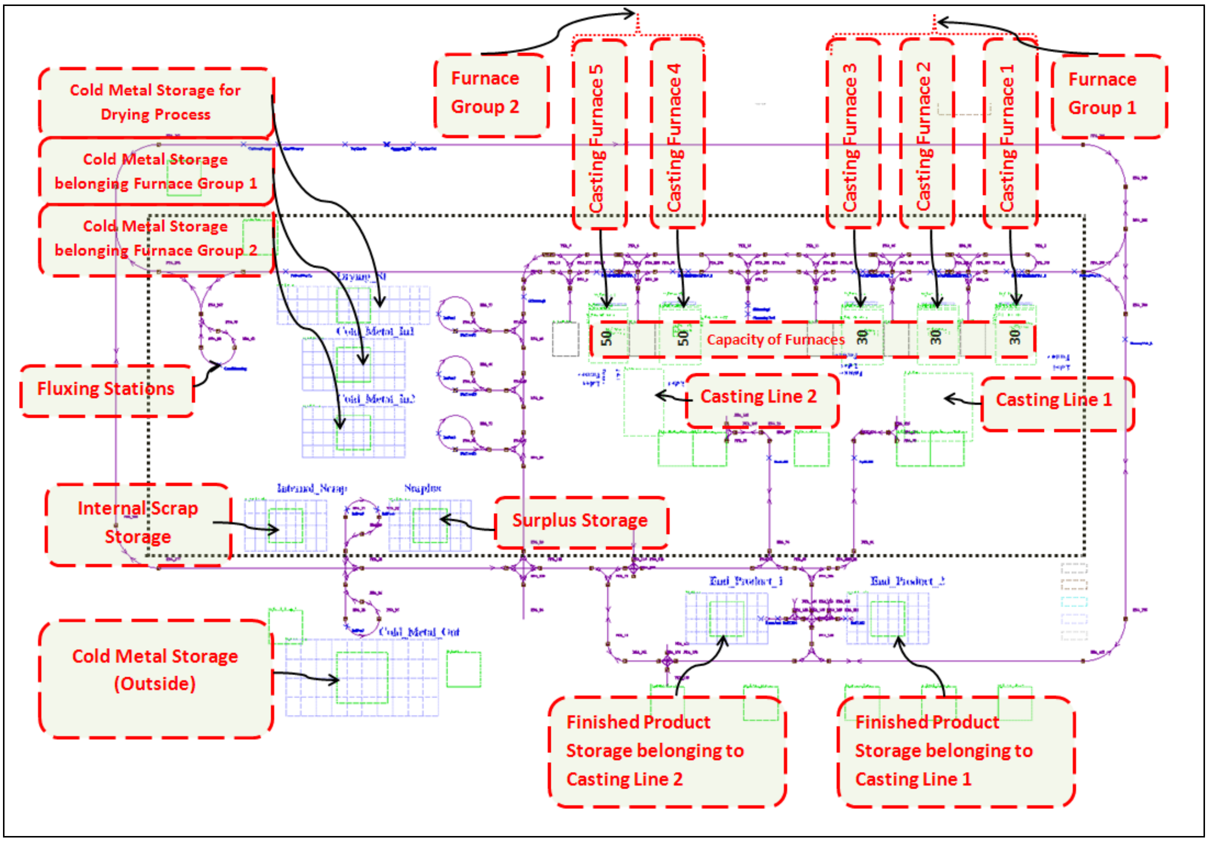

Figure 42 Layout of the casthouse defined for the case study

Rectangle with black dotted lines on Figure 42 represents the border of casthouse facility. Outside of its border, there are some storage areas for cold metal and end products which belong to casthouse internal supply chain. The reasons to keep them outside the casthouse are their big capacities and their contact to external trucks. Incoming and outgoing materials are transported with external trucks which are not allowed to enter the boundary of the casthouse.

7.1.2 Storage Specifications

Important logistical activities in the internal casthouse supply chain related to storage management are stocking of end products, surplus and incoming cold metal (containing also external scrap material and alloys), their inventory management and relocation strategies. Locations of the storages have to be well determined to reduce unnecessary movements. For the case study, the layout of storages is taken from a casthouse owned by Hydro Aluminium. Figure 42 shows the storage locations on the layout. The definitions and properties of the storages are:

- There are four cold metal storages in the casthouse internal supply chain, one is outside and three of them are located inside of the facility

- The outside metal storage is used to unload the incoming material from the supplier. The incoming material concept contains both cold and external scrap metals.

- Cold metals are transported from the outside storage to the drying storage inside the casthouse. The drying process is considered as duration in the simulation model. Therefore, each cold metal supplied from the customer spends the drying duration in this storage before filled into the casting furnace.

- After the drying process cold metal is transported to one of two cold metal storages located inside the casthouse. These internal cold metal storages are separated according to the casting furnace groups, so the cold metals are split to these storage areas depending on the related casting furnaces.

- There are two end product storage locations in the finished goods area (shown on Figure 43) assigned to each casting line. End products are stocked as a bundle or containerized depending on the customer order specification. The container filling operation takes also place in these storages.

- The casthouse layout contains one storage area for the rejected products by the production. The internal scrap materials are directly transported to the casting furnaces according to the batch plan.

- There is one surplus storage area for the finished products which are not assigned to any customer order. The materials are kept waiting in this storage for a while to be allocated to the subsequent customer orders.

7.1.3 Vehicle Fleet

Vehicle fleet of the casthouse is composed of forklifts with different stack capacities, skimming machine and front loader. Besides this internal fleet, there are tapping vehicles controlled by both electrolysis and casthouse units. Vehicles in the casthouse, their tasks and handling capacities are shown on Table 8. Details of their properties are:

- Two “7.5 ton” forklifts assigned to transport cold metal between the storages and also from storages to casting furnaces

- One “5 ton” forklift” assigned to unload external trucks carrying incoming materials such as cold metal, external scrap, alloys etc.

- One “32 ton” forklift allocated to transport empty and full containers in the finished product storage (shown on Figure 42). This forklift is also assigned to load and unload the external outgoing trucks.

- Two “5 ton” forklifts transport the bundles of PFA ingots from the conveyor of casting line to storage or directly into the container. The conveyors are placed behind the casting units. They transport the finished products from casting unit or packaging station to intermediate storage. Forklifts transport the products from this storage to permanent end product storage.

- One “5 ton” forklift transport bundles of PFA ingots from production unit to the surplus or internal scrap storage

- One skimming machine is used for skimming and stirring processes of the casting furnaces. This vehicle has a special mechanism to handle a skimming beam for the skimming process.

- One front loader assigned to transport dross bins to and from the dross cooling area. This vehicle works in coordination with the skimming machine. It transports the empty dross box in front of the furnace before the skimming process starts. And after the process it transports the full dross box to the dross cooling area.

- Besides the internal vehicle fleet of the casthouse, four tapping vehicles are allocated to transport hot metal from the electrolysis to the casthouse. These tapping vehicles have their own equipment on board to empty the crucible into the casting furnace.

Id No	Vehicle Type	Task Definition	Handling Capacity
1	Forklift	Cold Metal and Scrap	7.5 ton
2	Forklift	Cold Metal and Scrap	7.5 ton
3	Forklift	Unloading External Trucks	7.5 ton
4	Big Forklift	Container Transport	32 ton
5	Small ForkLift	End Product Area	5 ton
6	Small ForkLift	End Product Area	5 ton
7	Small ForkLift	Surplus & Production Scrap	5 ton
8	Skimming Machine	Skimming and Stirring	1 SKU
9	Front Loader	Dross Bin Carrying	1 SKU

Table 8 Vehicle fleet of the casthouse

The allocation of transportation areas which are split according to transported material and appointed vehicle types are shown on Figure 43. The areas for incoming materials involve the transported material types of cold metal and external scrap material. The first part of it highlights the unloading fields of the materials, another part internal stocking areas and the last part buffer locations in front of the furnaces. In this area, three “7.5” tons forklifts operate and according to the workload they can share the tasks.

The second storage area group contains finished good, surplus and production scrap. In this part of the layout three small forklifts and one big forklift operate. If the surplus or the production scrap is assigned to any casting furnace to be re-melted again, then materials are transported into the incoming materials area to be filled into furnace.

The routing of tapping vehicles can be seen schematically on Figure 43. Tapping vehicles enter the casthouse from the left hand side after visiting the fluxing station and leave from the right hand side. This course helps to prevent any accidents due to the vehicle turning and encounter passing the gates. One-way rule is a typical safety control strategy in casthouses. Additionally, Figure 43 shows the parking location of the skimming machine and the skimming tool. The parking position of the skimming machine is located between the casting furnace groups to access all furnaces in a short time.

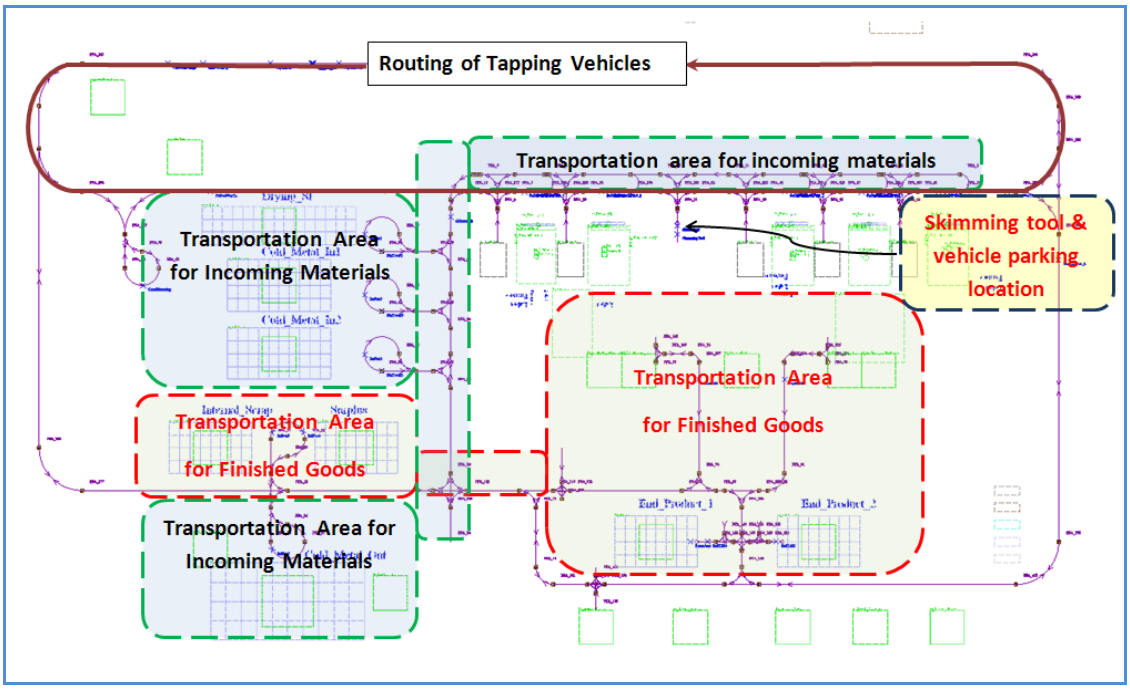

Figure 43 Areas according to transported material

7.1.4 Casting Furnace Specifications

Some specifications of the casting furnaces in the casthouse can be seen on Table 9. Assigned casting line and the capacity of the furnaces are discussed in subchapter 7.1. Melting rate of each furnace can also be seen at the table. First three furnaces belonging to the same furnace group have the melting rate of “6 tons / hr” and the last two have “8 tons / hr”. The values are considered as average melting rates of cold metal, external scrap material and production scrap.

Another data gathered from Table 9 is the hatch number of the furnaces and its position according to the casting line. All of the furnaces in the casthouse contain one hatch (furnace lid) and this is located at the front side when the orientation of casting line is considered behind the furnace. These hatches are the access points of the furnaces for the vehicles to fill metal in, to skim and to stir the furnace.

Id No	Name	Type	Casting Line Index	Capacity [ton]	Melting Rate (ton/hr)	Hatch Number	Hatch Position
1	PFA1	Casting furnace	1	30	6	1	Front
2	PFA2	Casting furnace	1	30	6	1	Front
3	PFA3	Casting furnace	1	30	6	1	Front
4	PFA4	Casting furnace	2	50	8	1	Front
5	PFA5	Casting furnace	2	50	8	1	Front

Table 9 Some specifications of the casting furnaces

Processes of casting furnaces and their sequence in the simulation model are discussed in Chapter 4 in detail. Their short definitions and sequence in the case study are:

1. *Cold metal addition;* addition of pure aluminium ingots to balance the production. The preparation process is also considered as duration in the cold metal addition process when needed.

2. *Pre-heating*; melting the cold metal addition

3. *Hot metal filling*; filling primary metal coming from electrolysis

4. *Alloying*; adding alloy depending on the order

5. *Holding*; holding the temperature constant

6. *Casting*; end product casting process. Casting furnace empties the metal to the casting line during this process

After the casting process, if the next batch does not start immediately, the furnace will turn to inactive state. There is not any production in the furnace but it is also not totally “off”, so this state is called “idle”.

7.2 Parameter Set for the Simulation Model

The simulation model contains a plenty of assumptions to create a virtual environment by imitating the whole supply chain. In the simulation model, the decision support system controlling the material flow has to be well determined. The hot material flow specifications, material types used in the study and storage characteristics are discussed in this subchapter in detail. All of the items in the supply chain have to be defined in Automod as a separate simulation object. The last part of this subchapter contains these items and the concept highlighting how they are integrated into Automod.

7.2.1 Primary Hot Metal Flow Specifications

Primary hot metal, as described in Chapter 3 in detail, is the metal transferred between electrolysis and casthouse units. Therefore, it depends also on the specifications of electrolysis to initiate the flow. Table 10 shows the specifications of the electrolysis designed for the case study by considering characteristics of a modern smelter. The electrolysis in the study contains one pot line having 240 pots in total. The tapping cycle which is used to calculate the number of crucibles per shift is also defined as 40 hours in the table. Hot metal transportation per shift, day and year compensate the required amount by the casthouse system specifications.

Potline		1
Potline Specification	# of Pots	240
	# of Rows	2
	# of Pots/Row	120
Tapping Cycle [hr]		40
Metal Production (avg)	[ton/Cycle/Pot]	2.5
	[ton/Shift]	120
	[ton/day]	360
	[ton/year]	131400
Tapping per Shift	Pots/Crucible	2
	Pots/Shift	48
	Crucibles/Shift	24

Table 10 Electrolysis specifications

Hot metal flow specifications and process durations can be seen on Table 11. All of the data related to hot metal flow specifications are used to calculate the primary hot metal distribution which is defined in Chapter 4 for the simulation model. Besides the resource specifications, operation and transportation durations are also defined in the same table. This data helps to map the transportation between electrolysis and casthouse in an accurate way. All of the data described on Table 10 and Table 11 is integrated into hot metal transportation part of the simulation model.

Hot Metal Flow Specifications		
Shift Duration [hr]		8
Crucible Design Capacity [ton]		5
# of Vehicles in Operation per Shift		4
# Crucible on Board		1
Number of Pots per Crucible		2
Operation and Transportation Durations		
Tapping Duration per Pot [min]		2
Driving Duration Round Trip outside Casthouse [min]	Average	30
	Shortest	25
	Longest	35
Average Fluxing Operation Duration (min)		5
Average Tilting Operation Duration (min)		3

Table 11 Hot metal flow characteristics

7.2.2 Material Types and Storage Descriptions

All material types defined in the case study and mapped in the simulation model, except the primary hot metal are described in Table 12. The table contains the category of the material type, the amount been carried per transport, the vehicle index number matching to the fleet defined in Table 8 and the handling duration containing the picking up and setting down durations of processes.

All of these material types are defined as separate loads in the simulation model. Figure 44 shows the loads definition window of Automod where each load item defined separately. Alloys in the simulation model are grouped and they are clustered as one load type.

Id No	Material Type	Material Category	Transportation Capacity (SKU)	Vehicle Id No	Handling Duration (sec)
1	Bundle	Ingot	2	1,2,3	45
2	T-Bar	Ingot	2	1,2,3	45
3	Sow	Ingot	2	1,2,3	45
4	Top-Bottom Pieces	Pure Metal	2	7	45
5	Surplus	Pure Metal	2	7	45
6	Production Scrap	Pure Metal	2	7	45
7	Litho Scrap	Scrap	1	1,2,3	60
8	Bale Scrap	Scrap	1	1,2,3	60
9	Dross Pigs	Scrap	1	1,2,3	60
10	Silicon	Alloy	1	1,2,3	30
11	Mangan	Alloy	1	1,2,3	30
12	Magnesium	Alloy	1	1,2,3	30

Table 12 Material types and their properties

As a storage strategy "Advanced" mode is selected among the storage strategies defined in the subchapter 4.5.4. The material type and their categories required for the advanced mode are identified on Table 12. The storage bays are classified according to the material type and the filling strategy is applied based on these types. The incoming material is firstly unloaded to the outside storage and then allocated to the internal storage.

Id No	Storage Description	Material Type Id No	Capacity (SKU)	Warm-up level (SKU)
1	Outside Storage	1,2,3,7,8,9,10,11,12	250	150
2	Inside Storage (Drying)	1,2,3,7,8,9	50	50
3	Storage Furnace Group 1	1,2,3,7,8,9,10,11,12	100	100
4	Storage Furnace Group 2	1,2,3,7,8,9,10,11,12	100	100
5	Internal Scrap Storage	4.5	50	20
6	Surplus Storage	5	50	20
7	Finished Product Storage (CL1)	-	250	100
8	Finished Product Storage (CL2)	-	250	100

Table 13 Storage descriptions and their properties

The storages in the casthouse supply chain and the material types assigned to them are shown on Table 13. Their capacity and the warm-up level amounts at the beginning of the simulation can also be found on the table. The internal metal storage classified also according to the furnace groups that the materials are allocated to. There is a separate storage for the internal production scrap and also another one for the surplus material coming from the production. For the finished goods, two storages are considered and split based on the casting line where the metal is casted.

7.2.3 Simulation Model Items in Automod

As mentioned in Chapter 4, Automod enables to define the objects and the control logic separately. Figure 44 shows the defined items in the simulation model. The main objects (loads, resources, queues) and the source files containing the control logic are highlighted on the figure. Besides these items, vehicle fleet and paths are defined in the “Path-Mover” part of Automod.

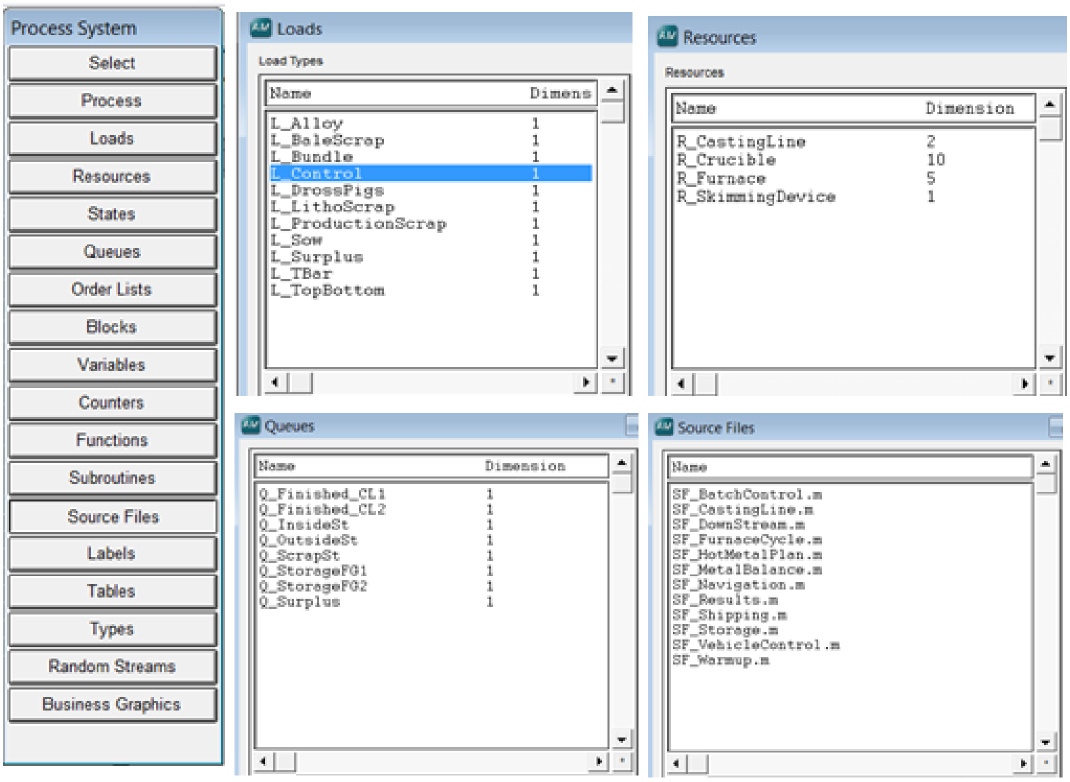

Figure 44 Simulation model items described in Automod

The “Loads” category contains the materials and the control load which is used to drive the logic of the simulation model. Each material type has its own load image and attribute in the model. The control load which is used to control the logic in the simulation model triggers the source files containing processes and functions. It cannot be visualized during the simulation as a flowing item but can be traced to see any information attached to it.

The “Resources” group consists four main items that can be claimed by the loads during the simulation. These four items specify the casting line, casting furnaces, skimming device and crucibles used to transport the hot metal. Their capacity, availability and status lead the material flow in the model. Item numbers of each resource are also mentioned under the column “Dimension” of the “Resources” window in Automod.

The “Queues” part contains the storage units. The container feature of a queue definition in Automod enables to design the storages in three dimensions. It is possible to give capacity to axes of container to stack the material in the queue. The exact position of the load in the storage can be identified by this feature.

The “Source Files” category helps to define control logic of the model in Automod. In the simulation model several source files are created. These files contain the logic to control the batch management, production in the casting line, casting furnace cycle management, metal balance in the furnace, shipping of finished goods, delivery of incoming materials, hot metal planning and transportation, warm-up period at the beginning of the simulation, traffic in the casthouse, navigation concept and the results obtained from the model.

7.3 Parameter Set for the Optimization Models

It is required to define the system characteristics of casthouse supply chain of the case study in detail to set the values of parameters in the objective functions and constraints of optimization models. Strategies behind the operational management of the casthouse are also considered during this parameter set. The last part of the chapter contains the information about the assumptions made for the optimization models which are based on the specifications of real casthouses.

7.3.1 Parameters for the Short-term Production Planner

Considering the costs in the objective function of the short-term planner, impact of system definition of the case study and related assumptions are:

- Casting lines in the casthouse are assumed to cast batch wise which increase the impact of production scheduling.

- Each batch belongs to one customer. In other words, the customer orders have different specifications so it is not possible to split a batch to the different customers.
- Orders from Europe have higher priority due to the penalty rate. This affects the value of "$OPri_{order}$" in Equation (6.9) which is used to calculate late delivery cost (COST_LD) in the objective function.
- Orders have to be ready three days before the shipment. This period is necessary to handle the official procedure to send the products out of the country.

7.3.2 Parameters for the Production Scheduler

The production scheduler requires the specifications about the processes handled in the casthouse supply chain. The first assumption of the production scheduler is about the hot metal transportation from electrolysis to the casting furnace. The hot metal filling process at the casting furnace schedule can take place only at the first five hours of the shift. If the filling process happens in the last three hours then it will create non-value added cost for the casthouse. This affects the value of "$WTHM_{furnace\ batch\ shift}$" in Equation (6.26) which is used to calculate "COST_HM" by setting "PHTP" value as "5" in Equation (6.24).

The restriction helps to plan the hot metal flow between electrolysis and casthouse units. The rest of the shift, both facilities have time to compensate their production schedule. With this restriction, "$WTHM_{furnace\ batch\ shift}$" can be calculated by using Equation (7.1).

$$WTHM_{furnace\ batch\ shift} = \max[0, (TrHM_{furnace\ batch\ shift} - 5)] \qquad \forall_{furnace}, \forall_{batch}, \forall_{shift} \tag{7.1}$$

where;

- $WTHM_{furnace\ batch\ shift}$ Waiting time of hot metal per furnace per batch per shift (hr)

- $TrHM_{furnace\ batch\ shift}$ Time of hot metal transportation for the defined batch at the furnace in the shift (hr at the current shift according to the shift begin)

The second assumption is about the duration of processes which has influence on the optimization model. Process durations of the casting furnaces have to be defined at the beginning of the interface to be able to run the optimization tool "short-term production planner" at first. These process durations are changed after interfacing with the simulation model. One of the data flow from the simulation model to the production scheduler is the new duration of each process.

Pre-assumed Process Durations (min)		
Process Name	**Furnace Group 1**	**Furnace Group 2**
Cold Metal Addition	30	30
Pre-heating	60	60
Hot Metal Filling	60	60
Alloying	30	30
Holding	60	60
Casting	120	180
Batch Lead Time	**360**	**420**
Idle	120	60

Table 14 Pre-assumed process durations of the furnace groups

Table 14 shows the pre-assumed duration of each process according to the furnace groups. The batch lead time of each furnace is calculated at the end, which is shorter than the duration of the shift for both groups. Therefore, the rest of the shift is assumed as idle for the furnaces because of "one batch production per shift" restriction. Figure 45 shows the duration of processes and their allocation for each furnace group in a shift.

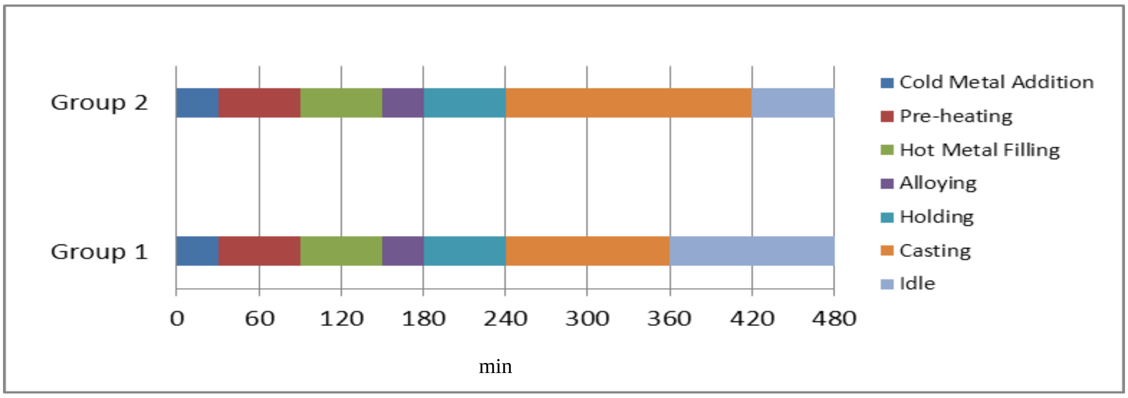

Figure 45 The duration of processes and their allocation for each furnace group in a shift

7.3.3 Parameters for the Coefficients of Optimization Models

Casthouse specifications which contain the system capacity and annual production amount were discussed in subchapter 7.1 in detail. These two parameters are used to calculate the coefficient of the tool production scheduler. There are some other items that have not been discussed. Table 15 shows the rest of the required parameters to calculate the coefficient of both optimization models. Their short definitions, values, units, equations containing the parameter and the source where the value is obtained are presented on this table.

Abbreviation	Short Definition	Value	Unit	Source
SalesPr	Sales price of the order	1700	"Euro / ton"	[BR12]
PenRate	Penalty rate	1	"% per day"	[TCE10]
ManHrC	Man hour and equipment cost	5	"Euro / SKU / day"	Assumed
InvC	Inventory cost	5	"Euro / SKU / day"	Assumed
CMC	Market price of external cold metal	1200	"Euro / ton"	[BOR12]
ReqEn	Required energy for 1 ton aluminium	2500	"kWh / ton"	[BCS07]
EnCost	Energy cost	0.04	"Euro / kWh"	[DA10]

Table 15 Required parameters for coefficients of optimization models

8 Scenarios & Evaluation

In this chapter, the results obtained from the simulation and optimization models are discussed. Two scenarios are created to analyze the effects of optimization models on the casthouse supply chain and the impact of their communication with the simulation model. The description of two scenarios and their analysis are the main focus of this chapter.

Scenarios handled in this chapter are based on the case described in detail in Chapter 7. The basic characteristics of the casthouse are kept the same for both scenarios. The main difference between the scenarios is the hot metal ratio in the production capacity. This difference enables to change the production amount independently from the amount of hot metal transported per shift.

8.1 Scenario I: Fixed Production Amount

"Scenario I" represents the case with a fixed hot metal ratio which restricts the production amount of the casthouse. The fixed ratio concept is preferred in some casthouses having constant cold metal supply with high cost. This assumption causes single batch production per furnace per shift. The ratio of hot metal to total batch amount is determined around 63%.

The production plan and schedule are prepared for the reference case, without interfacing the optimization models, according to the historical data analysis of a real casthouse. The aim of the production plan is to sequence the orders according to the ascending delivery dates. The production schedule intends not to utilize the casting lines by two furnaces at the same time which enables to reduce the waiting time of the furnaces. Batches are assigned to furnaces according to the shift length, which arranges the production start time at the same hours of the shifts for each furnace. Disturbances on the material flow and delays due to resource unavailability may interrupt this sequence if the batch lead time exceeds the shift duration.

8.1.1 Analysis of Scenario I with and without Optimization Models

Analysis of scenario I is divided into phases and steps. Phases are specified according to existence of communication between the simulation and the optimization models. This analysis is split into four phases:

1. Phase 0: represents the reference case in which the simulation model is run with the prearranged production plan and schedule prepared for this analysis.

2. Phase 1: represents the case in which only optimization model 1 is integrated in to the analysis. Data transfer between optimization model 1 and the simulation model takes place in this phase.

3. Phase 2: represents the case in which only optimization model 2 is integrated in to the analysis. Data transfer between optimization model 2 and the simulation model takes place in this phase.

4. Phase 3: represents the next level of the analysis where both of the optimization models are integrated into.

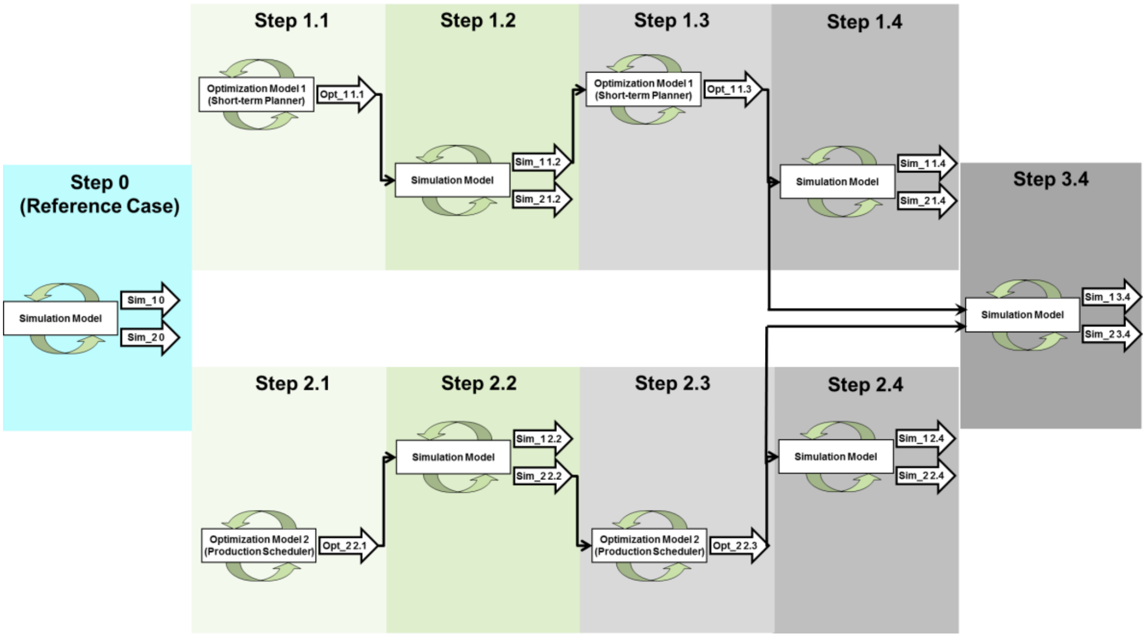

Figure 46 Stepwise visualization of the analysis of Scenario I

In each phase, the values for the analysis are obtained from the simulation model and the optimization models separately for the non-value costs defined in each objective function. As described in Chapter 6, the objective functions show the non-value added logistical costs in primary aluminium casthouse internal supply chain. Figure 46 shows the stepwise visualization of the analysis of Scenario I. Name of the steps highlights the phase and the communication step of this phase. For example, step 1.2 represents the second step of the first phase.

Optimization models provide only the total value of the costs defined in their own objective functions. On the other hand, the simulation model generates results for the total cost amount of each objective function. Depending on the phase, the data flows from the simulation model to the optimization model which is integrated into this phase. For example in the phase 1, the data transfer takes place only between the simulation model and the short-term production planner optimization model.

In each phase, step 2 represents the half of the interfacing loop, the concept of which was defined in detail in the subchapter 6.5. The loop is completed at the end of step 4, when the data flow takes place in both directions. In step 3.4, the data flows to the simulation model from both optimization models. The results obtained at the end of step 3.4 from the simulation model contain the impact of both optimization models.

		Opt_1	Opt_2	Sim_1	Sim_2	Sim_Total
Reference Case	Step 0			52680	31513	84193
With Optimization Model 1	Step 1.1	14280				
	Step 1.2			21770	31513	53283
	Step 1.3	13200				
	Step 1.4			13200	31513	44713
With Optimization Model 2	Step2.1		27875			
	Step2.2			53419	34975	88394
	Step2.3		29125			
	Step2.4			53471	28363	81834
With Both Models	Step3.4			14020	28363	42383

Table 16 Optimization and simulation model results with and without optimization tools

The values of objective functions obtained from both the simulation and optimization models are shown on Table 16. “Optimization Model 1” represents the short-term production planner and “Optimization Model 2” is used for the production scheduler optimization model. The time frame of the analysis is considered as two days and the results gained from the simulation model are based on this two days run period. The reason of setting the time frame to two days is that updating of the production schedule takes place in two days interval which was explained in detail at Chapter 3.3.1.

The abbreviations on Table 16 and their explanations are;

Opt_1= Value obtained from optimization model 1 showing the non-value added logistical costs defined in the objective function of optimization model 1 in Euro

Opt_2= Value obtained from optimization model 2 showing the non-value added logistical costs defined in the objective function of optimization model 2 in Euro

Sim_1= Value obtained from the simulation model showing the non-value added logistical costs defined in the objective function of optimization model 1 in Euro

Sim_2= Value obtained from the simulation model showing the non-value added logistical costs defined in the objective function optimization of model 2 in Euro

Sim_Total = Sum of the values of Sim_1 and Sim_2

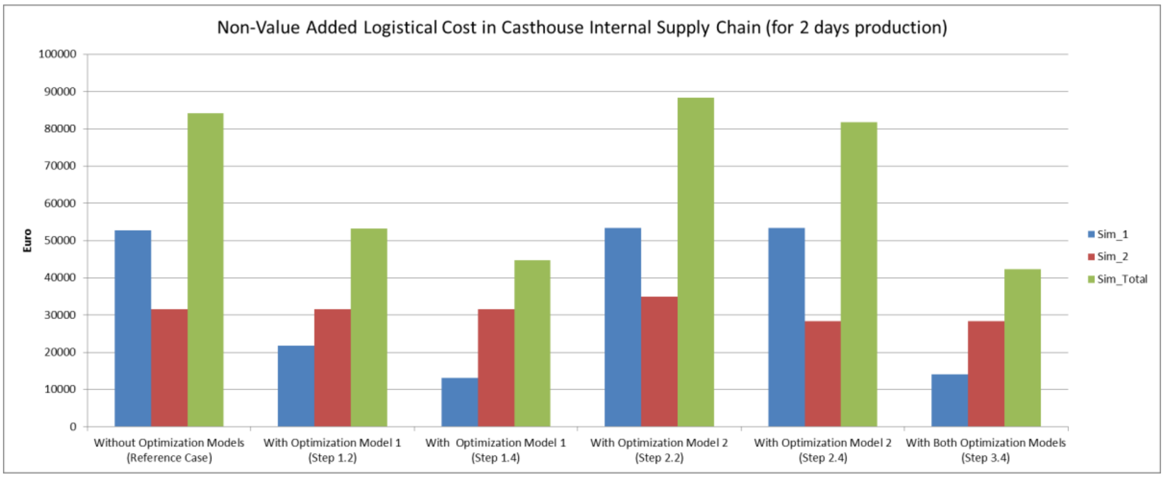

Figure 47 Non-value added logistical cost supplied from two days simulation run

The results of these phases can be seen graphically on Figure 47. According to the values of objective functions presented on Table 16 and Figure 47, the following conclusions can be drawn:

- After each step in interfacing the short-term production planner optimization model with the simulation model, the reduction in non-value added costs increases. After completing half of the loop in the interfacing concept (Step 1.2), the reduction in the total costs reached in both objective functions is around 30000 Euro for two days. By completing the whole loop of in the interfacing methodology (Step 1.4) additional 9000 Euro is gained.

- Analysis of phase 1 shows that optimization model 1 does not have any impact on the costs defined in the objective function of optimization model 2. In step 0, step 1.2 and step 1.4, the value obtained from the simulation model for the costs of objective function of optimization model 2 does not change.

- If the simulation runs only with optimization model 2 without any data flow in the direction from the simulation to the optimization model (step 2.2), the costs in the objective functions are increased. This means that the system creates more non-value added costs compared to the reference case. The reason of this result is that the predefined parameters (in step 2.1) for the optimization tool 2 have considerable difference compared to the parameters obtained from the simulation run (in step 2.3).

- On the other hand, after completing the interfacing concept, by reaching to step 2.4, the result gets better than the reference case by around 3 %.

- After completing the interfacing loop, values obtained from the optimization models and the simulation model become closer. For example, the difference in values of Opt_1 in step 1.3 and Sim_1 in step 1.4 is smaller than the difference of Opt_1 in step 1.1 and Sim_1 in step 1.2. This convergence is also valid for optimization model 2.

- After completing the interfacing concept with both optimization models (step 3.4), the value of Sim_1 gets higher than the value in phase 1.4. The reason of this result is that the production scheduler tool reduces the batch lead time which causes for some batches to be produced earlier than the other cases. This early production brings extra end product storage cost (COST_EPS) which increases the objective function of model 1. On the other hand, the value of objective function 2 is not influenced from optimization model 1.

- The total non-value added logistical costs in the reference case are reduced nearly by half after interfacing with both optimization models (step 3.4). Haller et. al. [HKK07] calculated the aluminium production cost around 1800 “Euro/ton“. The cost reduction on non-value added logistical activities in the casthouse supply chain renders around 2 % of this cost.

8.1.2 Detailed Analysis of Scenario I with and without the Short-term Production Planner

The results of detailed non-value added logistical costs analysis done with and without short-term production planner are shown on Table 17. To remind the cost items in each objective function, definition of cost abbreviations are:

COST_LD = Punishment cost of late delivery

COST_EPS = Inventory cost for waiting at the end product storage

COST_SR = Cost of surplus product

COST_HM = Cost due to the hot metal waiting time of the casting furnace

COST_FI = Cost due to the idle time of the furnace in between two batches

COST_OLD = Cost of longer batch lead time than planned duration

		Reference Case	With Optimization Model 1			
		Step 0	Step 1.1	Step 1.2	Step 1.3	Step 1.4
Opt_1	COST_LD		0		0	
	COST_EPS		9280		8200	
	COST_SR		5000		5000	
	TOTAL		**14280**		**13200**	
Sim_1	COST_LD	0		8400		0
	COST_EPS	7680		8370		8200
	COST_SR	45000		5000		5000
	TOTAL	**52680**		**21770**		**13200**
Sim_2	COST_HM	7425		7425		7425
	COST_FI	22363		22363		22363
	COST_OLD	1725		1725		1725
	TOTAL	**31513**		**31513**		**31513**
Sim_Total		**84193**		**53283**		**44713**

Table 17 Detailed cost analysis with optimization model 1 (the short-term production planner)

According to the graph (shown on Figure 48), it can be concluded that the value of "COST_SR" after implementing optimization model 1 equals to one ninth of the value of the reference case. This 89 % reduction in the surplus cost affects the total value of the objective function. Another conclusion drawn from the graph is that the late delivery cost appears in the step 1.2 “with optimization model 1”. This cost is eliminated after completing the loop of interfacing the simulation and optimization model (step 1.4).

The reduction in the cost evaluation, after implementing a short-term production planner optimization model, helps to increase the overall profit of aluminium production (according to Pahladsingh [Pah04]) by around 10 % compared to reference case.

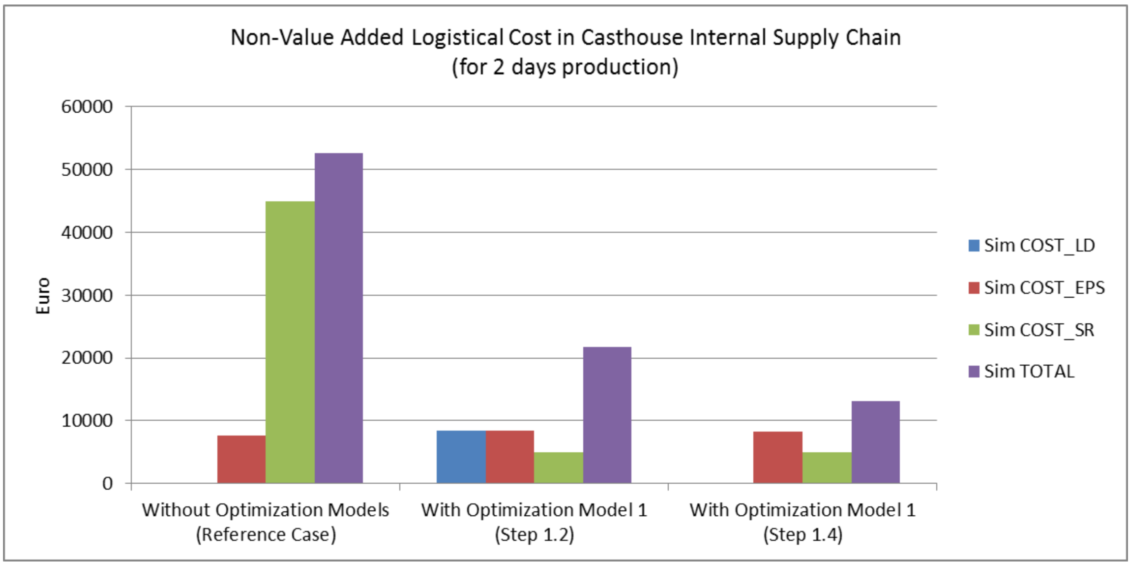

Figure 48 Analysis of cost items in the objective function of tool 1 (the short-term production planner)

8.1.3 Detailed Analysis of Scenario I with and without the Production Scheduler

The detailed cost distribution of scenario I with and without the production scheduler optimization model is shown on Table 18. The cost improvement with the second optimization tool is not as high as the saving obtained with the short-term production tool. A single batch production per furnace per shift restriction is the main reason of this result. This assumption prevents to reduce the costs occurred due to furnace idleness and order lead time which have the biggest portion of the value of the objective function. Figure 49 shows distribution and the comparison of the cost items in each case of scenario I on the graph.

		Reference Case	With Optimization Model 2			
		Step 0	Step2.1	Step2.2	Step2.3	Step2.4
Opt_2	COST_HM		4875		10500	
	COST_FI		23000		18625	
	COST_OLD		0		0	
	TOTAL		**27875**		**29125**	
Sim_1	COST_LD	0		0		0
	COST_EPS	7680		8419		8471
	COST_SR	45000		45000		45000
	TOTAL	**52680**		**53419**		**53471**
Sim_2	COST_HM	7425		4250		4188
	COST_FI	22363		29138		22125
	COST_OLD	1725		1588		2050
	TOTAL	**31513**		**34975**		**28363**
Sim_Total		**84193**		**88394**		**81834**

Table 18 Detailed cost analysis with optimization model 2 (the production scheduler)

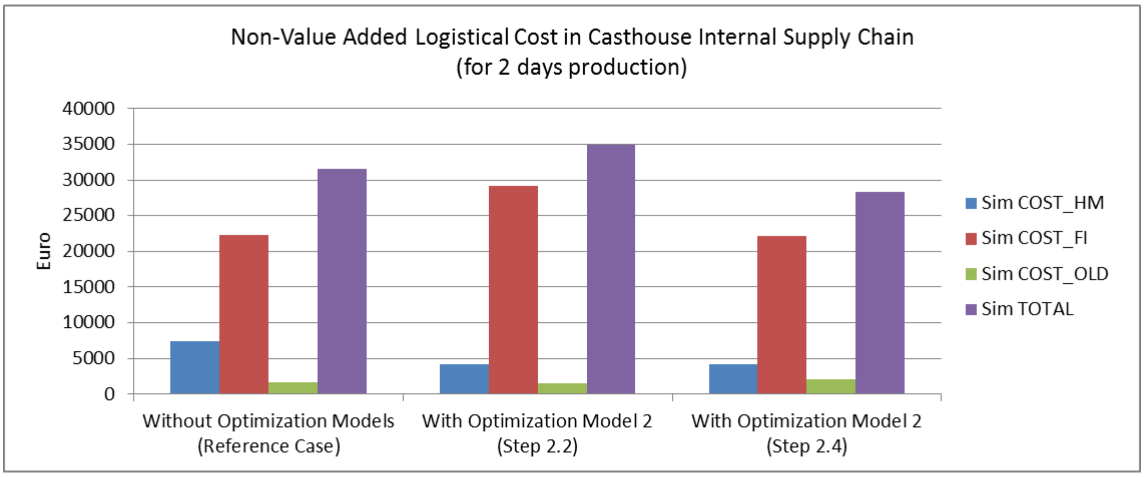

Figure 49 Analysis of cost items in the objective function of tool 2 (the production scheduler)

The achievement of reduction in the non-value added logistical costs with production scheduler equals to 3 % of the total required energy in the casthouse production. The amount of total energy cost for the annual production of casthouse is calculated by using the values presented on Table 15 (in Chapter 7).

Figure 50 and Figure 51 show the distribution of process durations for each furnace in two days simulation run period. It is expected to produce six batches per each furnace during this time frame, due to the assumption of one batch production per shift per furnace. The warm-up durations at the beginning of the first batches of each furnace are excluded from the graphs. Therefore, it can be seen that on both graphs only two furnaces per each case can succeed to finish six batches production in a two days period. PFA1, PFA2, PFA3, PFA4 and PFA5 represent the casting furnaces in casthouse. Their specifications were discussed in the previous chapter.

The percentage of total non-value added waiting time of the casting furnaces in step 2.4 equals to 25.5 % of the overall production time. For the reference case, this value is calculated as 26.9 %. For two days period 1.4 % reduction in the waiting time of the furnaces nearly equals to two days more production in a year basis.

One of the assumptions of the case study is that hot metal transportation takes place in the first five hours of the shift, so the last three hours cause additional cost to the system. Figure 52 and Figure 53 show hot metal distribution occurring in the last three hours of shifts. The data is taken from the simulation model. The improvement in the step 2.4 compared to reference case appears not only in the amount of the cost value but also in the number of the furnaces. In other words, the hot metal filling process in the last three hours of shifts after interfacing with optimization tool 2 takes place in less number of furnaces compared to the reference case.

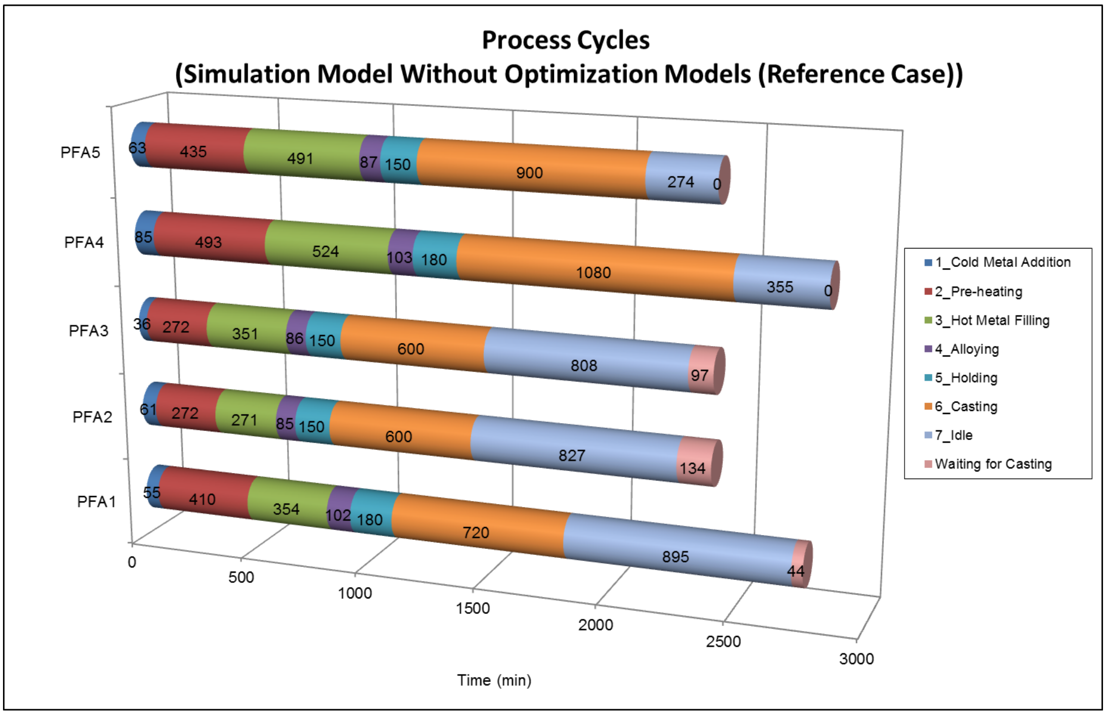

Figure 50 Process cycle of furnaces as output of the simulation model without optimization models (reference case)

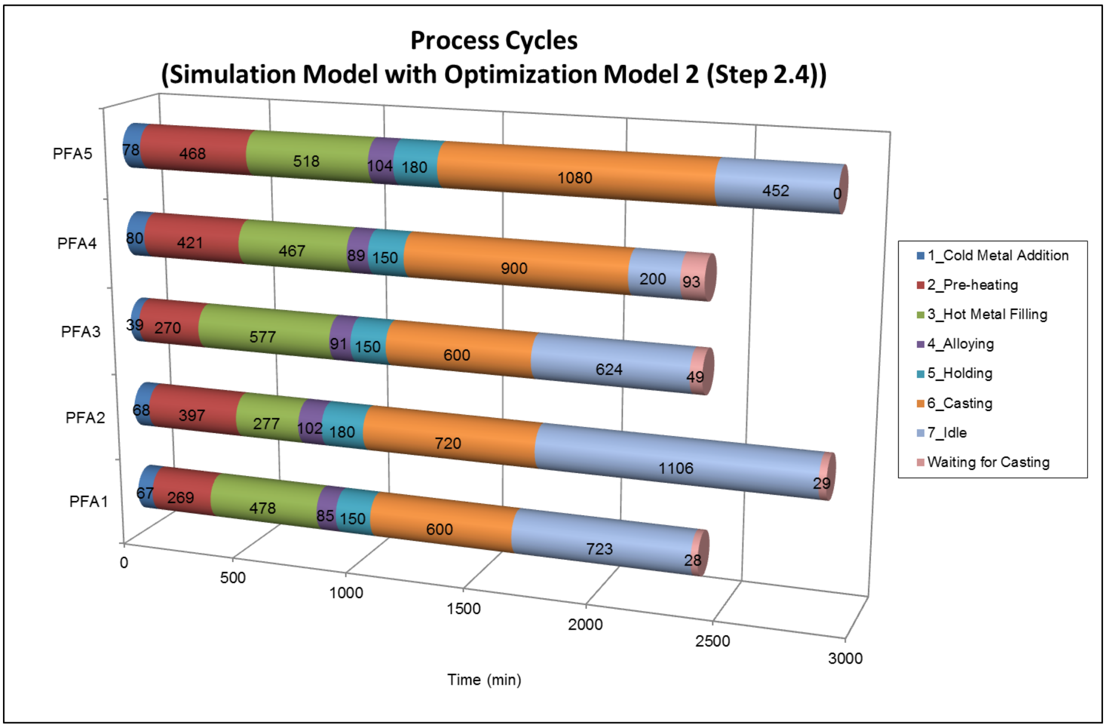

Figure 51 Process cycle of furnaces as output of the simulation model after interfacing with optimization model 2 (Step 2.4)

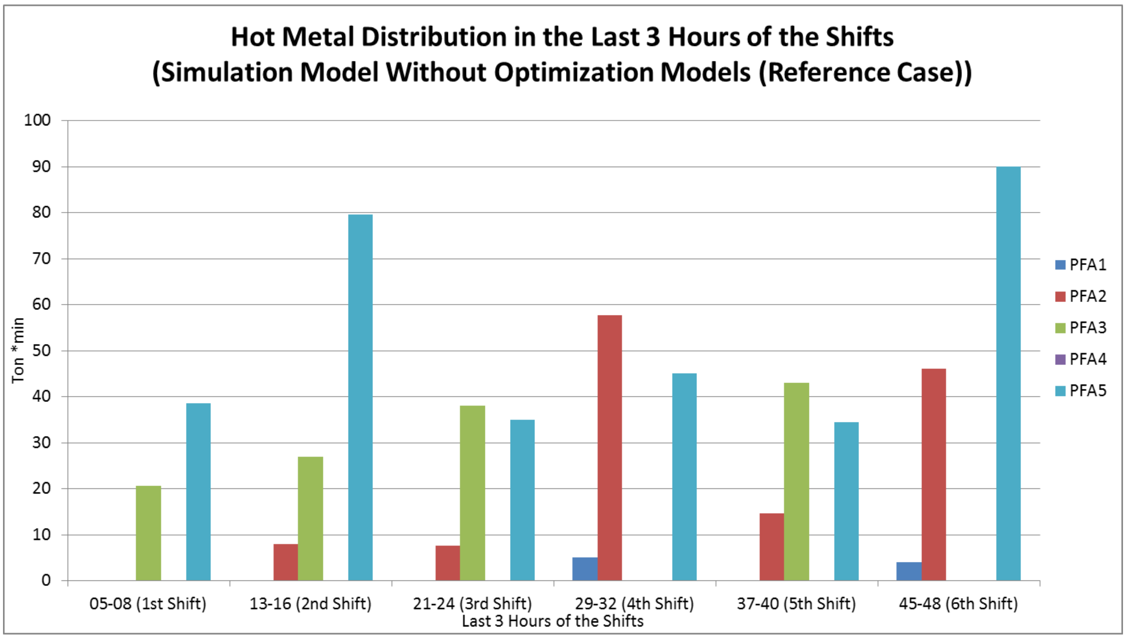

Figure 52 Hot metal distribution in the last three hours of shifts supplied from the simulation model without optimization models (reference case)

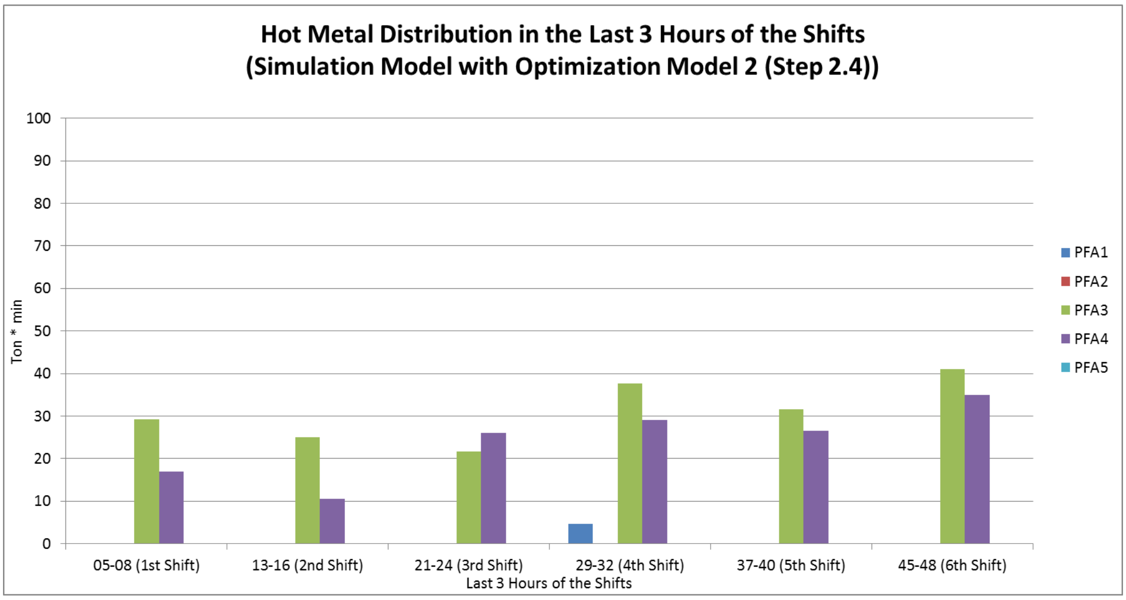

Figure 53 Hot metal distribution in the last three hours of shifts supplied from the simulation model after interfacing with optimization model 2 (Step 2.4)

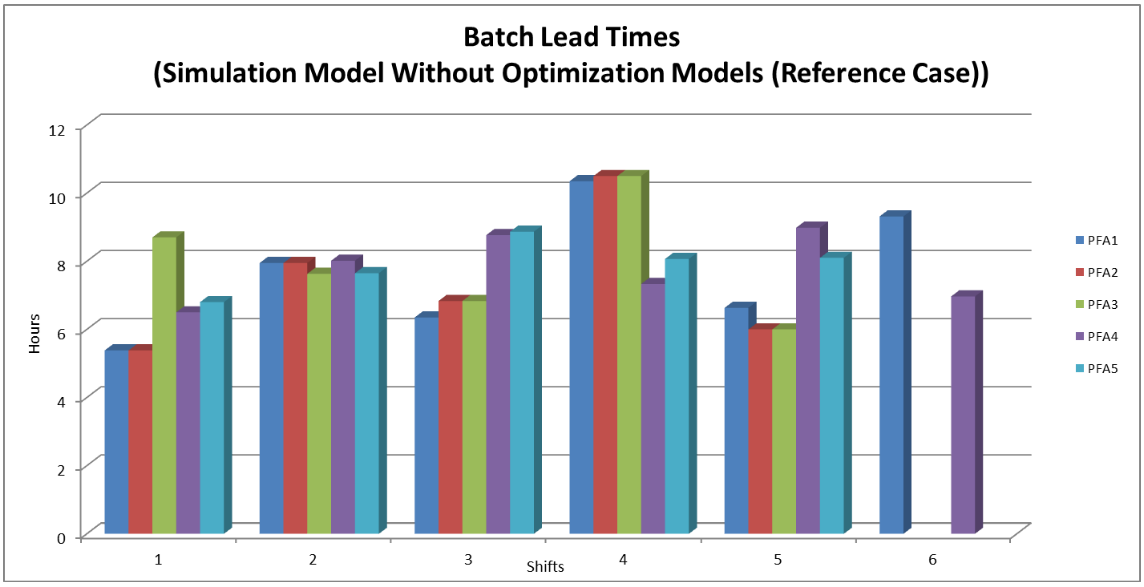

Figure 54 Batch lead times of furnaces supplied from the simulation model without optimization models (reference case)

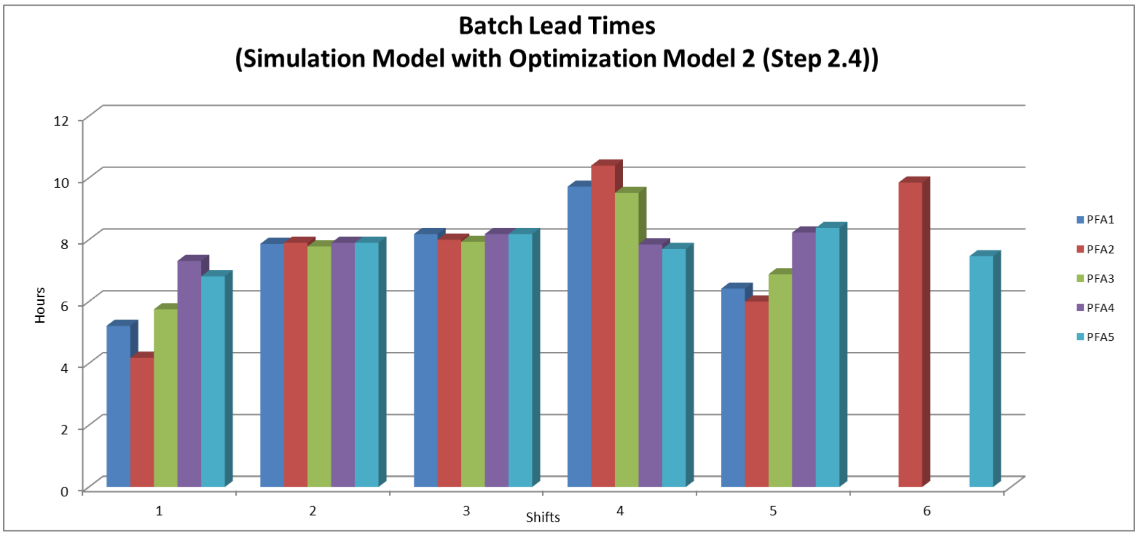

Figure 55 Batch lead times of furnaces supplied from the simulation model after interfacing with optimization model 2 (step 2.4)

Figure 54 and Figure 55 show the batch lead time distribution of each furnace for six shifts period. As mentioned before some furnaces as shown on the graphs cannot achieve finishing the batch production in the last shift. On both graphs it can be observed that some batches exceed the value of the shift duration (eight hours). In this case, at the beginning of the next shift the furnace finishes the batch from the last shift and then starts the planned batch of the current shift.

To be able to analyze the effect of optimization model on precision of batch lead time, the statistical parameter "Relative standard deviation (RSD)" can be used. RSD is a measure of stability which is calculated by Equation (8.1)

$$RSD = (\sigma / \mu) * 100 \tag{8.1}$$

The mean value, standard deviation and RSD of batch lead times for the reference case and the analysis with interfacing the optimization model 2 (Step 2.4) are shown on Table 19.

	Without Optimization Models (Reference Case)	With Optimization Model 2 (Step 2.4)
μ	7.71	7.68
σ	1.45	1.38
RSD	18.81%	17.97%

Table 19 The mean value, standard deviation and RSD values for both steps

RSD value of the reference case is 18.81 % whereas after the interface with optimization model 2 (step 2.4) RSD value decreases to 17.97 %. Based on these numbers, it can be concluded that the case with the optimization model is more stable than the reference case.

8.2 Scenario II: Variable Production Amount

During the detailed analysis of scenario I with the production scheduler optimization model, a possible production amount increase was recognized. Fixed ratio of hot metal to the batch size limits to increase the production capacity in the casthouse. In this part of the analysis, a new scenario is prepared by removing this restriction. This new assumption has direct impact on the objective function of the second optimization model. Therefore, the analysis of this scenario is done only with the production scheduler.

8.2.1 Definition of Scenario II

After recognizing possible increase in production due to shorter lead time, scenario II with adding more cold metal to the batch recipe is considered. This allowance enables the system not to have a fixed ratio of hot metal to the production amount. In scenario I, the hot metal ratio was assumed to be around 63 %. However, due to the melting rate of the furnaces minimum hot metal rate is assumed to be 55 % for scenario II. Therefore, hot metal ratio in the casting furnace may vary between 55 % and 65 % for this new scenario depending on the situation in the casthouse. On the other hand, this causes more melting duration compared to scenario I. The restriction of having one batch production per furnace per shift is kept for this scenario due to the availability of casting lines.

With this scenario, it is possible to increase the production capacity by replacing required hot metal with cold metal. This analysis is useful in the real case when electrolysis cannot supply the demand or cold metal prices go down in the market.

8.2.2 Analysis of Scenario II with and without the Production Scheduler Tool

To compare the results of scenario II with the values of scenario I in the same situation, Table 20 reminds the results of the analysis of scenario I with and without production scheduler. The amount of production is 1030 tons in the simulation model for each phase of the analysis of scenario I. With the variable batch content, it is expected that the amount of production will increase. Table 21 shows the results of scenario II with and without the second optimization model. For the reference case “without optimization tools” the values are the same as the scenario I because without optimization tools it is not possible to reflect the dynamic metal ratio to the production schedule.

It can be concluded that with this new scenario, the production amount may increase. Additional to that, it is achieved having higher production amount with less non-value added costs. On Table 21, it can be seen that the simulation after interfacing with optimization model (step 2.4) has lower values than the analysis without optimization model (reference case).

By comparing the results with and without optimization model for scenario II, the reduction on the non-value added logistical costs is calculated as around “7 euro / ton” for the case with optimization tool. This reduction is reached with not only due to cost minimization but also more production. Additional important output of the analysis is that hot metal waiting and furnace idleness costs are reduced in the case with optimization tool while the cost due to batch lead time is increased. The explanation of this increase is higher utilization of casting line which causes longer waiting time for casting of furnaces.

			Without Optimization Models (Reference Case)	With Optimization Model 2, Scenario I (Step 2.2)	With Optimization Model 2, Scenario I + Interfacing (Step 2.4)
Costs in Objective Function	Simulation	Cost_HM	7425	4250	4188
		Cost_FI	22363	29138	22125
		Cost_OLD	1725	1588	2050
		TOTAL	**31513**	**34975**	**28363**
	Optimization	Cost_HM		4875	10500
		Cost_FI		23000	18625
		Cost_OLD		0	0
		TOTAL		**27875**	**29125**
Production Amount	Simulation	**TOTAL** (ton)	**1030**	**1030**	**1030**
	Optimization	**TOTAL** (ton)		**1060**	**1060**

Table 20 Results for scenario I with and without optimization model 2 (the production scheduler)

			Without Optimization Models (Reference Case)	With Optimization Model 2, Scenario II (Step 2.2)	With Optimization Model 2, Scenario II + Interfacing (Step 2.4)
Costs in Objective Function	Simulation	Cost_HM	7425	6663	4513
		Cost_FI	22363	20200	18000
		Cost_OLD	1725	2600	2850
		TOTAL	**31513**	**29463**	**25363**
	Optimization	Cost_HM		4313	10000
		Cost_FI		8688	10625
		Cost_OLD		0	0
		TOTAL		**13000**	**20625**
Production Amount	Simulation	**TOTAL** (ton)	**1030**	**1090**	**1090**
	Optimization	**TOTAL** (ton)		**1120**	**1090**

Table 21 Results for scenario II with and without optimization model 2 (the production scheduler)

Figure 56 presents the graph of the comparison of results for the scenarios with and without optimization tools. The benefit gained from interface of simulation and optimization models can be seen on the graph. The difference in values of the objective function of simulation and optimization tools gets smaller after interfacing the models. Without the interface, the optimization model delivers lower cost value compared to the simulation model. As mentioned before, the results obtained from the simulation model represent more reliable values compared to values from optimization model due to mapping the dynamic interaction between the operations.

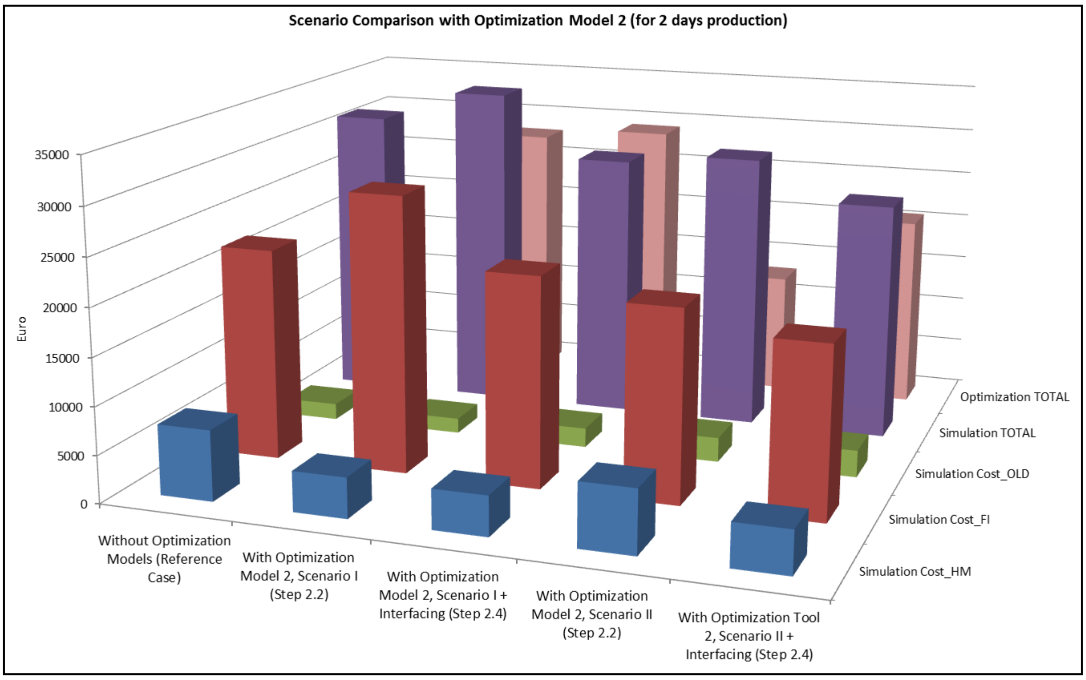

Figure 56 Scenario comparison with and without optimization model 2 (the production scheduler)

As a conclusion optimization models help to reduce the non-value added logistical costs in the primary aluminium internal supply chain. Completing the loop of the interfacing concept until the last step (step 4) renders to reduce the cost values in considerable amount. In scenario I, the short-term production planner optimization model helps to reduce the costs more than the production scheduler. On the other hand, the results of analysis with the second optimization model indicate possible increase in production amount which was analyzed in scenario II.

9 Research Summary & Future Work

Primary aluminium smelters attempt to reduce operational expenditure to survive in the current competitive market situation. The technological developments in aluminium industry focus on how to reduce the production costs. It is also recognized that logistical activities in the facilities have potential to be improved. Therefore, the focus of the research was to quantify and to reduce the redundant logistical costs in aluminium casthouse facility.

9.1 Research Summary

The main objective of this thesis was to develop a new concept that controls the non-value added logistical costs in primary aluminium casthouse supply chain. Steps that were followed to reach this main objective and the summary of the results obtained from the thesis are:

1. It was verified that the casthouse unit has potential to eliminate non-value added logistical costs in its internal supply chain.

2. The alternative approaches to control logistical activities such as hot metal flow, casting furnace control and storage management enabled to develop a universal simulation platform which is capable of being implemented to any casthouse.

3. The boundary of the primary aluminium casthouse internal supply chain was simulated without mapping the hot metal flow in electrolysis unit. For this, a primary hot metal distribution concept was developed for the simulation model covering the metal flow occurring in the electrolysis.

4. The navigation concept that dynamically manages the traffic in the casthouse simulation model was developed and implemented. The required decisions in the

vehicle routing were taken by using this tool. It enabled the user to model and control complicated traffic situations in the simulation program.

5. Defining the input data of the simulation model in MS Excel created flexibility to modify the model without changing the programmed logic in the simulation tool. Casting furnace control, vehicle fleet of the casthouse, customer orders, delivery plan for incoming materials, the storage control strategies and the batch plan of the casting furnaces can be modified in these MS Excel sheets.

6. It was verified that the simulation method was an efficient evaluation tool for the casthouse aluminium supply chain. Some standard results (e.g. resource utilization, storage analysis, traffic density, safety and bottleneck analysis etc.) which are valid for each casthouse can be obtained from the simulation model.

7. It can be concluded that it is possible to apply a lean thinking approach to the continuous process sectors like aluminium industry.

8. With the combination of simulation and lean thinking approach, non-value added logistical costs in the aluminium casthouse supply chain were specified. Simulation as an analyzing tool enabled the user to elaborate the details in the supply chain.

9. A short-term production planner was developed to split customer orders to the batches and dispatch the batches to the casting furnaces. It was achieved to reduce the non-value added logistical costs occurred due to poor production planning such as late delivery, early production and surplus rate.

10. A production scheduler optimization model was developed to sequence the processes of the casting furnaces. Reduction in hot metal waiting time, furnace idle time and batch lead time were succeeded after applying this model.

11. A new concept was developed to interface the discrete event simulation with linear optimization. Data transfer was achieved between two models. The output of one of the models served as input of the other.

12. After interfacing with the simulation model, both of the optimization models separately succeeded in improving the casthouse supply chain by reducing the non-value added logistical costs specified by lean thinking approach. The study gave the best result after interfacing both of the optimization models at the same time with the simulation model.

13. Besides the reduction in non-value added costs, the interface between models provided more accurate results of the optimization models compared to the analysis without simulation interface. And also the values of the objective functions determined in simulation and optimization models were converged.

14. A real based case study helped to test the models. It also highlighted the possible increase in casthouse production amount besides the reduction in the logistical costs. The scenario for more production was also developed and tested in the case study.

9.2 Recommendations for Future Work

In this thesis, it was verified that the interfacing between the simulation and optimization models helps to reduce the non-value added logistical costs in the primary aluminium casthouse supply chain. However, further investigations can be done for cases containing the extended supply chain boundary or different industrial requirements. The potential points for the further research are recommended as:

1. A simulation model can be prepared for the electrolysis unit which will interface with the casthouse simulation model to identify and analyze the effects of other logistical activities occurring in electrolysis on the hot metal flow.

2. The analysis period was kept as two days for each model. This timeframe can be increased because the simulation model is capable of running limitless when the required data is supplied.

3. The interfacing between the simulation model and the optimization models was done manually in the research. The data flow may be progressed automatically by using a computer program providing a dynamic interface.

4. The selected final product type for the case study can be changed to analyze the possible impacts on the optimization models with different product types. Especially the short-term production planner may be affected due to the restrictions of product dimensions.

References

1. [AAC08] Araujo S., Arenales M., Clark A., Lot-sizing and Furnace Scheduling in Small Foundries, Computers and Operations Research, Vol. 35-3, 2008, Pp. 916-932

2. [Abd03] Abdullah F., Lean Manufacturing Tools and Techniques in The Process Industry with A Focus on Steel, Ph.D Thesis, School of Engineering, University of Pittsburgh, 2003

3. [AR07] Abdulmalek F.A., Rajgopal J., Analyzing the Benefits of Lean Manufacturing and Value Stream Mapping via Simulation: A Process Sector Case Study, International Journal of Production Economics, Vol. 107, 2007, Pp. 223–236

4. [ARA10] Awheda A., Rahman M.N., Arshady H., Key Factors Influencing the Effectiveness and Efficiency of Supply Chain Management in Small and Medium Enterprises (SMES) in Malaysia, 15th International Symposium on Logistics, 2010

5. [BADW04] Buxmann P., Ahsen A., Diaz L.M., Wolf K., Usage and Evaluation of Supply Chain Management Software – Results of an Empirical Study in the European Automotive Industry, Info Systems Journal 14, 2004 Pp. 295-309

6. [Ban04] Banks, J.: Getting Started with AutoMod. Second Edition. Chelmsford, MA: Brooks Automation, Inc., May 2004.

7. [BB99] Beddoes J., Bibby M.J., Principles of Metal Manufacturing Processes, Butterworth-Heinemann, 1999

8. [BBB11] Berlioux J., Baudrenghien J.L., Bourgier A., New Casthouse Smelter Layout for the Production of Small Nonalloyed Ingots: Three Furnaces/Two Lines, Light Metals, TMS(The Minerals, Metals & Materials Society), 2011, Pp. 635-639

9. [BBJLM02] Banks J., Buckley S., Jain S., Lendermann P., Manivannan M., Panel Session: Opportunities for Simulation in Supply Chain, Proceedings of the 2002 Winter Simulation Conference, Vol. 1, 2002, Pp. 1652-1658

10. [BBTM09] Baxter R., Bouk T., Tikasz L., McCulloch R.I., Simulation-Based Approach for Validating a Lean Anode Plant Configuration, Light Metals, TMS (The Minerals, Metals & Materials Society), 2009 , Pp. 1043-1048

11. [BC02] Borge G., Cooper P., Recent Studies of Compacted Additives Including Industrial Scale Tests, Light Metals, TMS(The Minerals, Metals & Materials Society), 2002

12. [BCS07] BCS, U.S. Department of Energy, U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical Limits and Current Practices, Industrial Technologies Program Energy Efficiency and Renewable Energy, 2007

13. [Bea98] Beamon, B. M., Supply Chain Design and Analysis: Models and Methods, International Journal of Production Economics, 55(3), 1998, Pp. 281–294

14. [Bee01] Beeley P.R., Foundry Technology, Edition 2, Elsevier, 2001

15. [Ben97] Benson D., Simulation Modeling and Optimization Using ProModel, Proceedings of the 1997 Winter Simulation Conference, Vol. 1, 1997, Pp. 587-593

16. [BM00] Barnett M.W., Miller C.J., Analysis of the Virtual Enterprise Using Distributed Supply Chain Modeling and Simulation: An Application of e-SCOR, Proceedings of the 2000 Winter Simulation Conference, 2000, Pp. 352-355

17. [BMND05] Branke J., Middendorf M., Noeth G., Dessouky M., Waiting Strategies for Dynamic Vehicle Routing, Transportation Science, Vol. 39, No. 3, 2005, Pp. 298–312

18. [BOR12] Benefits-of-Recycling.com, Aluminum Recycling Prices, www.benefits-of-recycling.com/aluminumrecyclingprices.html, 2012

19. [BPS08] Böse F., Piotrowski J., Scholz-Reiter B., Autonomously Controlled Storage Management in Vehicle Logistics - Applications of RFID and Mobile Computing Systems, International Journal of RF Technologies: Research and Applications , iFirst Article, 2008, Pp. 1–20

20. [BR12] Brandtzeg S.R., Rostrup J.C.A., First Quarter 2012: Lower Aluminium Prices, Strong Energy Result, Hydro Aluminium, 2012

21. [Bra10] Braziotis C., Towards the Extended Enterprise: Clarifying Paradigms and Concepts in Supply Chain Management, 15th International Symposium on Logistics, 2010

22. [BW10] Babulak E., Wang M., Discrete Event Simulation, Discrete Event Simulations, Sciyo, 2010

23. [CHH06] Chatfield D.C., Harrison T.P., Hayya J.C., SISCO: An Object-oriented Supply Chain Simulation System, Decision Support Systems, 42, 2006, Pp. 422-434

24. [Chi01] Chinneck J.W., Practical optimization: A Gentle Introduction, Electronic Document, http://www.sce.carleton.ca/faculty/chinneck/po.html, 2001

25. [CM11] Campuzano F., Mula J., Supply Chain Simulation: A System Dynamics Approach for Improving Performance, Springer, 2011

26. [CWD09] Chesonis D.C., Willliams E.M., DeYoung D.H., Meeting Environmental Challenges in the Casthouse, Light Metals, TMS (The Minerals, Metals & Materials Society), 2009 , Pp. 653-657

27. [DA10] Driscoll K., Adams R., The Strategic Impact of Changing Energy Markets on the Aluminium Industry, Light Metals, TMS(The Minerals, Metals & Materials Society), 2010

28. [DD07] Dong L., Dingwei W., A Simulation Based Research on Loading – Unloading Strategy in Railway Container Terminal, Proceedings of ICM' 2007, The 6th International Conference on Management, 2007, Pp. 180-185

29. [DD09] Dey T.K., Dinakar R., Linear Programming, Advanced Algorithms, Department of Computer Science and Engineering, The Ohio State University, 2009

30. [Des110] Desjardins J., Storage Mode Overview, Concept Description, Internal Documentation, IDEcraft, 2010

31. [Des210] Desjardins J., Technical Considerations for Further Step, Internal Documentation, IDEcraft, 2010

32. [Dij59] Dijkstra E.W., A note on two problems in connexion with graphs, Numerische Mathematik 1, 1959, Pp. 269–271.

33. [DK97] Drexl A., Kimms A., Lot Sizing and Scheduling - Survey and Extensions, European Journal of Operational Research Vol. 99, 1997, Pp. 221-235

34. [DN08] Damiron C.,Nastasi A., Discrete Rate Simulation Using Linear Programming, Proceedings of the 2008 Winter Simulation Conference, 2008, Pp. 740-749

35. [DO05] Duda J., Osyczka A., Multiple Criteria Lot-sizing in A Foundry Using Evolutionary Algorithms, Lecture Notes in Computer Science, Vol. 3410, 2005, Pp. 651-663

36. [DY00] Detty R.B., Yingling J.C, Quantifying Benefits of Conversion to Lean Manufacturing with Discrete Event Simulation: A Case Study, International Journal of Production Research, Vol.38-2, 2000, Pp. 429- 445

37. [EAA12] European Aluminium Association, http://www.alueurope.eu/, 2012

38. [Ebb01] Ebben M., Logistic Control in Automated Transportation Networks, Ph.D. Thesis, University of Twente, 2001

39. [EKP96] Eklund P.W., Kirkby1 S., Pollitt S., A Dynamic Multi-source Dijkstra's Algorithm for Vehicle Routing, Australian and New Zealand Conference on Intelligent Information Systems, 1996, Pp. 329 - 333

40. [EVB01] Eick I., Vogelsang D., Behrens A., “Planning Smelter Logistics: A Process Modeling Approach”, Light Metals, TMS(The Minerals, Metals & Materials Society), 2001, Pp. 393-398

41. [Fer12] Ferguson T.S., Linear Programming: A Concise Introduction, Electronic Document, www.math.ucla.edu/~tom/LP.pdf, 2012

42. [FKM09] Fischer W.K., Keller F., Mannweiler U., Anode Plants for Tomorrow’s Smelters: Key Elements for the Production of High Quality Anodes, Aluminium International Today, Volume 21 No. 1, 2009

43. [FKZM05] Freeman N., Kelly J.D., Zhang W., Mann J.L., Scheduling Optimization for Aluminium Smelter Casthouses, Light Metals, TMS(The Minerals, Metals & Materials Society), 2005, Pp. 843-848

44. [Fri04] Friedrich B., Aluminium-Primärgewinnung, IME Institut für Metallurgische Prozesstechnik, RWTH Aachen, 2004

45. [Fu01] Fu M.C., Simulation Optimization, Proceedings of the 2001 Winter Simulation Conference, 2001, Pp.53-61

46. [Fu02] Fu M., Optimization for Simulation: Theory vs. Practice, Journal on Computing 14 (3), 2002, Pp. 192–215

47. [GAN06] Guan Y., Ahmed S., Nemhauser G. L., A Branch-and-Cut Algorithm for the Stochastic Uncapacitated Lot-Sizing Problem?, Mathematical Programming, Springer, 2006

48. [GH95] Ganeshan, R., Harrison, T. P., An Introduction to Supply Chain Management; Technical Report; Department of Management Science and Information Systems, Penn State University, 1995.

49. [GK93] Grjotheim K. , Kvande H., Introduction to Aluminium Electrolysis Understanding the Hall-Héroult Process, Aluminium-Verlag, 1993

50. [GW88] Grjotheim K., Welch B.J., Aluminium Smelter Technology, A Pure and Applied Approach, 2nd Edition, Aluminium-Verlag, 1988

51. [GKL99] Glover F., Kelly J.P., Laguna M., New Advances for Wedding Optimization and Simulation, Proceedings of the 1999 Winter Simulation Conference, 1999, Pp. 255-260

52. [GNS03] Ganapathy S., Narayan S., Srinivasan K., Simulation Based Decision Support for Supply Chain Logistics, Proceedings of the 2003 Winter Simulation Conference, 2003, Pp.1013-1020

53. [GPG02] Gravel M., Price W.L., Gagne C., Scheduling Continuous Casting of Aluminium Using A Multiple-objective Ant Colony Optimization Metaheutistic, European Journal of Operational Research, Vol. 143, 2002, Pp. 218–229

54. [GS02] Gupta A.K., Sivakumar A.I., Simulation Based Multi-objective Schedule Optimization in Semiconductor Manufacturing, Proceedings of the 2002 Winter Simulation Conference, Pp. 1862-1870

55. [GT96] Goldberg A.V., Tarjan R.E., Expected Performance of Dijkstra's Shortest Path Algorithm, Technical Report TR-96-062, NEC Research, 1996

56. [Guo03] Guo X.J., Process Modeling and Intelligent System in Copper Smelter – The Concept of Future Smart Smelter, 5th International Copper Conference, Pyro metallurgy of Copper, 2003

57. [Har10] Harton T.W., Virtual Smelter Modeling for Metal Flow Management, Proceedings of the 45th Annual Conference of the ORSNZ, 2010, Pp. 50-59

58. [Har99] Harland C.M., Supply Chain Management: Relationships, Chains and Networks, British Journal of Management, Vol. 7, Special Issue, 1996, Pp. 63-80

59. [Hie98] Hieta S., Supply Chain Simulation with Logsim-Simulator, Proceedings of the 1998 Winter Simulation Conference, 1998, Pp. 323-326

60. [HKK07] Haller M., Kettle J., Kendrew G., Primary Aluminium Smelting and Power Costs, Summary and Analysis, Vol. 3, Brook Hunt & Associates Ltd. , 2007

61. [HMSW53] Hoffman A.J., Mannos M., Sokolowsky D., Wiegmann N., Computational Experience in Solving Linear Programs. Journal of the Society for Industrial and Applied Mathematics. 1953, Pp. 17–33

62. [Hoe04] Hoefler J., Aluminium Primärerzeugung, Vorlesungsreihe an der Fachhochschule Bonn-Rhein-Sieg, Hydro Aluminium Deutschland GmbH, 2004

63. [HS07] ten Hompel M., Schmidt T. Warehouse Management: Automation and Organization of Warehouse and Order Picking Systems, Springer, 2007

64. [IAI03] International Aluminium Institute, The Aluminium Industry’s Sustainable Development Report, 2003

65. [ISW09] Imran A., Salhi S., Wassan N.A., A Variable Neighborhood-Based Heuristic for the Heterogeneous Fleet Vehicle Routing Problem, European Journal of Operational Research Volume 197, Issue 2, 2009, Pp. 509–518

66. [ITC04] Industrial Technology Center, Principles of Lean Thinking Tools and Techniques for Advanced Manufacturing, National Research Council Canada, 2004

67. [Jai03] Jain P.L., Principles Of Foundry Technology, Edition 4, Tata McGraw-Hill Education, 2003

68. [Jao11] Jaouen G., Use of Process Simulation to Design A Billet Casthouse, Light Metals, TMS(The Minerals, Metals & Materials Society), 2011, Pp. 641-646

69. [JKG05] Jensson P., Kristinsdottir B.P., Gunnarsson H.P., Optimal Sequencing of Tasks in An Aluminium Smelter Casthouse, Computers in Industry Volume 56, Issue 2, 2005, Pp.221-234

70. [JWCEL01] Jain S., Workman R.W., Collins L.M., Ervin E.C., Lathrop A.P., Development of a High-level Supply Chain Simulation Model, Proceedings of the 2001 Winter Simulation Conference, 2001, Pp. 1129-1137

71. [KA03] Karim A., Adeli H., Radial Basis Function Neural Network for Work Zone Capacity and Queue Estimation, Journal of Transportation Engineering, ASCE, 2003, Pp. 494-503

72. [KKKF85] Karmarkar U.S., Kekre S., Kekre S., Freeman S., Load-sizing and Lead-time Performance in A Manufacturing Cell, The Institute of Management Sciences, 1985, Pp.1-9

73. [Kle05] Kleijnen J.P.C., Supply Chain Simulation Tools and Techniques: A Survey, International Journal of Simulation and Process Modeling, Vol. 1, 2005, Pp. 82–89

74. [KPM04] Kadar B., Pfeiffer A. and Monostori, L., Discrete-event Simulation for Supporting Production Planning and Scheduling Decisions in Digital Factories, Proceedings of the 37th CIRP International Seminar on Manufacturing Systems, Digital Enterprises, Production Networks., 2004, Pp. 441-448

75. [KR04] Kaufman J.G., Rooy E.L., Aluminum Alloy Castings: Properties, Processes, and Applications, American Foundry Society, ASM International, 2004

76. [KU07] Kaufmann H., Uggowitzer P.J., Metallurgy and Processing of High Integrity Light Metal Pressure Castings, Fachverlag Schiele & Schoen, 2007

77. [Kva11] Kvande H., Introduction to the Industrial Hall-Héroult Process, Hydro Aluminium, 2011

78. [KVHBD06] Koning H., Verver J.P.S., Heuvel J., Bisgaard S., Does R.J.M.M., Lean Six Sigma in Healthcare, Journal for Healthcare Quality, V. 28, N. 2, 2006, Pp. 4–11

79. [KVKMP03] Kovács, A., Váncza, J., Kádár, B., Monostori L., Pfeiffer, A., Real Life Scheduling Using Constraint Programming and Simulation, Proc. of IMS 7th IFAC Workshop on Intelligent Manufacturing Systems, 2003, Pp. 233–239.

80. [Lar09] Larrivée Y., Hot Metal Transport: A MES Role in Inter-Sector Data Exchange, Aluminium International Today, 2009

81. [LJI02] Liu C., Jula H., Ioannou P.A., Design, Simulation, and Evaluation of Automated Container Terminals, IEEE Transactions on Intelligent Transportation Systems, VOL. 3, NO. 1, 2002, Pp.12-26

82. [LMKO01] Lakhal, S., Martel A., Kettani O., Oral M., On the Optimization of Supply Chain Networking Decisions, European Journal of Operational Research, 129(2), 2001, Pp. 259–270

83. [LPM01] Lendermann P., Ping G. B., McGinnis L.F., Distributed Simulation with Incorporated APS Procedures for High-fidelity Supply Chain Optimization, Proceedings of the 2001 Winter Simulation Conference, 2001, Pp.1138-1145

84. [Mat08] Matta A., Simulation Optimzation with Mathematical Programming Representation of Discrete Event Systems, Proceedings of the 2008 Winter Simulation Conference, 2008, Pp. 1393-1400

85. [MDKMNSZ01] Mentzer J.T., DeWitt W., Keebler J.S., Min S., Nix N.W., Smith C.D., Zacharia Z.G., Defining Supply Chain Management, Journal of Business Logistics, Vol.22, No. 2, 2001

86. [Meg91] Megiddo N., Linear Programming, Encyclopedia of Microcomputers, School of Mathematical Sciences, Tel Aviv University, 1991

87. [Mei10] Meijer M., New Logistic Concepts for 400 and 500 kA Smelters, Light Metals, TMS (The Minerals, Metals & Materials Society), 2010 , Pp. 345-348

88. [Mei11] Meijer M., Aluminium Smelter Logistics- Can These Bring Cost Savings?, Light Metals, TMS (The Minerals, Metals & Materials Society), 2011 , Pp. 421-423

89. [Mel05] Melton T., The Benefits of Lean Manufacturing: What Lean Thinking has to Offer The Process Industries, Chemical Engineering Research and Design Vol. 83-A6, 2005, Pp. 662–673

90. [Mey03] Meyer U., Average-case complexity of single-source shortest-paths algorithms: lower and upper bounds, Journal of Algorithms 48, 2003, Pp. 91–134

91. [ML06] Maiwald D., Leisenberg W., Charging and Melting Management in Primary and Secondary Casthouses, Innovatherm-Paper Casthouse, 2006

92. [MML08] Maticevic G., Majdandzic N., Lovric T., Production Scheduling Model in Aluminium Foundry, Journal of Mechanical Engineering 54, 2008, Pp. 37-48

93. [MP00] Miller S., Pegden D., Introduction to Manufacturing Simulation, Proceedings of the 2000 Winter Simulation Conference, 2000, Pp. 63-66

94. [MRFK03] Mason S.J., Ribera P.M., Farris J.A., Kirk R.G., Integrating the Warehousing and Transportation Functions of the Supply Chain, Transportation Research Part E 39, 2003, Pp. 141–159

95. [MSL03] Mirchandani P., Syal R., Lucas D., Traffic Assignment Using Iterated Route-based Simulation, Transportation Research Board 82nd Annual Meeting Compendium of Papers (CD ROM), 2003.

96. [NO05] Nonas S.L., Olsen K.A., Optimal and Heuristic Solutions for A Scheduling Problem Arising in a Foundry, Computers & Operations Research, Vol. 32, No. 9, 2005, Pp. 2351-2382

97. [Ohn88] Ohno T., Toyota Production System: Beyond Large-Scale Production, Productivity Press, 1988

98. [Oke84] O'keefe R.M., Developing Simulation Models: An Interpreter for Visual Interactive Simulation, Ph.D. Thesis, University of Southampton, 1984

99. [Pah04] Pahladsingh R.R., Introduction of an Integrated Aluminium Production Plant with High Economical Profit, Minimal Energy Consumption and Maximum Environmental Protection, Surinam Industrial Engineering, 2004

100. [PBNN02] Peres S.D., Brahimi N., Najid N.M., Nordli A., Uncapacitated Lot-Sizing Problems with Time Windows, Research Report, 02/4/AUTO, Ecole des Mines de Nantes, 2002

101. [PBTM11] Pires R.L., Baxter R., Tikasz L., McCulloch R.I., Integrated Approach for Safe and Efficient Plant Layout Development, Light Metals, TMS (The Minerals, Metals & Materials Society), 2011 , Pp. 437-441

102. [Pie08] Piehl T.S., Cell Batching Optimization for the New Zealand Aluminium Smelter, Annual Conference of ORSNZ, 2008

103. [PN02] Peterson R.D., Newton L., Review of Aluminium Dross Processing, Light Metals, TMS(The Minerals, Metals & Materials Society), 2002

104. [PP04] Pacciarelli D., Pranzo M., Production Scheduling in A Steelmaking-Continuous Casting Plant, Computers and Chemical Engineering, No. 28, 2004, Pp. 2823–2835

105. [Pri04] Prins C., A Simple and Effective Evolutionary Algorithm for the Vehicle Routing Problem, Computers & Operations Research 31 ,2004, Pp. 1985–2002

106. [PW92] Potts C.N., Wassenhove L.V., Integrating Scheduling with Batching and Lot-sizing: A Review of Algorithms and Complexity, Journal of the Operational Research Society Vol. 43, 1992, Pp. 395-406.

107. [RS03] Rother M., Shook J., Learning to See: Value Stream Mapping to Create Value and Eliminate Muda, Lean Enterprise Institute, 2003

108. [Rya98] Ryan D.M., Optimized Cell Batching for New Zealand Aluminium Smelters Ltd, Annual Conference of ORSNZ, 1998

109. [Sau02] SauerJ., Multi-Site Scheduling Hierarchisch Koordinierte Ablaufplanung auf Mehreren Ebenen, Habilitationsschrift, Fachbereich Informatik, Universität Oldenburg, 2002

110. [SB10] Schriber T.J., Brunner D.T., Inside Discrete-Event Simulation Software: How it works and Why It Matters, Proceedings of the 2010 Winter Simulation Conference, Pp. 151-165

111. [SB99] Sadowski D., Bapat V., The Arena Product Family: Enterprise Modeling Solutions, Proceedings of the 1999 Winter Simulation Conference, 1999, Pp. 159-166

112. [Sch07] Schmitz C., Handbook of Aluminium Recycling, Vulkan-Verlag GmbH, 2007

113. [SER06] Soriguera F., Espinet D., Robuste F., A Simulation Model for Straddle Carrier Operational Assessment in a Marine Container Terminal, Journal of Maritime Research, Vol. 3,No. 2, 2006, Pp. 19-34

114. [SF96] Shekhar S., Fetterer A., Path Computation in Advanced Traveler Information Systems, Proceedings of the 6th Annual Meeting and Exposition of the Intelligent Transportation Society of America, 1996, Pp.304-312

115. [Shi89] Shingo, S., A Study of the Toyota Production System from An Industrial Engineering Viewpoint, Productivity Press, 1989

116. [SKS03] Simchi-Levi D., Kaminsky, P., Simchi-Levi, E., Designing and Managing the Supply Chain: Concepts Strategies and Case Studies, 2nd Edition, McGraw-Hill ,2003

117. [Sum08] Summerauer W., Solution Methods for Lot-Sizing Problems – Multi-Level Models with and without Linked Lots, Diplomarbeit, Wien University, 2008

118. [SWW00] Schulz F., Wagner D., Weihe K., Dijkstra's Algorithm On-Line: An Empirical Case Study from Public Railroad Transport, Journal of Experimental Algorithmics, Volume 5(12), 2000

119. [TA03] Truong T.H., Azadivar F., Simulation Based Optimization for Supply Chain Configuration Design, Proceedings of the 2003 Winter Simulation Conference, 2003, Pp.1268-1275

120. [TBPM10] Tikasz L., Read C.M., Baxter R., Pires R.L., McCulloch R.I., Safe and Efficient Traffic Flow for Aluminium Smelters, Light Metals, TMS (The Minerals, Metals & Materials Society), 2010 , Pp. 427-432

121. [TCE10] Tokyo Commodity Exchange, Aluminum Delivery Detailed Rules, www.tocom.or.jp, 2010

122. [TK05] Tan R.B.H., Khoo H. H., An LCA Study of a Primary Aluminum Supply Chain, Journal of Cleaner Production, 2005, Pp. 607–618

123. [TLRY01] Tang L., Liu J., Rong A., Yang Z., A Review of Planning and Scheduling Systems and Methods for Integrated Steel Production, European Journal of Operational Research No. 133, 2001, Pp. 1-20

124. [TM03] Totten G.E., Mackenzie D.S., Handbook of Aluminum: Alloy Production and Materials Manufacturing, CRC Press, 2003

125. [TMPB12] Tikasz L. G., McCulloch R.I., Pentiah S.D., Baxter R. F., Simulation Tools to Complement Cast House Design and Daily Operation, Light Metals, TMS (The Minerals, Metals & Materials Society), 2012 , Pp. 993-997

126. [Tod01] Todd M.J, The Many Facets of Linear Programming, Springer-Verlag 2001

127. [TS98] Tompkins J.A., Smith J.D., The Warehouse Management Handbook, Second Edition, Tompkins Associated, North Carolina, 1998

128. [Tum96] Tumay K., Business Process Simulation, Proceedings of the 1996 Winter Simulation Conference, 1996, Pp. 93-98

129. [TW08] Tang L., Wang G., Decision Support System for the Batching Problems of Steelmaking and Continuous-casting Production, Omega, The International Journal of Management Science 36, 2008, Pp. 976 – 991

130. [UAKEN07] Upenieks V.V., Akhavan J., Kotlerman J., Esser J., Ngo M.J., Value-Added Care: A New Way of Assessing Nursing Staffing Ratios and Workload Variability, The Journal of Nursing Administration, V.37, N.5, 2007, Pp. 243-252

131. [VW03] Voss S., Woodruff D.L., Introduction to Computational Optimization Models for Production Planning in A Supply Chain, Springer, 2003

132. [WEDS09] Winkelmann A., Eick I., Droste C., Segatz M., Logistic Simulation Discrete Material Flow and Processes in Aluminium Smelters, Light Metals, TMS (The Minerals, Metals & Materials Society), 2009 , Pp. 523-527

133. [WG03] Williams E.J., Gunal A., Supply Chain Simulation and Analysis with Simflex, Proceedings of the 2003 Winter Simulation Conference, 2003, Pp. 231-237

134. [WHP98] Whitman L., Huff B., Palaniswamy S., Commercial Simulation over the Web, Proceedings of the 1998 Winter Simulation Conference, Vol. 1, 1998, Pp. 335-340

135. [Wis11] Wisner J.D., Principles of Supply Chain Management: A Balanced Approach, Cengage Learning, 2011

136. [WJR91] Womack J., Jones D., Roos D., The Machine that Changed the World., Harper-Perennial, 1991

137. [WW58] Wagner H.M., Whitin T.M., Dynamic Version of The Economic Lot Size Model, Management Science Vol.5, 1958, Pp.212-219.

138. [YKSBT04] Yuan X.M, Khoo H.H., Spedding T.A., Bainbridge I., Taplin D.M.R., Minimizing Total Setup Cost for A Metal Casting Company, Proceedings of the 2004 Winter Simulation Conference, 2004, Pp. 1189-1194

139. [YP04] Yadlapati S. S., Park B., Development and Testing of Variable Speed Limit Control Logics for Work Zones Using, Center for Transportation Studies, the University of Virginia, Research Report No. UVACTS-13-0-43, 2004

140. [ZKB99] Zeigler B.P., Kim D., Buckley S.J., Distributed Supply Chain Simulation in A DEVS/CORBA Execution Environment, Proceedings of the 1999 Winter Simulation Conference, 1999, Pp. 1333-1340