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HENCON

MASTERS' THESIS

Development of a Planning and Control Strategy for AGVs in the Primary Aluminium Industry

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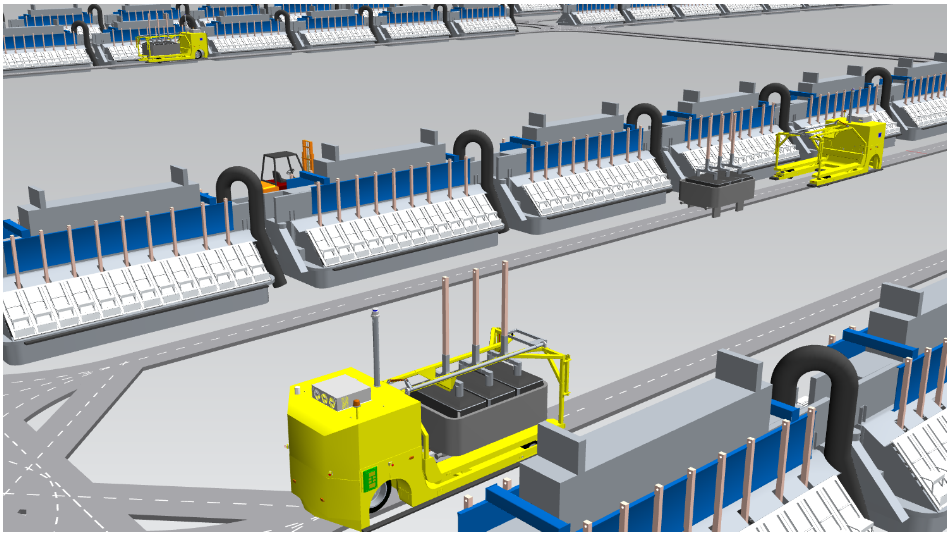

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Management Summary

Automated Guided Vehicle (AGV) developments in the primary aluminium industry are in a relatively early stage. Hencon is a company active in this industry as it manufactures AGVs and other relevant vehicles. Hencon's goal is not only to build AGVs for the aluminium industry but also to advise their clients about the impact AGVs could have on their production environment. However, the reliability and validity of currently used methods for providing insights into the performance impact that a certain AGV configuration yields, are accompanied by deficiencies. Moreover, in this capital-intensive industry, only a marginal improvement with the application of a sophisticated analytical approach can lead to considerable cost reductions realized by aluminium producers. A promising improvement direction for Hencon as being a full-service provider and, therefore, focus of this study, is the supportive activity of anode pallet transport by means of AGVs. This study focusses on the involved logistics regarding the transport of those pallets in the primary aluminium industry.

Research Objective

Improving the decision-making process of aluminium smelter operations with a focus on anode pallet logistics forms the subject of this report. The objective is this study is as follows.

Research Objective: *To develop a generic and efficient operational planning and control strategy for AGVs involved in anode transportation, within the smelting process of primary aluminium manufacturing.*

This objective is two-fold and contains two mutually dependent objectives. First, an operational planning and control strategy that provides an efficient approach for dispatching anode transportation activities. Second, a reliable generic model for evaluating the performance of AGV implementations of anode transport. The model should be generic and able to evaluate the performance under various scenarios. Although it is for this studies outcome irrelevant which objective is leading, the first one is chosen as leading.

Method

The developed evaluation model relies on the development of three models. The first model is the Multi-Agent System (MAS). The MAS supports the AGV system and functions as a planning and control system. A MAS is a group of intelligent and autonomous computational entities (agents) which coordinate their capacities and plans in order to achieve certain goals. The Prometheus methodology is employed for designing the MAS. This detailed and comprehensive method is evolved out of practical industrial and pedagogical experience, and consists of three phases: system specification, architectural design, and detailed design.

The second model is the AGV system which is designed by using the framework of Le-Anh and Koster (2006). Their approach involves design choices on several hierarchical levels and is used as a guidance for making decisions regarding the AGV system.

The third model involves a simulation model to evaluate the performance under MAS control. Simulation is a means to systematically access changes in settings for a wide spectrum of scenarios. More specifically, discrete-event simulation is used for conducting experiments. This type of simulation models the system as a series of countable events that may change the state of the system.

To the best of our knowledge, this study's particular application within the primary aluminium industry has not been studied before. Compared to existing AGV implementations that incorporate agent-based technologies, this study does not solely focus on the transportation of goods but includes the application to a wide scope of realistic large-scale scenarios that are not per se limited to application in the aluminium industry. Additionally, the model shows the applicability with various demand patterns that could arise from Manufacturing Execution Systems (MES).

Results

This study contributes to the development of three models: a MAS, an AGV system, and a scenario evaluation model of which the latter one is built by using discrete-event simulation. The MAS consists

of entities which each have their own functionalities. As agents we defined a *Demand Management*, *Section Management*, *AGV Parking Management*, *Vehicle Scheduling*, *Vehicle Routing*, *Conflict Resolution*, and *Battery Management*. Next, the AGV system was developed. Consequently, we built a conceptual model and verified and validated this model by several techniques.

The generic scenario evaluation model can assess not only the current situation but also experiment with alternative operational planning and control strategies and AGV system designs. We validated the simulation model by conducting experiments and analyzing the results. To this end, we performed techniques such as white-box validation (to validate the behavior of subsets of the system) and black-box validation (to validate the overall behavior of the model). For discussing the yielded simulation results, we considered an aluminium smelter layout that represented a smelter which is quite similar to one of Hencon's customers. We concluded that the simulation model accurately represented the smelter for the objectives of Hencon. A remarkable result of simulations for this particular factory is that we observed a decrease in the average travel time per vehicle per trip for a relatively small number of vehicles in the system, while we observed an increase for a larger number of vehicles in the system. Other performance indicators such as the number of jobs that are delivered too late and the average response time per vehicle per trip indicate similar trends. An explanation of this behavior might be that for a large number of AGAPTVS the number of collision avoidance procedures are higher and thus consume relatively more amount of the travel time. We concluded that more AGAPTVs in the system will likely not always lead to a better system performance concerning several perspectives. The trade-off regarding the number of AGVs in the system and the system performance should be examined and tailored to the wishes of Hencon and its customers.

Recommendations

The practical relevance emerges as Hencon can start to employ the scenario evaluation model to not only enhance customers' AGV logistics but also their potroom planning and control strategies. Even with a limited set of input parameters and confined information concerning, for example, anode demand patterns, the model can provide insights into expected yielded performance. During the implementation phase at a client, the evaluation model may be used to find appropriate AGV planning and control rules customized to specific client's needs. Moreover, the piece of software may be used to periodically, based on recent developments at the customer site such as potroom expansions or the placement of additional charging stations, re-evaluate scenarios and configurations. Ultimately, Hencon can then use the developed model as a tool during its full-service providing activities.

In addition to the aforementioned recommendations, this study and resulting model face some limitations and, therefore, future research and model extensions are desirable. Practical and theoretical recommendations can be made. A full list of recommendations is given in Chapter 9 of this report. The following practical and theoretical recommendations can be made (remark that some recommendations are relevant from both perspectives):

Practical

1. Although the model is applicable to a wide variety of clients, there is no guarantee that every imaginable smelter can be evaluated. Extension of the evaluation model by considering side-by-side positioned cells seems a suitable next step.
2. An attractive extension is the inclusion of smelter logistics. Modelling smelter operations and involved logistics would enhance the validity of the system. In a further stage, Hencon could consider their fleet capable for these type of jobs with AGV technology as well.
3. Crane movements are not covered in full detail. A noteworthy direction for further research is the detailed inclusion of crane blockades.
4. This study assumes an infinite capacity at the rodding shops (pick-up and drop-off locations) while smelters face space and capacity restrictions. A promising future research direction is the integration of rodding shop activities. Likewise, considering transshipment points that could act as a buffer can lead to performance benefits.

Theoretical

1. A thoughtless design of experiments can quickly explode the possible solution search space because of the many possible configurations and parameterizations. Some configurations may be excluded on beforehand because they are not considered as valid in practice. However, fine-tuning parameters and methods to find good solutions quickly, still require more attention in future research. To address this deficiency, simulation optimization techniques may be an interesting future direction. These techniques try to find the best input factors without accessing each experimental configuration. One then searches for the best solutions with regard to, for example, computational time constraints.
2. The model is generic and thus its potential use goes beyond the application area of the primary aluminium industry. Besides that other Hencon software platforms may use technology developed in this study, existing AGV systems such as warehouse management systems can be evaluated as well (as long as they are similarly parameterized).
3. The developed MAS acts as a framework for further research. Different hierarchical MAS structures can be studied as an extension. A promising direction is the inclusion of auction mechanisms for decision-making.

Preface

When I was young, I could not have imagined that the adventure of completing a master study with all its facets, was such a pleasure. For me as an *Industrial Engineering and Management* student, I am proud to cordially present you this thesis, which marks the end of my master program at the *University of Twente*. This report contains the result of a battle against virtual vehicles that refuse to drive autonomously and efficiently. With the small amount of intelligence we gave to them, the battle of man versus vehicle has just been started.

I was lucky to have the chance to be supervised by Martijn Mes and Peter Schuur from the *University of Twente*, and Wim Buys and Rudi Roth from *Hencon*. I can imagine it sometimes must have been a real struggle to read this report in such an extensive manner most of you did. It is motivating to know that someone takes the time to read your work with such care.

Martijn, thank you for the feedback and the several meetings to effectively discuss everything that was required to progress to the next stage. You left me free to execute my study making sure to point me in the right direction with good feedback when necessary. Peter, your constructive feedback and suggestions, have significantly improved the quality of this thesis. Also, the coffee talks are really appreciated and contributed to a pleasant and fruitful working atmosphere.

I would also express my thanks to Wim and Rudi, for their valuable expertise. They kept me focused on doing practically relevant research. Wim and Rudi, thank you for taking the time to discuss my progress, as well as giving me the room to find out things by myself. I would also like to kindly thank Mathijs Ruesink and Gerrit Hiddink from *Hencon* for their contribution to this thesis.

The whole journey made me realized how fortunate I was to be studying at such a motivating university. I owe gratitude to many inspiring people I met or collaborate with during my study adventure. Summer schools, study tours, associations, institutional visits, inspirational talks, study related competitions, workouts in the gym, coffee drinks with (random) people, and other interruptions of a working day were definitely supporting me. In particular, thanks to my study mates for the good time we had. I'm sure many contacts would stay life-long.

Combining numerous hours of working on this thesis in combination with various other duties resulted in many (literally) sleepless nights. Nevertheless, it was worth it.

I'm curious about what the future will bring!

Rob

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List of Abbreviations

AAD	**A**gent **A**cquaintance **D**iagram
ACV	**A**node **C**hanging **V**ehicle
ACOM	**A**node **co**ver **m**aterial
AGAPTV	**A**utomated **G**uided **A**node **P**allet **T**ransport **V**ehicle
AGV	**A**utomated **G**uided **V**ehicle
AIF	**A**luminium **f**luoride
APSM	**A**node **P**allet **S**torage **M**anagement
APTV	**A**node **P**allet **T**ransport **V**ehicle
BDT	**B**utt (anode pallet) **d**rop-off **t**ime
BERT	**B**utt (anode pallet) **e**arliest **r**elease **t**ime
BLRT	**B**utt (anode pallet) **l**atest **r**elease **t**ime
BM	**B**attery **M**anagement
BPT	**B**utt (anode pallet) **p**ick-up **t**ime
BTV	**B**ath **T**apping **V**ehicle
CC	**C**onstruction **C**rane
CLRT	**C**losest to **L**atest **R**elease **T**ime
CR	**C**onflict **R**esolution
CCL	**C**avity **Cl**eaner
DARP	**D**ial-**a**-**r**ide-**p**roblem
DCD	**D**ata **C**oupling **D**iagram
DM	**D**emand **M**anagement
ERP	**E**nterprise **R**esource **P**lanning
FAV	**F**irst **A**vailable **V**ehicle
FCFC	**F**irst-**C**ome-**F**irst-**S**erved
FCV	**F**ully **C**harged **V**ehicle
FDT	**F**resh (anode pallet) **d**rop-off **t**ime
FERT	**F**resh (anode pallet) **e**arliest **r**elease **t**ime
FLRT	**F**resh (anode pallet) **l**atest **r**elease **t**ime
FPT	**F**resh (anode pallet) **p**ick-up **t**ime
FTL	**F**orklift
HCB	**H**ammer **c**rust **b**reaker
HHP	**H**all-**H**éroult **P**rocess
HTC	**H**encon **T**raffic **C**ontrol
LCIT	**L**east **C**umulative **I**dle **T**ime
LDF	**L**ow **D**ischarge **F**eeder
LIV	**L**ongest **I**dle **V**ehicle
LTD	**L**ongest **T**ravel **D**istance
LTV	**L**adle **T**ransport **V**ehicle
LFT	**L**arge 6t **F**orklift
LUV	**L**east **U**tilized **v**ehicle
MAS	**M**ulti-**a**gent **s**ystem
MES	**M**anufacturing **E**xecution **S**ystem
MILP	**M**ixed-**I**nteger **L**inear **P**rogramming
MTV	**M**etal **T**apping **V**ehicle
NV	**N**earest **V**ehicle
OR	**O**perations **r**esearch
P/D	**P**ick-up and **D**elivery
PDC	(160t) **P**ot **D**isplacement **C**rane
PDP	**P**ick-up and **D**elivery **P**roblem
PDPTW	**P**ick-up and **D**elivery **P**roblem with **T**ime **W**indows

PDT	**P**rometheus **D**esign **T**ool
PSUT	**P**ot **S**tart-**U**p **T**ilter
PTC	**P**ot **T**ending **C**rane
PM	**P**ark **M**anagement
RJ	**R**andom **J**ob
RUP	**R**ational **U**nified **P**rocess
RV	**R**andom **V**ehicle
STD	**S**hortest **T**ravel **D**istance
SM	**S**hift **M**anagement
TCS	**T**ransport **C**ontrol **S**ystem
UML	**U**nified **M**odeling **L**anguage
VR	**V**ehicle **R**outing
VS	**V**ehicle **S**cheduling
VRP	**V**ehicle **R**outing **P**roblem
VRPTW	**V**ehicle **R**outing **P**roblem with **T**ime **W**indows
WEST	**W**orkforce **e**arliest **s**tart **t**ime
WLST	**W**orkforce **l**atest **s**tart **t**ime
WST	**W**orkforce **s**tart **t**ime

Chapter 1

Introduction

In the framework of completing the Masters *Industrial Engineering & Management* at the *University of Twente*, this report contains a graduation thesis conducted at *Hencon BV*. This chapter gives an introduction to this thesis. Section 1.1 introduces the company. Subsequently, Section 1.2 contains the problem identification, in which we state the problem that is subject to this research. Section 1.3 formally describes our research design, including the research objectives, the scope of this research, the research questions, and the research approach. Finally, Section 1.4 provides the outline of the remaining part of this thesis.

1.1 Company Introduction

Hencon is a world-wide supplier of specialized vehicles for the heavy industries. Where conventional vehicles like forklift trucks and tractors cannot operate to full satisfaction due to particular circumstances, Hencon equipment provides a solution. The machines are designed to perform in for example hot smelter environments with high magnetic fields, in underground mines with rough operations, and in the primary aluminium industry where space is often an issue. Areas of expertise of Hencon are the primary aluminium industry in which alumina is smelted to pure aluminium metal, and the secondary aluminium industry in which aluminium scrap is recycled into aluminium that can be used again. The special designed, custom-made vehicles (see Figure 1.1 for some examples) are in operation all over the world at various kind of industries, such as:

- Primary aluminium industry
- Secondary aluminium industry
- Light metal industry
- Concrete industry
- Steel industry
- Mining

Hencon has its origin in 1956 where it started with mainly manufacturing side loaders and road construction vehicles like motor graders. Since 1972, Hencon provides equipment solutions for the light metal industry. Approximately from then onwards, Hencon expended their market by developing other custom-made vehicles as well. Nowadays, with customers like Alcan, Alcoa, BHP Billiton, Corus, Hydro aluminium and Thyssen, but also companies of smaller sizes, Hencon aims to be a full-service provider. Besides consultancy, installation, and commissioning, Hencon provides after sales services like service operators and maintenance training, spare parts & consumables services and overhauls as well.

Hencon is currently investigating possibilities to strengthen their competitive position by gaining access to the emerging technology of Automated Guided Vehicles (AGVs). This rising technology (see Appendix A) can complement their current assets and capabilities and therefore lead to new market opportunities and additional after sales services. Hencon did already do some research and underlines the importance of AGVs and their unique position as supplier within this industry. The primary aluminium industry, as one of the core industries of Hencon, seems promising for applications of this technology. We advocate the emergence of this technology and in particular the role of Hencon in the two subsequent sections in more detail.

(A) Aluminium tapping vehicle. (B) Anode changing vehicle.

(C) Cavity Cleaner. (D) Ladle transport and tilting vehicle.

FIGURE 1.1: Examples of vehicles made by Hencon.

1.2 Problem Context

This section first explains the background of the problem studied in this thesis, which is described in Subsection 1.2.1. In that subsection we introduce some terminology and elaborate on the context of the problem. Subsection 1.2.2 reveals the formulated problem in a concrete manner.

1.2.1 Problem Background

This graduation project is the first work package of a larger research project that focuses on just-in-time material handling for the primary aluminium industry. With over 60 primary aluminium clients worldwide, a substantial client base is dedicated to this industry. Hencon selected their fleet within this industry as most promising one for employing the AGV technology and therefore we demarcate this thesis to those vehicles.

This work package deals with the operational control of AGVs in a 24/7 production environment for primary aluminium. Let us start with briefly outlining the aluminium production process, since this influences our scope. Subsequently, we go into detail about the primary production process, where we focus on the so-called Hall-Héroult production process. This basic process description is essential to understand the role of Hencon as AGV provider within this industry.

1.2.1.1 Outline of Aluminium Production Process

The aluminium production process, as explained by the American Chemical Society National Historic Chemical Landmarks (1997), can be classified in five steps. Figure 1.2 depicts those five steps. In the first step, aluminium production starts with mining the raw material bauxite. The second step is the refinement of alumina, in which raw ore is ground and mixed with lime and caustic soda and then heated in high-pressure containers. The aluminium oxide is dissolved by the caustic soda, precipitated out of the solution, washed and heated to eliminate water. The resulting alumina is a white powder resembling icing sugar. So, the aluminium oxide (alumina) is extracted from bauxite in a refinery. The production process continuous with smelting the alumina into aluminium, which is the third step. The next paragraph describes this in more detail. In the fourth step, aluminium products are fabricated. Aluminium is alloyed with other metals and is then fabricated into a range of products through forging, casting, extrusion or rolling. Fluxing purifies the metal, which is then poured into molds or cast into ingots. The last step, step five, is the recycling of aluminium.

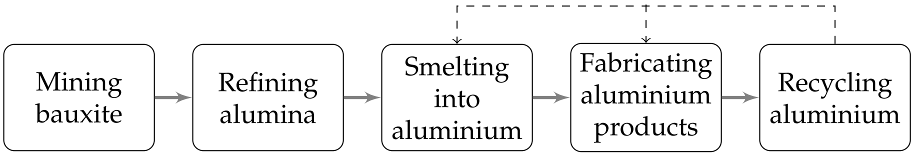


FIGURE 1.2: Steps of aluminium production process

1.2.1.2 Primary Aluminium Production Process and the Role of Hencon

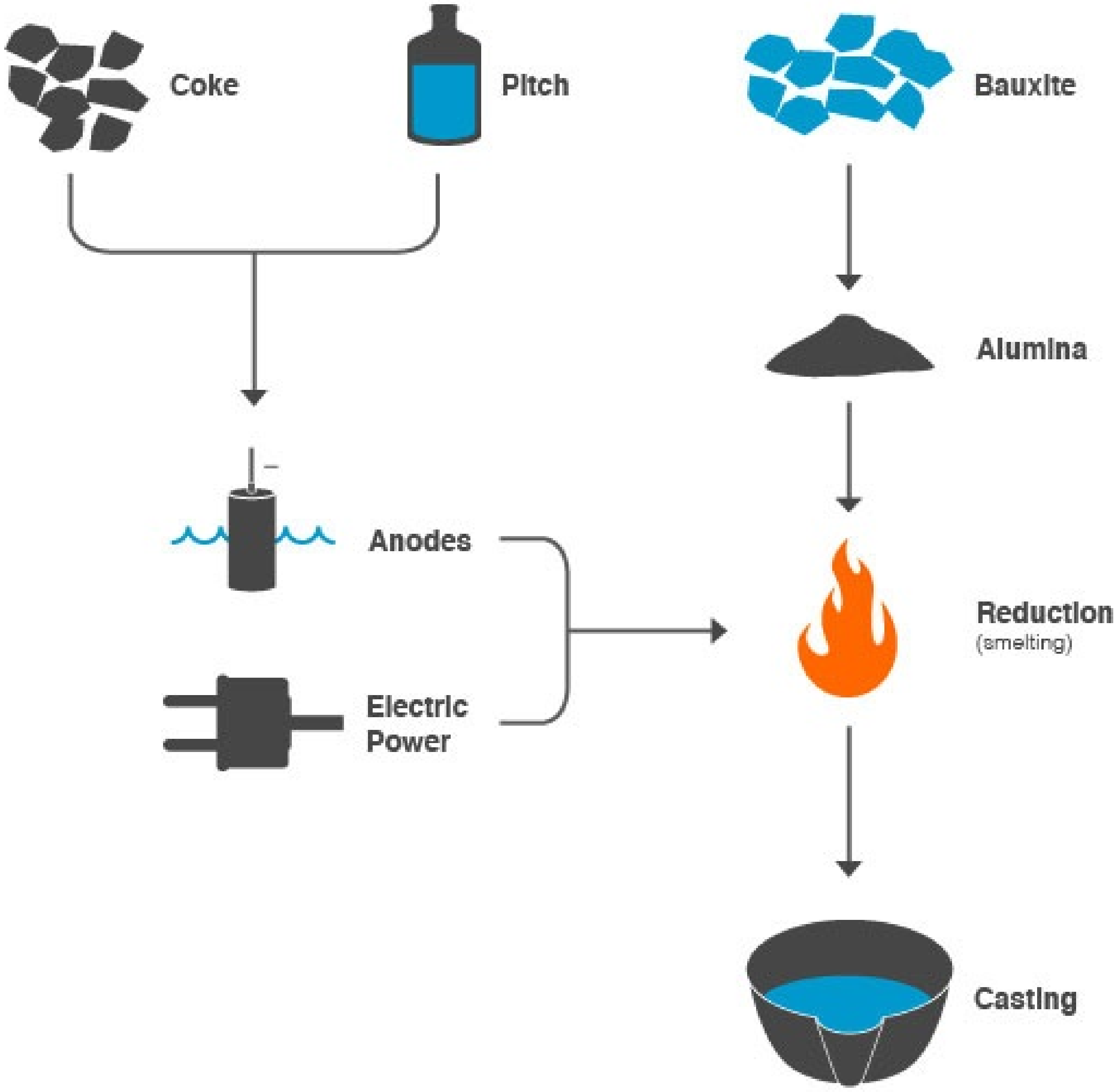
Hencon provides vehicles suitable for several applications within the aluminium production process. To understand the role of Hencon, we now further concisely explain the processes involved in the primary aluminium production and thereby discuss the functionalities of some vehicles from Hencon.

The primary aluminium process is the process in which refined alumina is smelted to pure aluminium metal (step three of Figure 1.2), while in the secondary aluminium industry the recycling process (step five) is included as well. This thesis is mainly bounded to the primary aluminium industry.

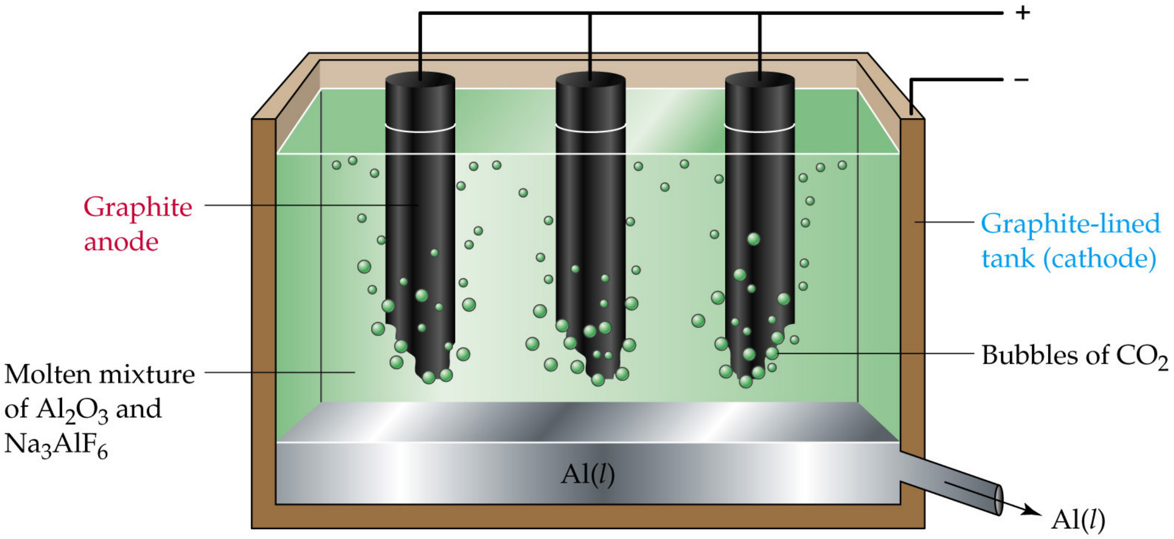
Figure 1.3 graphically illustrates the main steps in primary aluminium production. The production of aluminium from bauxite exists of two steps: refining bauxite to obtain alumina and smelting alumina to produce aluminium. The process starts with separating alumina from bauxite. The so-called Bayer process, with various modifications, is widely used to obtain alumina from the bauxite (Totten and MacKenzie, 2003b). The smelting process of alumina to produce aluminium is mostly carried out via the so-called Hall-Héroult process, invented in 1886 (Hydro, 2012). In this process, alumina is dissolved in an electrolyte that consists of molten fluoride salts kept at about $950 - 970°\text{C}$ (Totten and MacKenzie, 2003b). Basically, the aluminium atom in alumina is bonded to oxygen and the electrolysis process breaks this boundary to produce aluminium metal. This succeeds in electrolytic cells (often called "pots"), where carbon cathodes form the bottom of the pot and act as the negative electrode. Anodes (positive electrodes) are held at the top of the pot and are consumed during the process when they react with the oxygen coming from the alumina. When direct high electric current is passed through this melt, the alumina is decomposed into molten aluminium, deposited at the cathode, and oxygen, which reacts with the carbon anode to form carbon-dioxide. The process ends with siphoning off the molten aluminium, blending the aluminium to an alloy specification (if required), cleaning and casting into different semi-products.

The anode blocks, which may weigh around 1 metric ton each, are consumed for roughly 80% (Hydro, 2012) and need to be replaced by new ones. As said previously, aluminium smelters consists of multiple electrolytic cells that often contains several of those blocks. According to Totten and MacKenzie (2003b), cells in which the primary aluminium process takes place are nowadays of two types: those with pre-baked anodes and those with baked-in-place anodes (Söderberg). Most of the pot-lines built since the early 1970s use the pre-baked anodes, where the anodes, manufactured from a mixture of petroleum coke and coal tar pitch (acting as a binder), are "pre-baked" in separate electrode plants. Totten and MacKenzie (2003b) describes that in the Söderberg technology, the carbonaceous mixture is fed directly into the top part of the pot, where "self-baking" anodes are produced using the heat released by the electrolytic process. Hencon's vehicles are constructed to execute this replacement task and closely-related tasks (e.g., see Figure 1.1b, 1.1c and 1.4). Figure 1.5 on the subsequent page, shows an impression of how this replacement process takes place.

Depending on how and where it will be processed further, liquid aluminium is often deposited at the bottom of the pot and siphoned off periodically and then taken to a holding furnace (Hydro, 2012). Hencon provides specialized vehicles that are able to transport and tap hot metal (e.g. see Figure 1.1a and 1.1d).



(A) Overview primary aluminum production process (Hydro, 2013b)



(B) Electrolytic cell for production of aluminum by the Hall-Héroult process (McMurry, 2003)

FIGURE 1.3: Primary aluminum production process

(A) Specials.

(B) Articulated.

FIGURE 1.4: Examples of anode pallet transport vehicles

We only explained the primary aluminium process concisely and addressed a limited number of associated vehicles that are designed and manufactured by Hencon for the primary aluminium industry. In practice, the aluminium production process is complex and takes place on a large scale. For example, aluminium manufacturing facility typically consists of hundreds of cells, and each electrolytic cell usually produces about a ton of aluminium a day. Also, the diversity of possible functionalities from Hencon's vehicles is underexposed. For a comprehensive explanation of the aluminium production process, we refer to the Handbooks of aluminium as written by Totten and MacKenzie (2003a, 2003b). In the next chapter, we explain parts of the primary aluminium process and address the involved internal logistics in particular.

(A) Anode taking. A burned anode is removed from an electrolytic-cell.

(B) Anode placing. An fresh anode is placed in an electrolytic-cell.

FIGURE 1.5: Anode replacement in the aluminium production process.

1.2.2 Problem Identification

In the previous sections, we have mentioned Hencons increasing interests in developing and implementing AGV technology to their vehicles used in the primary aluminium industry. Since 2006, Hencon investigated the Hall-Hérault production process of aluminium in order to come to an integrated automatic logistic approach for feeding the Hall-Héroult cell as efficient as possible with the introduction of AGVs. Although Hencon already did do some ground work research in setting up the

AGV technology, there are still some major barriers to overcome. Below, we start with briefly describing Hencon's current situation regarding the AGV implementation, where we focus on the difficulties they are currently facing. We succeed with Hencon's wishes regarding the further realization of this promising technology, after which this discrepancy leads us to a problem statement.

Currently, Hencon is using and further developing the Transport Control System (TCS) openTCS® (Fraunhofer Institute for Material Flow and Logistics) control system software for their clients in the aluminium industry. OpenTCS is a vendor-independent, platform-independent and free and open-source piece of software that acts as a control system for AGVs and other non-continuous conveyors. Hencon will use openTCS for setting up a basic AGV network grid and traffic management ruling system. The implemented system Hencon developed so far, is denoted as the so-called Hencon Traffic Control (HTC) system. HTC can be seen as an extension of the openTCS software and provides for example data visualization, routing information, battery management and data analytics. In Chapter 2, we explain the role of HTC in more detail. Hencon already developed the fundamentals for utilizing this system (like including sensor components in the AGV design). However, regarding the further development of this system there are two closely interrelated obstacles to overcome which are discussed below.

A major challenge for Hencon is to accurately evaluate the impact AGVs could have on the manufacturing facilities of their clients. Hencon is not able to provide their clients reliable information about the impact a certain AGV configuration (e.g., amount of AGVs, load capacity, battery capacity, etc.) has on their manufacturing processes. To elaborate on this, the introduction of AGVs allow a 24/7 operation, while customers currently mainly operate on a shift-based planning strategy. Although rough estimations currently provide an answer, it is uncertain how this will turn out in practice. To emphasize on the complexity of the problem: every client has its own specific facility layout instances, and likewise the AGV network grid will differ in every instance. Since the initial investment in AGVs might be a major obstacle for customers to proceed with the purchase, it is prudent to perform a thorough analysis of their performance.

Another closely related issue for Hencon, is to come to an optimized vehicle routing strategy that is able to support the aluminium production process and deliver or pick up materials in time. Based on the actual requirements of a real-time operational planning system, the optimal routing and handling of anodes (and metal) needs to be handled in order to have the anodes (and metal) arrive in time and safe at the required destinations. The openTCS software (version 3.2) is currently not able to avoid deadlocks for concurrently scheduled vehicles. In other words, it is possible that two or more vehicles moving in the same area run into a deadlock. Furthermore, the system performance under various dispatching and traffic rules cannot easily be evaluated and require a more sophisticated approach to comprise other operations going on in the plant as well. In smelters, this can, for example, be observed through the delays in the physical distribution process. Delays and other logistical disturbances may have serious consequences, such that corrective plant actions can be invoked. Limited attention has also been given to dealing efficiently with the reverse logistics. Since the AGVs are electrical vehicles and therefore need regular charging time due to limited Li-ion battery capacity, there is a need to include an efficient battery charging strategy as well. To summarize, the currently used planning and control strategies require a more sophisticated approach to enhance the smelter operations.

As a full-service provider, Hencon's goal is not only to build the AGVs but also to advise their clients about the impact an efficient AGV implementation has on their environment. For that reason, two needs can be derived from the problem description above: (1) a generic model that provides a reliable evaluation for different kinds of facility layouts, AGV configurations and network grids, and (2) a planning and control strategy that is suitable to that generic model and provides an efficient workflow. Thus, based on the discussed problem description, we construct the following problem statement:

Problem Statement: *Hencon is currently not able to provide a reliable indication to their customers, within the primary aluminium industry, about the impact an efficient AGV implementation for anode transportation has on the performance of their manufacturing facilities.*

As discussed above, the problem addressed in this thesis is twofold. First, Hencon is currently not able to provide a reliable and valid indication to their customers in the primary aluminium industry about the performance impact that could be expected from implementing a certain AGV configuration. Second, Hencon's current operational planning and control approach to transport anodes in this industry is not able to deal efficiently within modern manufacturing environments. With this thesis we aim to provide a satisfactory solution to this two-fold problem.

1.3 Research Design

In this section, we start with defining the scope of this project in Subsection 1.3.1. Subsection 1.3.2 discusses the research objectives. In Subsection 1.3.3, we emphasize on the research contribution. We proceed in Subsection 1.3.4 with declaring our research questions and the methodology used to answer them.

1.3.1 Demarcation

The previous sections already define a broad outline of the scope, but to cope with the complexity of this study, we will now specify the boundaries in more detail.

Although some fundamental understanding of the aluminium fabricating process is needed to understand the logistic processes, we do not describe the manufacturing process in excessive detail (e.g., chemical equations, byproducts, disruptions, etc.). For the aim of this project we focus on the smelting process of alumina into aluminium (see Figure 1.2), since Hencon pinpoints the internal logistics within that area to be the most promising one. More specifically, we demarcate our scope even further to the process of anode transportation. Internal operations in this environment such as workforce scheduling, maintenance, (optimal) balancing the levels of anodes in the cells, and transportation of pots, require complex systems and would tremendously increase the complexity of the system as a whole. Therefore any other external operations that are not explicitly mentioned, are not part of the solution we provide. Since some ground work research has been done for setting up an AGV network grid and traffic management ruling system, we use and extend these models and systems within this project.

For Hencon and their (prospective) clients, it is essential that we develop a generic system that can be tailored to various situations. However, in practice and due to time limitations, it is not realistic to develop a comprehensive system that can handle with all possible varieties that one can imagine. Therefore, our first goal is to develop a generic evaluation tool that is suitable for different type of facility layouts and AGV configurations. By using parametrization or extensions, manufacturing environments and scenarios can be examined and adjusted to client instances.

The operational control of the AGV is part of the HTC tool for data visualization, routing, battery management and data analytics. The HTC tool is connected to the control software of a client, being often ORACLE/SAP orientated, with custom made modules and control algorithms that initiate the events such as anode setting or metal tapping. Hence, HTC receives information from the client about events that trigger for example the routing control system. We focus on the part of the HTC, aiming to coordinate operational traffic control actions for anode transportation in an aluminium smelter with a dynamic working routine. Within the scope of this research, the AGV controller that actually takes care of executing the driving functionality correctly (e.g., accelerating, braking, maneuvering, turning, equipment moving, drilling, etc.), is not included. In fact, our solution is somewhat in the middle of an Enterprise Resource Planning (ERP) system (or similar system) of the client and the AGV controller, and acts as a mediator between several systems. To clarify this, from a logistics perspective our second aim is to provide an operational planning and control strategy of AGVs, while the actual (physical) actions are executed by other systems.

1.3.2 Research Objectives

The main research goal of this thesis is to provide an adequate solution to the formulated problem as discussed in Section 1.2.2. On the one hand, the operational planning and control strategy for these AGVs should be able to achieve an efficient workflow in the smelting department of the primary aluminium industry. On the other hand, we have to develop a generic model that is capable of providing insights into the performance that will be achieved under different scenarios when implementing a certain AGV configuration. Hence, the goal of this research comprehends two aspects:

1. An operational planning and control strategy that provides an efficient approach for dispatching activities associated with anode transportation, within the smelting process of primary aluminium manufacturing.

2. A reliable generic model to evaluate the performance an AGV implementation of anode transportation within the smelting process of primary aluminium manufacturing.

These two aspects are mutually dependent. That is, to test the efficiency of design choices regarding the operational planning and control strategy, the performance need to be evaluated appropriately. Likewise, for evaluating the performance of various AGV implementations, it is convenient to consider applicable operational planning and control strategies. Although it is for the research outcome irrelevant which aspect is leading, we choose to formulate the research objective such that the operational planning and control strategy is leading. This leads us to the following research objective:

Research Objective: *To develop a generic and efficient operational planning and control strategy for AGVs involved in anode transportation, within the smelting process of primary aluminium manufacturing.*

As our objective is two-fold, we initially focus on the two aspects separately, after which we integrate them. The model should be generic in the sense that it is suitable for (1) different kinds of manufacturing facilities, varying in size or layout, (2) different AGV configurations, varying in type of vehicles (load capacity, speed, battery capacity, etc.), and (3) various operational planning and control strategies. Likewise, the model should be suitable for a major selection of (prospective) clients of Hencon.

We focus on modelling a so-called closed transportation network of AGVs in various manufacturing environments. This transportation network is defined as a closed network since no (external) AGVs can enter or leave the system. As we discuss in Chapter 2, our closed network is characterized by pick-up locations, delivery locations, battery charging and time-window restrictions. AGVs transport goods (anodes) between these locations and execute other transport movements as well, such as heading towards a battery recharging/replacement location. To model this environment, where several actors (i.e., entities) are interacting with other actors and the environment, we decided to use a multi-agent system (MAS). MAS can be defined as a group of intelligent and autonomous computational entities (agents) which coordinate their capacities and plans in order to achieve certain (local or global) goals (Wooldridge, 1999). The motivation for using this MAS technology is given in Chapter 3.

1.3.3 Research Contribution

In light of the previous sections and the literature studies conducted in Chapter 3, the main contributions of this study can be summarized as follows. In this study, we design and develop a multi-agent system for the control of anode transporting AGVs in the primary aluminium industry. Compared to existing AGV systems that incorporate agent-based technologies, our research does not solely focuses on the transportation of goods, but comprehends the application to a wide scope of realistic large-scale scenarios that are applicable to the primary aluminium industry. Little is known in literature about AGV implementations within flexible manufacturing systems that use MAS design. To the best of our knowledge, this particular application within the primary aluminium industry has not been studied before. Additionally, we contribute to the scarcity in literature by comparing the performance of our agent-based control method to more traditional control methods. In Chapter 3, we discuss the novelty of this research in more detail.

1.3.4 Research Questions

To reach our objective, we have composed a succession of research questions which we have to answer. The main research question, as formulated below, is a guiding theme of this research and can be answered through answering the sub-research questions. These research questions define a logical sequence of activities, which covers the entire scope of this project. The research questions are divided into five main parts of this research: (i) context analysis, (ii) literature review, (iii) model design, (iv) model validation, and (v) implementation plan. For each question, we provide a brief description including the planned approach for answering them. Also, we indicate the chapter in which the specific question will be answered. Our main research question is formulated as follows:

Main Research Question: *How should a generic operational planning and control model, based on agent technology, be designed such that it provides an efficient AGV implementation of anode transportation, within the smelting process of primary aluminium production?*

1.3.4.1 (i) Context Analysis

To get more insight into the aluminium manufacturing process, and in particular the aluminium smelting process and the involved logistics aspects, a thorough analysis of the aluminium smelting process and the current (often human-based) control system is needed. We familiarize ourselves with the functioning of the existing logistic processes and the existing planning strategy. Consequently, the functioning of the AGV network grid and the traffic management is examined. Essential is to design the newly developed system as generic as possible to cover a representative client population. For that reason, we designate several typical factory layouts that are representative of the population we consider in this study.

Our approach mainly consists of examining documents from Hencon, Fraunhofer Institute for Material Flow and Logistics, and a selection of clients from Hencon. Besides that, we conduct literature studies and interviews to obtain additional information and to ensure the validity of our documentation.

Research Question 1: *How are the internal logistic anode transport processes, material flows and information flows currently organized?*

(a) *How are the aluminium smelting process and corresponding material flows organized?*

(b) *What are common characteristics of the factory layouts?*

(c) *Which kinds of transport jobs are applicable for the AGVs?*

(d) *What are typical factory layouts that should be considered?*

1.3.4.2 (ii) Literature Review

The literature review includes the development of a theoretical framework for this research. After the current situation is known, we need to get familiar with existing models, to come up with a new logistic process that facilitates the transport of anodes. For that reason, we conduct a literature study by which we explore current approaches used in manufacturing environments, for (1) AGV control, (2) MAS and (3) dynamic scheduling. The dynamic scheduling study is required to explore solution approaches that can be integrated with the AGV control and MAS model. In addition, we conduct a concise literature study of closely-related operations research (OR) applications in the primary aluminium industry or comparable flexible manufacturing systems (such as the steel industry). This study is of importance because it reveals previously conducted studies in the primary aluminium industry, recent solution approaches in comparable industries, and possible extensions to the model in a further stage.

In this literature study, we primarily consult peer-reviewed scientific articles (e.g., journal papers and conference proceedings). However, the literature population is not limited to scientific papers only, since we do not exclude important work (e.g., books, dissertations, newspaper articles, etc.) that, for instance, can be found through backward search. Essential is that we provide a sound methodology that functions as a basis for our model design.

Although the research questions proceed sequentially, they interact with and build upon each other. We, therefore, start with studying AGV control systems. Next, dynamic scheduling approaches in manufacturing environments are examined. After this, we explore MAS design methodologies and choose an appropriate design methodology. The last research question explores OR applications in the primary aluminium industry and similar industries.

Research Question 2: *What is currently known in literature about AGV systems in manufacturing environments?*

(a) *What conventional AGV systems are used in similar industries?*

(b) *What are suitable practices for our AGV system?*

Research Question 3: *What is currently known in literature about dynamic scheduling approaches in manufacturing environments?*

(a) *What are conventional dynamic scheduling approaches for manufacturing environments?*

(b) *Which operational planning and control strategies of pickup and delivery problems with time windows are described in literature?*

(c) *Which operational planning and control strategies for pickup and delivery problems with time windows are suitable for the model design of anode transportation?*

Research Question 4: *Which multi-agent system design methodology should be used?*

Research Question 5: *What is currently known in literature about OR applications in the primary aluminium industry and closely-related industries?*

1.3.4.3 (iii) Model Design

After we have studied literature about AGV systems, dynamic scheduling techniques, and MAS methodologies, we need to design three models. The first model is the MAS, which supports the AGV system and functions as a planning and control system. The methodology following from the fourth research question will be used for the MAS design. The second model is the AGV system which is designed by following the approach resulting from the second research question. In the third model, the MAS and AGV system are integrated into an evaluation model that can be used to substantiate decisions regarding an AGV implementation of anode transportation, within the primary aluminium industry.

Additionally, we study supplementary literature and in particularly related case studies. Furthermore, we closely collaborate with the supervisors of this thesis to learn from their experience. The research question is answered by conducting a literature study and interviews with experienced Hencon specialists. Our priority is to ensure that we design a valid and robust model with preferably real-life data from customers of Hencon.

Research Question 6: *How should the multi-agent system be designed to support anode transportation with AGVs in the primary aluminium industry?*

Research Question 7: *How should the automated guided vehicle system be designed to support anode transportation with AGVs in the primary aluminium industry?*

After the MAS and AGV system are designed, the evaluation model should be built. This model must be generically built and able to evaluate the performance of the MAS model under various scenarios (as defined earlier). To this end, we decide to use a simulation model. Simulation is an often used tool for modeling and analysis of operations in industry. Its benefits rely on the presence of a computer model that allows for representing existing or would be operations over time in a realistic manner. Simulation can be used to systematically evaluate changes in settings for a wide spectrum of scenarios. More specifically, we use discrete-event simulation. Basically, in this type of simulation, a system is codified as an ordered sequence of changes in the system's state. Further motivation for this type of simulation is given in the corresponding section of this research question.

Before implementing the simulation model into simulation software, a conceptual model is built. The conceptual model acts as a blueprint for the actual model and contains a non-software specific description of the simulation model. The conceptual model describes the objectives, inputs (experimental factors), outputs (responses), content, assumptions, and simplifications (Robinson, 2008a). To this end, definition of appropriate performance indicators is required. After the conceptual model is described, the model is verified and validated. Model verification is the process of ensuring that the conceptual model has been implemented with sufficient accuracy (Robinson, 1997). Model validation concerns representing the reality in an accurate manner. Verification and validation are essential in model building as these enhance the confidence in a model for the results to be accepted.

Research Question 8: *How should the evaluation model of an AGV implementation with corresponding MAS control strategy under various primary aluminium manufacturing facility scenarios be designed?*

1.3.4.4 (iv) Model Validation

Model validation comprises the process of determining whether a simulation model is accurately representing the system, for the particular objectives of the study (Law, 2015). As part of model validation, we use the developed model from the previous research question to simulate and evaluate the overall performance of a primary aluminium production facility that closely mimics a real-world case. To this end, we analyze the model and discuss the results with employees of Hencon to establish creditability among the users.

Research Question 9: *How can we verify and validate the implemented simulation model, and assess the quality of the implementation?*

1.3.4.5 (v) Implementation Plan

The operating model we develop is part of the HTC system and should be implemented together with the openTCS software of Fraunhofer. We define extensions to be made. Additional software and programming work required to link the systems together will be included in this plan as well. Notice that the actual implementation is not part of this thesis.

Research Question 10: *How can the proposed agent-based AGV system be implemented?*

(a) *How can the HTC system be designed?*
(b) *Which extensions can be made to the system?*

1.4 Structure of the Report

The remainder of this report is organized such that each of the subsequent eight chapters answers associated research questions that are part of one of the six main parts of this thesis: (i) context analysis, (ii) literature review, (iii) model design, (iv) scenario evaluation, and (v) implementation plan. The model design part is separated in three chapters: MAS design, AGV System design, and Scenario Evaluation model. We finalize our report with conclusions, recommendations and suggestions for further research in Chapter 9. Figure 1.6 on the next page, gives a schematic representation of the structure of this thesis.

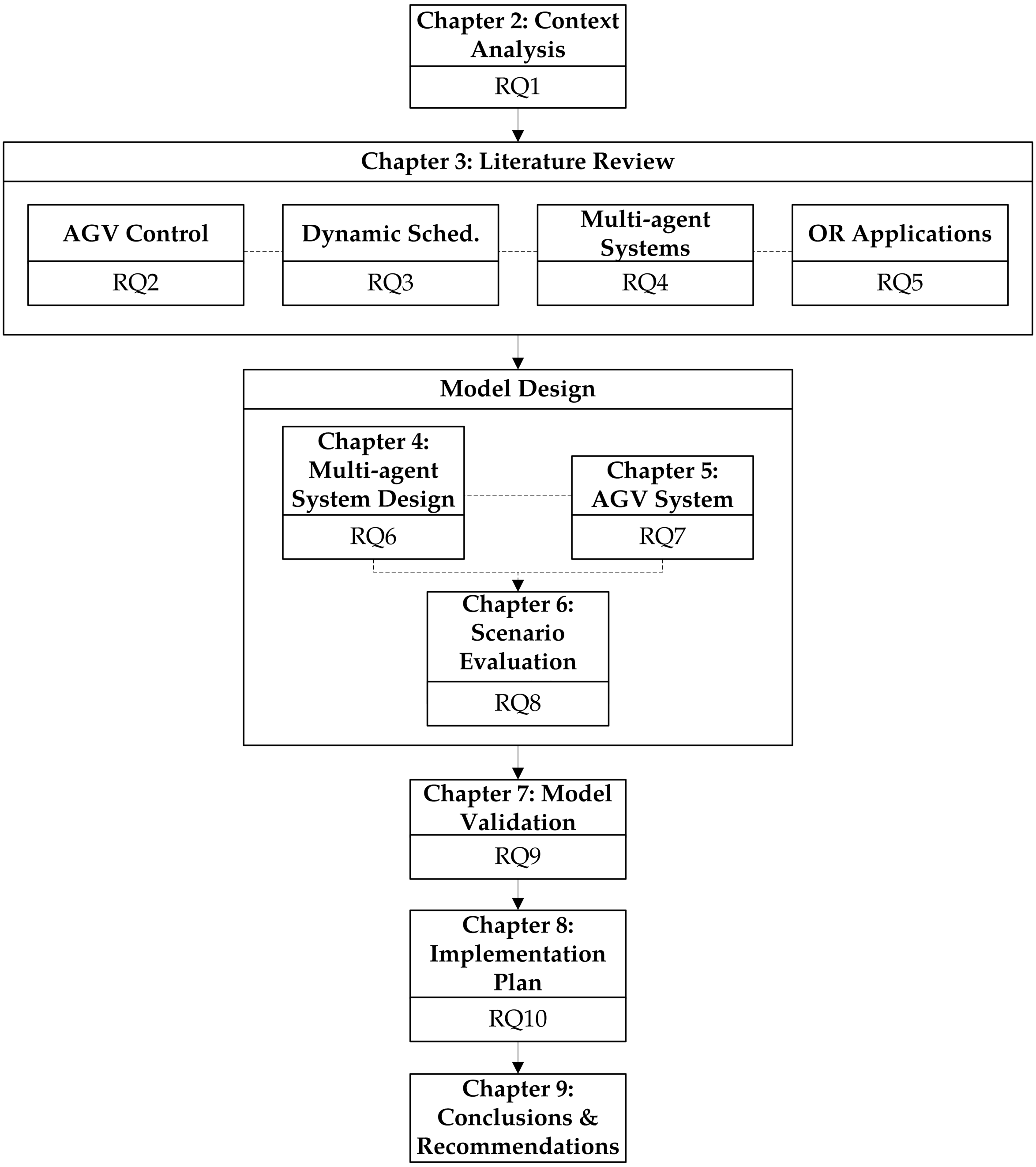


FIGURE 1.6: Thesis structure.

Chapter 2

Context Analysis

This chapter provides a context analysis of the current situation of (prospective) clients, active in the primary aluminium industry, of Hencon. Section 2.1 covers a general description of the primary aluminium processes. Section 2.2 outlines common factory layout characteristics. Section 2.3 continues with discussing the internal logistics processes and material flows of anode transportation. After that, Section 2.4 presents some typical factory layouts that should be incorporated in the model proposed in this thesis. Finally, Section 2.5 concludes this chapter.

Since the manufacturing process of aluminum can be carried out differently by different manufacturers, we base the content of this section primarily on discussions with employees from Hencon, internal documentation, and the handbooks of aluminum from Totten and MacKenzie (2003a, 2003b) and Schmitz (2006). Recall that the focus of this thesis is on aluminium production facilities that make use of pre-baked anodes.

2.1 Aluminium Production Processes

This section starts with a short recap of the aluminum manufacturing process. As discussed in the previous chapter, the manufacturing process of aluminum involves a variety of processes (see Figure 1.2): (1) mining bauxite ore, (2) refining the ore to alumina, (3) aluminium smelting, (4) fabricating of aluminium or alloy products, and (5) recycling aluminium. These steps are described in the subsections below. In addition, we refer to a simplified diagram as shown in Figure 2.1, to illustrate the processes and material flows of a typical aluminium plant using pre-baked anodes.

2.1.1 Mining Bauxite Ore

The first link in the chain is the mining of bauxite ore. Bauxite is formed over millions of years by chemical weathering of rocks, producing an ore rich in aluminium oxide. Bauxite is mined primarily in Africa, Australia and the Caribbean (American Chemical Society National Historic Chemical Landmarks, 1997). The bauxite is transported to crushing or washing plants to remove the overburden of several meters of rock and clay (Hydro, 2013a). After that, the bauxite is transported to a refinery for processing.

2.1.2 Alumina Refining

Aluminium oxide (alumina) is extracted from bauxite in a refinery. Bauxite contains a number of impurities and if these are not removed during refining, they will alloy with and contaminate the metal during the smelting process. Alumina is dissolved in an electrolyte that consists of molten fluoride salts kept at about $950 - 970°\mathrm{C}$ (Totten and MacKenzie, 2003b).

The Bayer process, with various modifications, is the most commonly used method for alumina refining and it involves four steps: digestion, clarification, precipitation, and calcination (Totten and MacKenzie, 2003b; Schmitz, 2006). In the first step, the ore is first ground and mixed with a hot solution of lime and caustic soda. The mixture is then pumped into high-pressure containers and heated. Next, a separation process that dissolves the aluminium oxide by a caustic soda, results in a clarified dissolved alumina. This alumina is pumped into precipitators and aluminium crystals are added to hasten the process of crystal separation. The crystals attract other crystals and form agglomerates. The agglomerates of aluminium hydroxide crystals are filtered, washed and calcined in rotary kilns or stationary fluidized-bed flash calciners at high temperatures. A dry and fine white powder of pure alumina is the result.

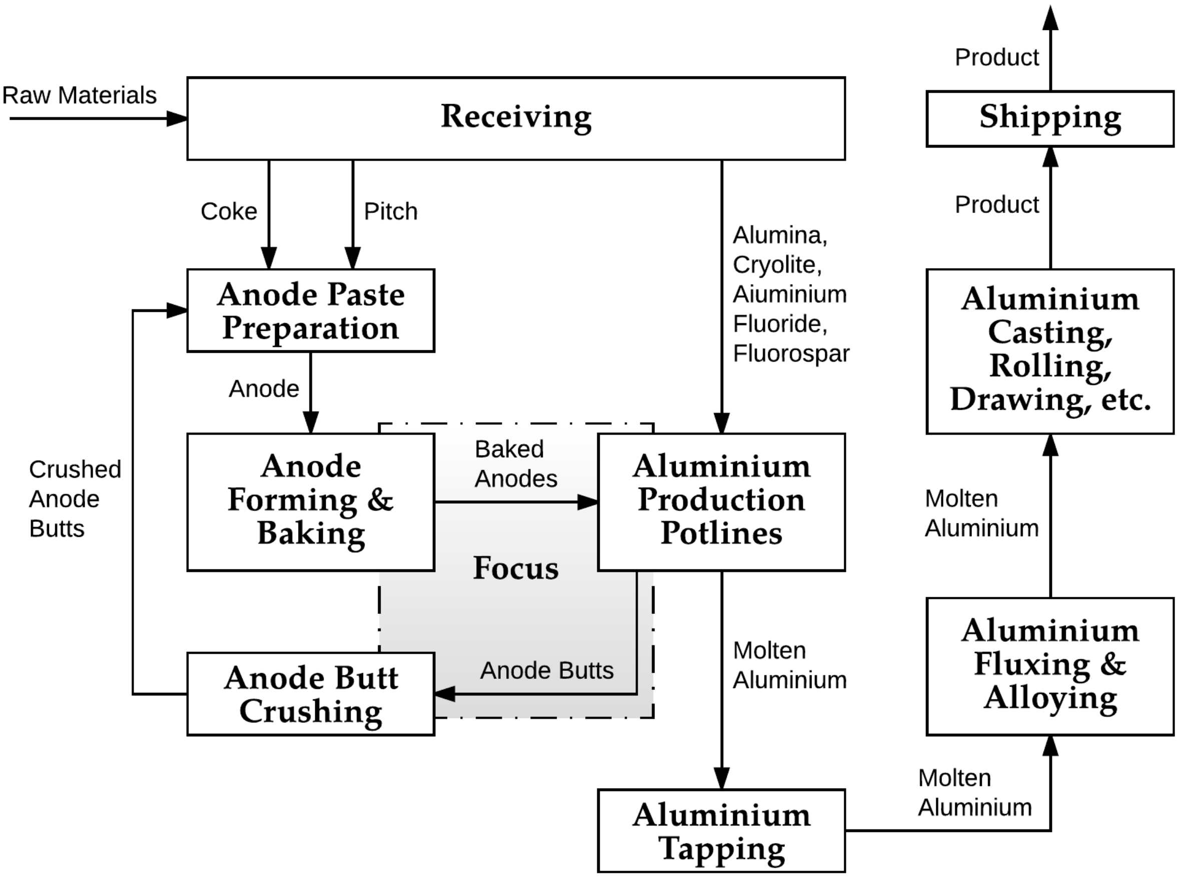


FIGURE 2.1: Simplified process flow of an aluminium production plant using pre-baked Anodes. Adapted from United States Environmental Protection Agency (1996).

Alumina refineries are mostly located close to the bauxite mine, or at the nearest harbor, where the alumina can be easily shipped to aluminium production plants. Raw materials (e.g., alumina, coke, and pitch) are delivered to the plant and stored. The process flow depicted in Figure 2.1 starts with this activity.

2.1.3 Aluminium Smelting

The smelting process transforms refined alumina into aluminium. In a modern smelter, alumina is dissolved in electrolytic-cells (also known as pots) - rectangular steel shells lined with carbon - that are filled with a mixture of sodium, aluminium, and cryolite fluorine. An aluminium smelter usually consists of hundreds of electrolytic-cells.

The Hall-Héroult smelting process is the most widely used approach for smelting alumina to produce aluminium (Hydro, 2012). For that reason, we focus on smelters that use this technology. The basic idea of the Hall-Héroult process is simple as we illustrate in Figure 2.2. The process requires anodes and cathodes, which are mostly made of carbon. The container accommodating the bath (molten solution of cryolite and alumina) is shaped as the cathode while the anode block is lowered into the bath from above (Schmitz, 2006). A direct current is passed through the bath and as the aluminium ion discharge their electrical load at the cathode, the liquid metal collects at the bottom of the electrolytic-cell.

As the smelting process is continuous, additional materials need to be added to the pot periodically. Alumina is added to the pot at frequent intervals by point feeders to keep the alumina content at a constant level while metal is separated (Schmitz, 2006). The feeders are equipped with an impact hammer required to break the crust that forms on the surface of the bath before alumina is charged. Also, a small amount of cryolite is consumed and need to be added from time to time. Furthermore, the anodes, which may vary in size, are dissolved during the process and therefore require replacement as well. The higher the amperes, the greater the anode consumption (Nicholls, 1995a). Hence,

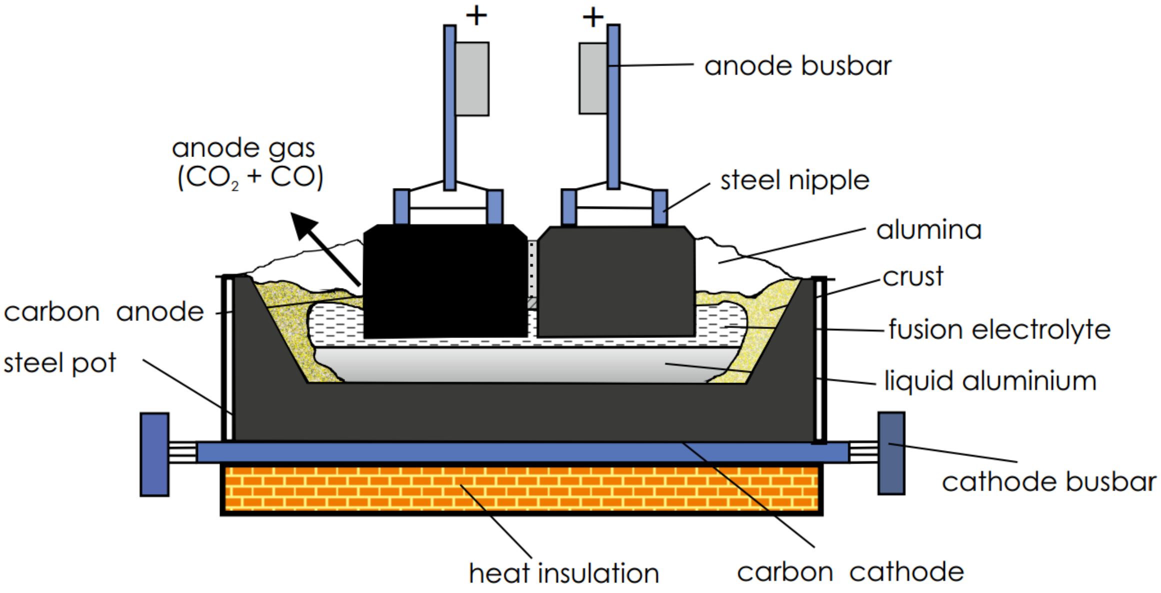


FIGURE 2.2: Principles of a modern electrolytic-cell for electrolysis of aluminium oxide (Schmitz, 2006).

the production of aluminium is directly proportional to the amperes passing through the electrolytic-cells. The anodes remain in the pots for a predetermined period (in general about 28 days) depending on, among other considerations, the amperes. The elapsed time from when anodes are placed into the pot until they are withdrawn is denoted as the *setting cycle* (Nicholls, 1995a), which is measured in days. Consumed anodes are replaced by new anodes. This is done by the pot tending crane equipped with the tools for changing the anodes. Similar as during the alumina feeding process, a crust breaking hammer is required to open the crust around the old anodes. The anodes are supported by the anode beam that can move vertically to maintain the proper (inter-polar) distance between the liquid aluminium and the anode (Schmitz, 2006). As the anode burns off or the metal level rises due to metal separation or lowers when metal is tapped, the anode beam reaches from time to time its lowest position and need to be raised to the top again. Figure 2.3a illustrates the beam raising process. A pre-baked carbon anode block is fixed to an aluminium rod (see Figure 2.3b) for feeding the electric power (Schmitz, 2006). The rod is connected to the anode beam by special clamps and screws. Typically, the set of anodes in a cell is arranged such that only one anode must be repositioned daily.

During the electrolytic process, the anode burns down to a residue providing just enough carbon to cover pins and cast iron nipple (Schmitz, 2006). There should always be a minimum percentage of the anode left on the bar from which it is suspended because otherwise the aluminium bath can be contaminated with metal from the bar. The used anode, the so-called butt (e.g., see Figure 1.5a and Figure 2.3b), can be used in the construction of new anodes. As we discuss later, recycling and construction of new anodes are done in a separate area in the production facility (the rodding shop).

The group of customers from Hencon we consider, transport the anodes on pallets. The placements of anode pallets are commonly carried out by human-driven anode pallet transport vehicles (e.g., see Figure 1.4), while we aim to provide a solution with AGVs. Cathodes are consumed slowly and need to be replenished only on a long-term basis and are therefore left out of scope in this study.

The aluminium smelting process proceeds by periodically siphoning liquid aluminium from the pots into large crucibles by means of a vacuum vessel. The liquid substance is poured into a crucible (e.g., see Figure 2.4) and transported to the casthouse where it is further processed. Typically, an overhead crane first transports the crucible to the main road from whereon it is further transported by means of crucible transport vehicles (e.g., see Figure 1.1d). The activities from siphoning off the molten aluminium until placing the filled crucible in the main road are comprised in the so-called tapping process.

Operational tasks carried out in the potrooms are depicted in Appendix B. Table B.1 displays different and shared vehicles, machinery, additional equipment and materials that are necessary for each potroom task. Notice that some activities can be performed by multiple types of vehicles or machines,

(A) Beam raising. The anode need to be repositioned on a daily basis in the electrolytic-cell. After the rod is disconnected, the anode is realigned in the cell.

(B) Anodes including their rods. The two anodes on the left are fresh anodes and the one on the right is an used (still scorching) anode.

FIGURE 2.3: Anodes positioned in or nearby electrolytic-cells.

and likewise, aluminium production facilities are not limited to using these vehicles and machines only. In this study, we focus on the logistics of the anode and butt transport (second task as shown in the table). Other activities, such as crane movements, cleaning activities, and crucible transporting, may interfere with the anode AGVs. In the next sections, we elaborate upon the relevance of these activities in more detail.

2.1.4 Fabrication of Aluminium

After the aluminium is tapped and poured into a crucible it is transported to the casthouse. If necessary, alloying components are added after which the metal passes through a metal treatment system (Schmitz, 2006). The metal treatment system removes impurities such as hydrogen, metallic contaminations, and mechanical contaminations. The fluxed aluminium is then cast into shapes as specified to specific wishes of customers. Depending on the desired product mix, further fabrication may include forging, casting, rolling, drawing or extruding to create different finished products. After a cooling period, the aluminium products are transferred to storage or prepared for shipment.

2.1.5 Recycling Aluminium

Aluminium products can be returned to recycling facilities to be melted down and fabricated into new aluminium products. Aluminium can be endlessly recycled without losing its quality. Only roughly 5% of the energy required to produce primary aluminium is needed to remelt aluminium (Staley, Bridenbaugh, and Horn, 2008; Hydro, 2013c). In general, the casthouse equipment used in primary smelters and secondary smelters (i.e., recycling aluminium) are quite similar (Schmitz, 2006). In this thesis, we focus on primary aluminium smelters. Plants that produce recycled aluminium or a combination of primary and secondary aluminium, could also be considered since the anode transport interfere limitedly with the processes executed in the casthouse. For more information about secondary smelters, we refer to the book of Schmitz (2006).

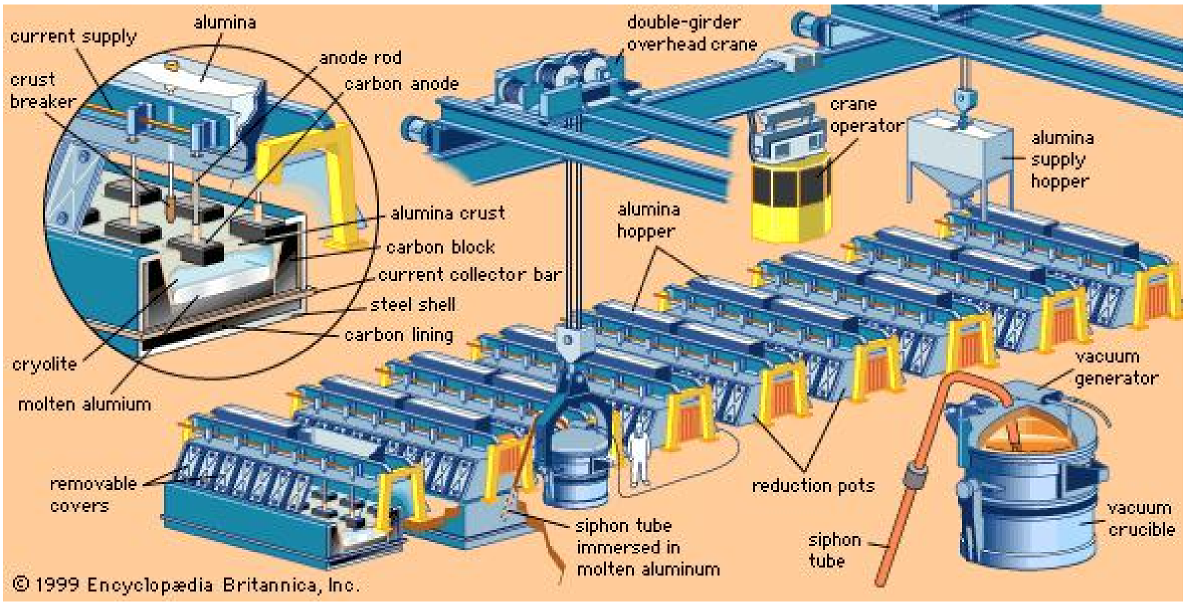


FIGURE 2.4: Part of a modern aluminium production potline (Staley, Bridenbaugh, and Horn, 2008).

2.2 Common Factory Characteristics

The production of primary aluminium takes place in large production lines containing hundreds of electrolytic-cells and a number of different areas common in aluminium smelters. Subsection 2.2.1 commences with describing each area in an aluminium production plant illustrated with a simple factory layout. After that, Subsection 2.2.2 describes involved vehicles, cranes and other moveable objects. Afterward, Subsection 2.2.3 outlines the shift-based scheduling approach.

2.2.1 Areas

The smelter includes the following areas: potrooms, carbon plant, casthouse, anode cooling area and additional anode storage areas, parking and battery charging area, and other areas. Each of these areas is concisely discussed below. Figure 2.5 gives an illustration of a simplified example of a factory layout.

2.2.1.1 Potrooms

The plant layout of a primary aluminium smelter is characterized by the typical extended parallel buildings, accommodating the electrolytic-cells (Schmitz, 2006). These electrolytic-cells are also named pots, reduction cells or cells. A cell comprises rectangular steel shells lined with carbon that are filled with a mixture of sodium, aluminium, and cryolite fluorine.

The cells may be lined up end-to-end (e.g., see Figure 2.6a) or side-by-side (e.g., see Figure 2.6b) in one or more parallel lines down the center of the potroom. In this study, we primarily focus on cells lining up according to an end-to-end position. Each cell is reachable from two opposite sides (see Figure 2.7) and contains a fixed number of anode places on each side (usually between 14 and 32 in total). A smelter roughly contains around 300 to 700 pots covering a total length of approximately 1 kilometer.

A different number of anodes may be used per cell. Likewise, the length of each cell might be different. An electric current is passed through the suspended anodes and cathodes in the pots. Cells are electrically connected in series (i.e., the cathode of a cell is connected to the anode of the next cell downstream). A series of connected cells is called a potline. Figure 2.8 illustrates an example of a plant in Iceland, with one potline whereby a clear physical separation can be observed from the first part of the series and the second part. As the cells are lined up in series, a connection between two cells caused by for instance a vehicle or a human, can lead to a short circuit (or even worse accidents). During the facility design phase, the consequences of cell alignments should be taken into account.

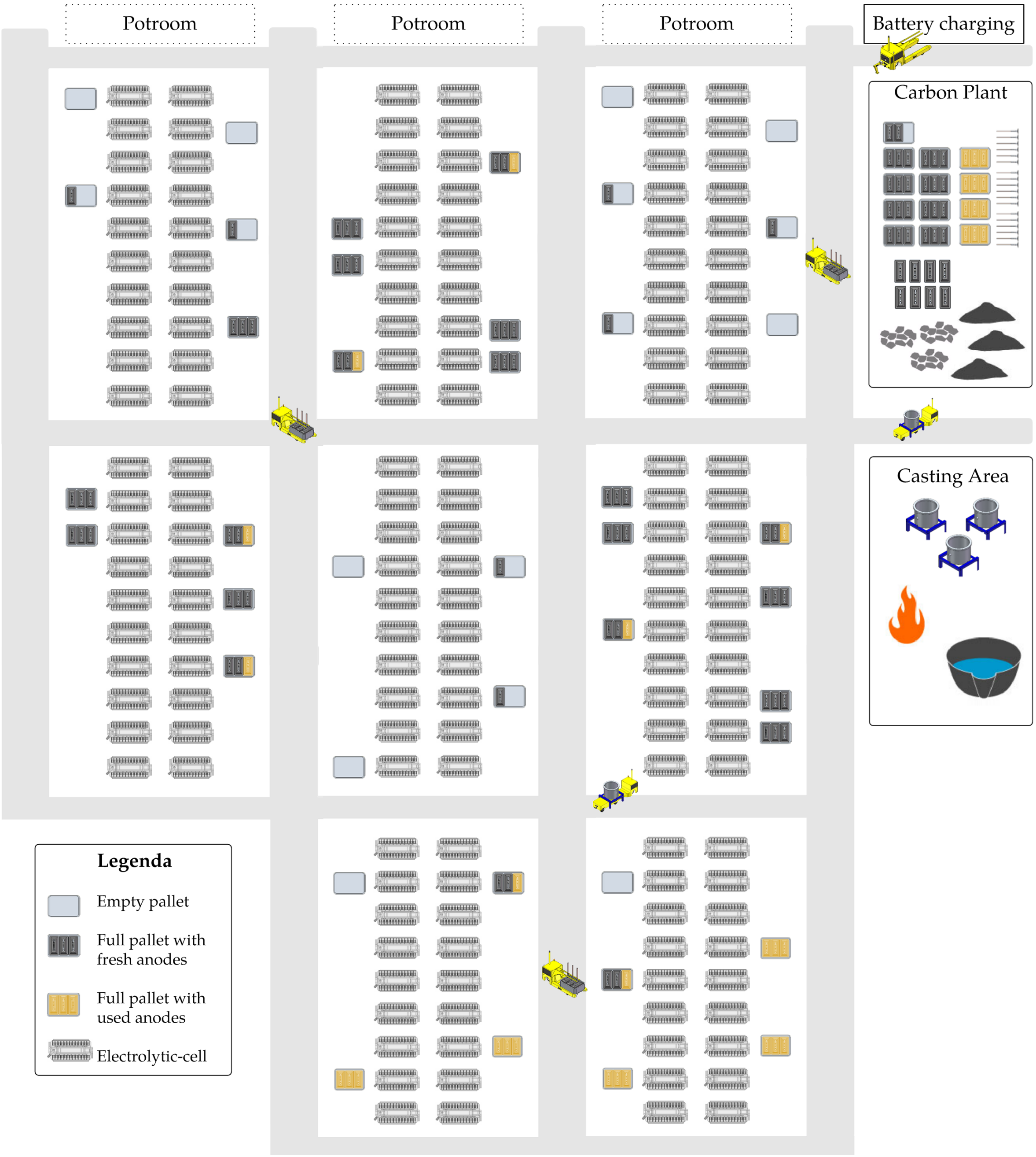
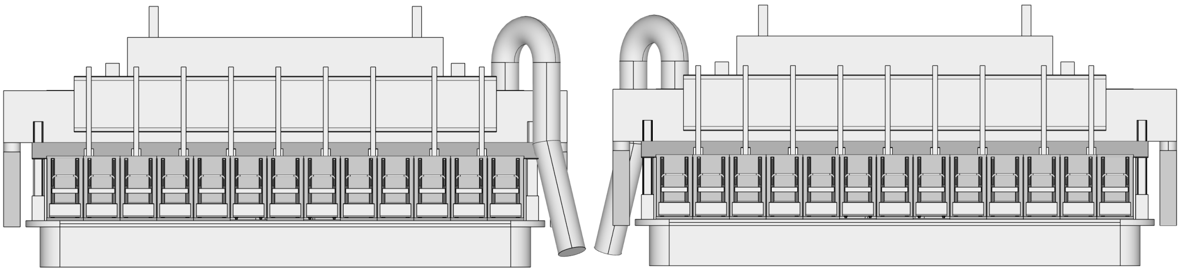


FIGURE 2.5: Simplified example of a side-by-side facility layout

(A) Cells lined up in an end-to-end position (Innovasjon Norge, 2012).

(B) Cells lined up in a side-by-side position (Qatalum, 2013).

FIGURE 2.6: Different potroom line ups.



(A) Front view of an electrolytic-cell.

(B) Rear view of an electrolytic-cell.

FIGURE 2.7: Electrolytic-cell views.

Roughly, every five years a major overhaul of a pot takes place. During this process, the pot will be emptied and cleaned. Usually, the pot is completely removed from the potroom and revised elsewhere.

2.2.1.2 Carbon Anode Plant

The carbon anode plant comprises the sections green carbon plant, baking furnace, and anode rodding shop. The carbon anode plant occupies a large area in the primary aluminium smelter and basically handles the manufacturing of anode blocks that go into the electrolytic-cells. Materials, such as calcined petroleum coke and pitch, are passed through various production steps before they are finally baked to form the anode block (Schmitz, 2006).

In the green carbon plant, the so-called green anodes are manufactured. Petrol coke is crushed and ground into the required grain size distribution first (Schmitz, 2006). Used anodes are recycled by crushing and then making up a coarse fraction. All fractions are mixed and liquid coal tar pitch is added as a binder. During the forming, the paste is shaped and compacted to the required size and density, after which the green anodes are obtained.

The green anodes are sent to the baking furnace where they are calcined at a high temperature. Typically, one or more baking furnaces are accommodated in a long building (Schmitz, 2006). The baking process consists of a pre-heating, heating, and cooling process. After the cooling period has elapsed, the block is transported to the rodding shop.

In the rodding area, a metal rod is applied to the baked anode. The rod allows both the anode to be suspended in the pot and the power may flow through it (Schmitz, 2006). Butts arrive in the rodding shop after which the rods are stripped of the anode block. The metal rod is prepared for re-use and the used anode is returned to the green carbon area for preprocessing. Usually, the whole carbon anode plant is capable to process all anodes required for the pot lines. In large smelters, this could be more then a thousand per day.

The carbon anode plant is driven by the anode setting cycle (Nicholls, 1995a). A longer setting cycle requires fewer anodes and therefore fewer raw materials and less cost. However, note that the

FIGURE 2.8: Alcoa Fjarðaál, Iceland (Google Maps, 2017).

setting cycle must not be so long as to leave less than the minimum required carbon proportion on the anodes in the pots. As the power supplied (measured in kilo Amperes, kA) affect the production of aluminium, the setting cycle is consequently dependent on the kilo Amperes. Nicholls (1995a) already addressed this variable dependency and declared that the rodding and anode areas are driven by the same "leading" variable kA and that the "follower" variable setting cycle should be decided on by the rodding and anode areas.

The setting cycle depends on, for example, the kilo Amperes used and the anode size. As we do not deliberate upon the power usage in the production plant, the setting cycle is then a variable dependent on the anode size. As addressed before, typically the setting cycle is around 28 days. That means, after a fresh anode is being placed in an electrolytic-cell, the anode need to be replenished within 28 days.

2.2.1.3 Casthouse

The resultant aluminium of the electrolysis process is transported from the potrooms to the casting area in crucibles. From thereon, alloys could be added, aluminium could be poured into holding furnaces prior to casting, or the aluminium could be directly cast into ingots. Figure 2.9 sketches a typical casthouse in a primary aluminium smelter. We refer to the book of Schmitz (2006) for a detailed functional description of the casthouse.

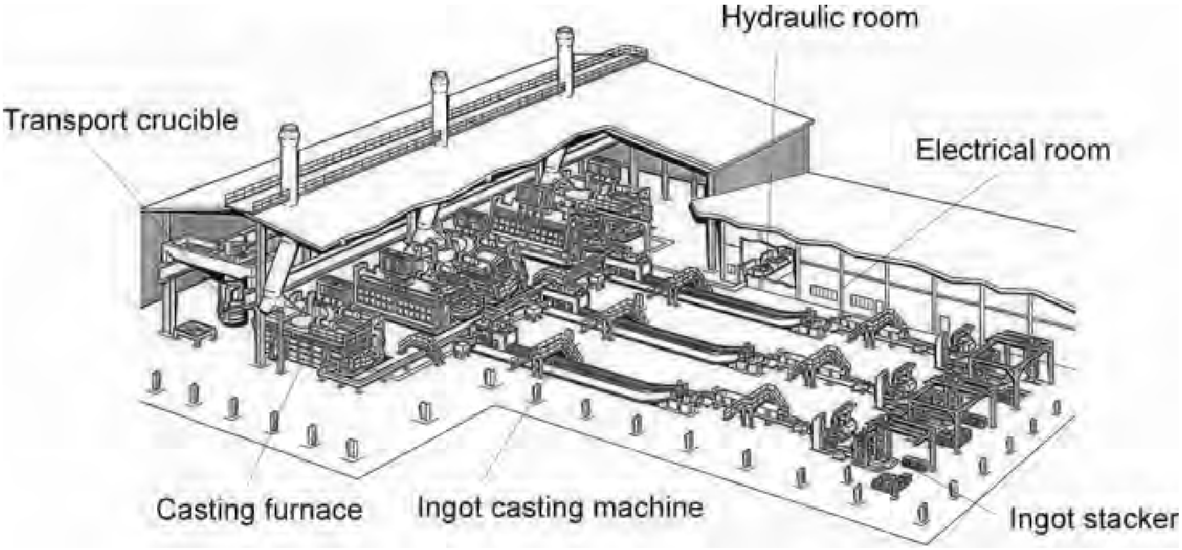


FIGURE 2.9: Principles of a casthouse for a primary aluminium smelter (Schmitz, 2006).

2.2.1.4 Anode Cooling Areas and Additional Anode Storage Areas

A cooling area is a physical location in the potroom in front of or nearby an electrolytic-cell where palettes containing fresh and/or used anodes are stored. The cooling area could be used for both the storage of new anode trays and used anode trays. Anode palette locations should be assigned to places where they are not blocking the workflow of cranes (either required for tapping operations or anode changing activities) or vehicles that need to execute tasks at a cell. In addition, the trays should not be placed too far from the cell where the anode change takes place because the cranes can either not reach them or crane movement operations may cause a delay in the changing process. Furthermore, the orientation of the anode palettes is of importance as we discuss in the next subsection. As the length of potlines can be long, it might be convenient to assign multiple areas as anode storage area.

2.2.1.5 Parking and Electricity Places

Parking places are dedicated to AGVs. Vehicles idling in pathways can block other important activities because of the relative small corridor width and, for that reason, it is often not allowed to let vehicles stand still in important passages. Consequently, an idling AGV is either dedicated to a specific parking place or continuously driving until the next job assignment.

Parking places are commonly combined with electricity charging stations. AGVs can recharge their batteries at these locations. Typically, multiple parking locations in the smelter are equipped with charging stations.

2.2.1.6 Other Areas

Besides the production facilities and dedicated areas as described previously, there are a number of other areas that could be identified in primary aluminium smelters. For instance, storage areas for alumina, petrol coke, green and bakes anodes, baking furnace, and rodding shop (Schmitz, 2006). Also, the aluminium produced and the final products are stored in dedicated areas. Another process going on in potrooms is the filling of buckets with bath materials. After a certain amount of anode changes, this bucket is full and need to be brought to a bath cooling conveyor where it is emptied. A maintenance and administrative department complete the plant.

2.2.2 Vehicles, Cranes and Other Moveable Objects

This subsection specifies commonly used vehicles, cranes, and other moveable objects in more detail. This subsection first addresses vehicles involved in the aluminum smelter. Next, crane operations are discussed. Then, other moveable objects that play a role in the logistics are outlined. As shown in Table B.1, some tasks can be performed by multiple operating entities. We focus on elucidating objects that are of importance for the transportation of anodes.

2.2.2.1 Vehicles

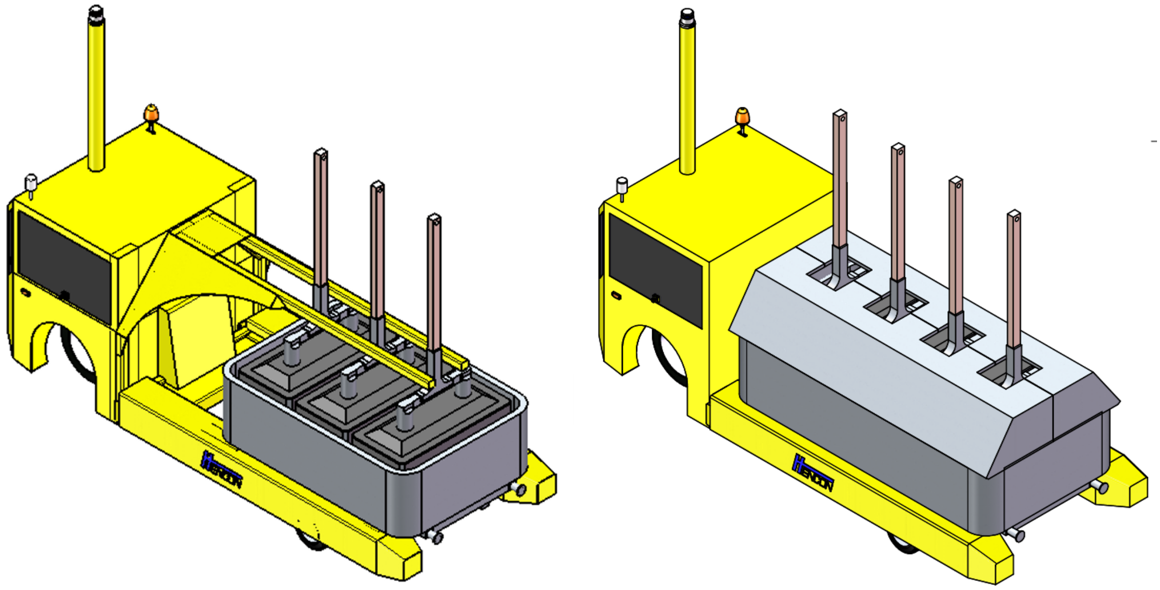
A number of vehicles and related substitutes can be identified in an aluminium smelter. Besides pedestrians and personnel vehicles, vehicle movements involved in an aluminium potroom include, for example:

- anode pallet transporters (e.g., see Figure 1.4);
- crucible transporters (e.g., see Figure 1.1d);
- forklifts;
- vacuum cleaners;
- cavity cleaners (e.g., see Figure 1.1c);
- bath tapping vehicles;
- anode changing vehicles (e.g., see Figure 1.1b).

Some vehicle may interfere with the anode pallet transporter. For example, pedestrians, personnel vehicles, vacuum cleaners, cavity cleaners, forklifts, bath tapping vehicles, crucible transporters, and anode changing vehicles can interfere with activities of the considered AGV. However, in general, these vehicles can maneuver freely and without blocking paths required for other activities, due to the way the shift-based working routine is arranged (see Subsection 2.2.3).

Furthermore, due to the availability of highly magnetic fields, areas or pathways may be blocked for vehicle movements. Some positions in a potroom facility are infested by this phenomena and consequently limited or no vehicle movement is possible. In this thesis, we consider the vehicles discussed below in detail.

Automated Guided Anode Pallet Transport vehicle (AGAPTV)
The Automated Guided Anode Pallet Transport Vehicle (AGAPTV) (see Figure 2.10) is responsible for transporting anode pallets. Anode pallets may be empty or contain a certain amount of either new or used anodes. Pallets with new anodes are transported from the rodding shop to nearby the cell. Empty pallets or pallets with burned anodes are transported from nearby the cell to the rodding shop. The pickup of pallets should be done by executing a special backward driving maneuver because physical vehicle properties prohibit the AGAPTV to pick-up pallets by forwards driving. More details about this maneuver and the tasks carried out by the AGAPTV is given in Subsection 2.3.


(A) AGAPTV with an open bucket.

(B) AGAPTV with a closed bucket.

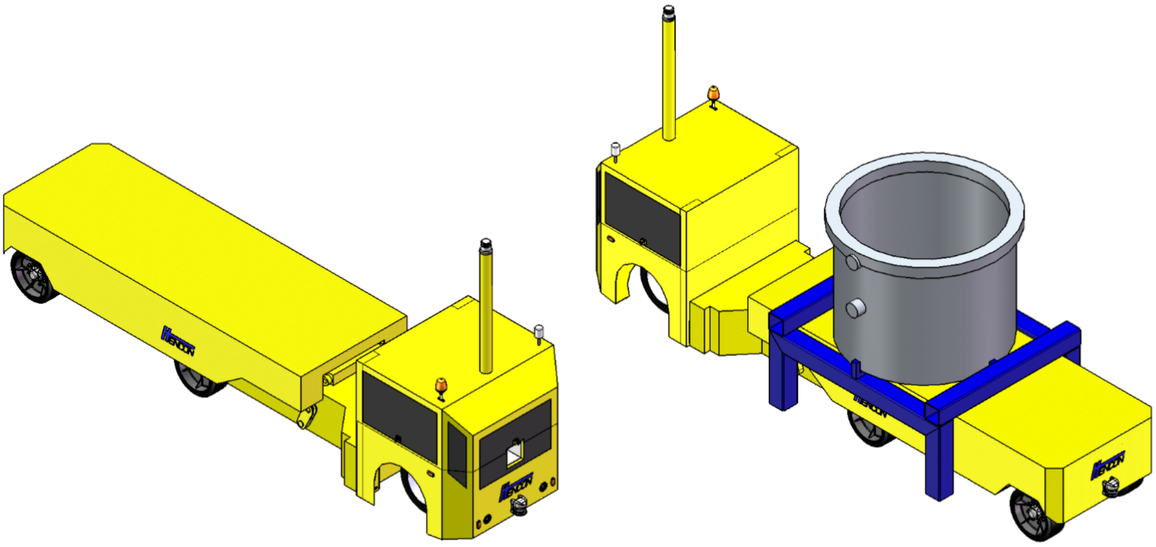
FIGURE 2.10: Automated guided anode pallet transport vehicle

The AGAPTV can drive both forward and backward at the same speed. Although the vehicle's speed can be much faster, it is considered as safe to let the AGAPTV drive at most the regular walking speed of pedestrians ($4.5 km/h$). To avoid possible collisions and to maneuver freely it is recommended to keep AGAPTVs at least a certain number of meters (usually 10 meters) away from other vehicles. Furthermore, the AGAPTV is an electric vehicle and therefore needs regular charging. Charging details and other vehicle properties are summarized in the overview in Appendix C.

Ladle Transport Vehicle (LTV)
The Ladle Transport Vehicle (LTV) (see Figure 2.11) is designed for the transport of pallets with filled or empty crucibles. A variant of the LTV is the LTV with the ability to tilt the crucible for operations carried out in the casthouse (e.g., see Figure 1.1d).

The LTV occupies quite some space to move and to conduct its driving maneuvers safely. It is important that the LTV can proceed its job without too much delay because a delayed arrival in the casthouse can affect continuity and efficiency of both the potroom and the casthouse. However, in general, the LTV can execute its tasks without much interruption. That is because the LTV mostly drives on main roads (so-called metal roads) in which other vehicles can pass the vehicle without too much interruption. Also, the LTV would only active in a limited number of sections at the same time because of the shift-based working routine (see Subsection 2.2.3). Furthermore, as LTV's drop-off and pick-up crucibles in main roads and cross aisles, they do limitedly interfere with the traffic in the cell segments. In addition, there are some other technological challenges to overcome before they are sufficiently mature for driving autonomous.

Although crucible transporters provide an interesting direction for automation by means of AGVs, there is no urgent reason to incorporate the logistics of this vehicle in detail. The exclusion of crucible transporters could subvert the validity of the model because these vehicles may cause deadlocks that



(A) LTV without crucible.

(B) LTV with crucible palette.

FIGURE 2.11: Ladle transport vehicle.

could have a significant impact on AGAPTV (and smelter) performance. However, the (explicit) involvement of crucible transporters would make the goal of an operational planning and control tool for the AGAPTV increasingly more complex. Therefore, the management decides to not explicitly involve crucible transporters.

Other Vehicles
Besides these two type of vehicles, forklifts are used for a variety of (mainly supporting) purposes in an aluminium potroom as well. Forklifts can, for example, be used to assist anode setting and pot change out. Forklifts may also be used for transportation of crucible tapping lids and (emergency) anode pallets. Nevertheless, most of its executing tasks can be carried out by other equipment such as cranes as well. Furthermore, forklifts are human-driven and usually maneuver freely in between the available trajectories while coping appropriately with blocking situations. This vehicle plays a supportive role in the smelters we consider.

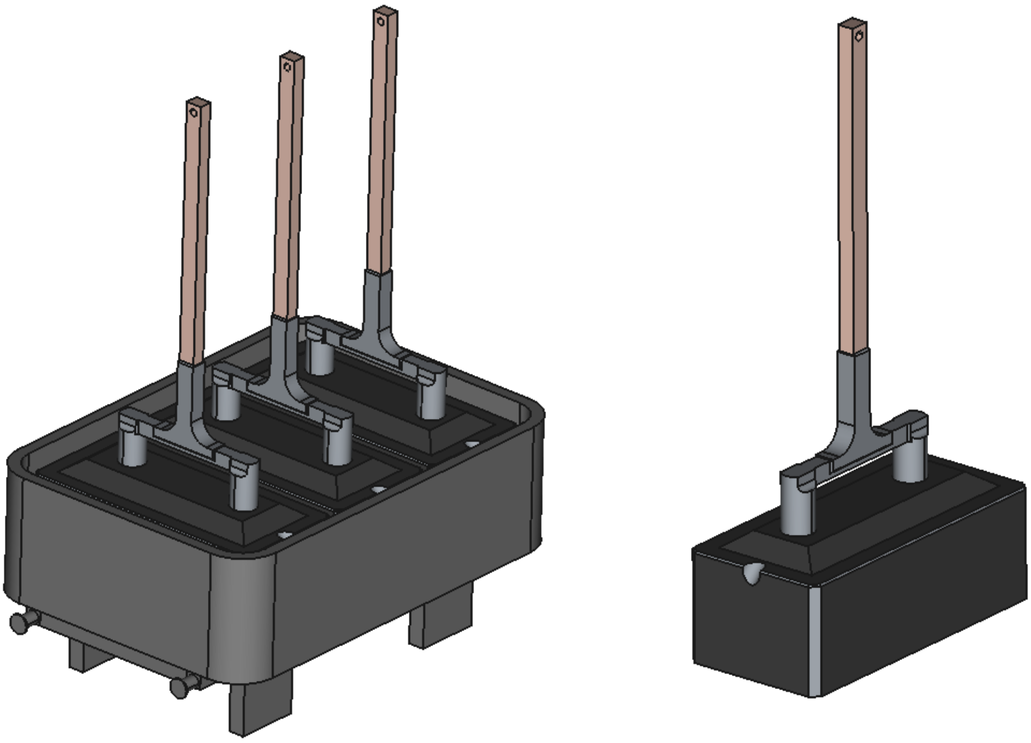
2.2.2.2 Cranes

Several cranes can be identified in an aluminium smelter. Examples are construction cranes, pot displacement cranes, and pot-tending cranes. Some crane types may serve multiple purposes. The crane operator can change the tool attached to the crane to make it suitable for different purposes. Because of safety regulations, the immense presence of the (overhead) cranes (e.g., see Figure 2.4), and the often limited space, areas could be (temporary) blocked for other vehicles during a specific shift (see Section 2.2.3). Furthermore, cranes need maintenance or could break. Crane behavior is not explicitly considered in this study. However, the processes involved are examined on a high-level (as time delay and operating sequence).

2.2.2.3 Moveable Objects

Moveable objects that are transported throughout the production facility include, for example, anodes and anode pallets, crucibles, and muck trays. Below we discuss them more detailed.

Anodes and Anode Pallets
Anodes are placed on pallets (see Figure 2.12). The pallets are transported by means of the AGAPTV (e.g., see Figure 2.10). Currently, the pallets can hold at most three (regular size) anodes, but Hencon wishes to investigate the impact of transporting a pallet containing pallets with an increased capacity as well. Figure 2.10b illustrates an AGAPTV with a pallet that can hold at most four anodes.



(A) Anode pallet with fresh anodes. (B) Fresh Anode.

FIGURE 2.12: Graphical illustration of the anode and anode pallet object. The rods are asymmetric attached to the anodes. Anode orientation can be observed through the small cove at the block width side.

Furthermore, the orientation of the pallet (i.e., north, south, east, west), is of importance because anode blocks (including their rods) are not symmetrical (see Figure 2.3b) and require a certain orientation in the cell. Notice that quite some cranes cannot easily rotate the anode 180 degrees and only align anodes for placing in the cell. Anodes are prepared such that they are suitable according to a specific orientation required in the cell, either for the front position (see Figure 2.7a) or rear position (see Figure 2.7b) of cells. During anode pallet transport, the pallet can be driven in according the required orientation by letting the transporter drive forward/backward in a section. For safety reasons (to avoid electrical short cut) and to enable drive through by other traffic, pallets cannot be placed anywhere. Subsection 2.3 gives attention to the anode transportation and pallet placement.

Crucibles
A crucible (also known as ladle) is a large metal bucket for transport of liquid aluminium. Crucibles are transported by means of crucible transport vehicles (e.g., see Figure 1.1d and Figure 2.11) and could be empty, filled or partly filled. A crucible is completely filled with metal after a certain amount of tapped pots. A lid is placed on the crucible before it is being transported. Crucibles and crucible lids are not considered in this study because this is part of the crucible transporter which is not embodied in the scope.

Muck Trays
Bath tapping fills a muck tray with bath material. This material is collected in a tray and after a certain amount of tapping, the muck tray is full and requires a transport to the bath conveyor belt where it is further handled. Muck trays are not considered in this study.

2.2.3 Shift-based Working Routine

Typically, aluminium production facilities operate based on a shift-based working routine. To this end, they divide the potroom into sections. In a section, one type of activity is ongoing during a shift. Repetitive activities are performed for a series of cells resulting in scale advantage. That is, each cell in the section undergoes the same activity and requires similar equipment and machinery. As the cells are (usually) positioned nearby each other in a section, the required machines, vehicles, and equipment can be shared and only the moment of job execution per cell slightly differs. For example, time-consuming overhead crane movements are then limited to the corresponding section only.

This subsection starts with clarifying how sections are defined, after which the shift-based working routine is discussed. We end this subsection with a discussion on how a continuous way of working may be realized by the introduction of AGAPTVs.

2.2.3.1 Potroom Sections

Each potroom is divided into sections. Each section holds a number of electrolytic-cells and an electrolytic-cell is dedicated to one section only. In a section, one type of activity is carried out for the entire group of cells. Basically, three types of activities sequentially alternate each other in shifts. These activities are: anode changing, metal tapping, and pot tending. So, for example, in the first shift anode changing takes place for a dedicated group of cells and in the second shift these cells undergo the metal tapping process, etc. We discuss these activities in the shift-based schedule explanation later on. In the sequel, we elaborate on the way sections are arranged in smelters.

To the best of our knowledge, there is no general consensus about how sections are defined in smelters. Nevertheless, the potrooms are usually divided such that either the sections contain approximately the same number of cells or the workload per section is roughly the same. However, there are also plenteous plants that classify their sections based on historical reasons (e.g., experience) or pragmatic approaches. A potential cause of the irregular section division is the plant expansion over the years.

There is a variety of possibilities to distribute the potroom into sections. One commonly used approach is to divide potrooms into three sections. Figure 2.13 sketches a smelter containing two potrooms with three sections each. For relative small plants, this might be an option, but when the plant size is enormous it may be unmanageable due to (practical) complications such as excessive congestions in sections or workforce and equipment limitations. Moreover, cell segmentation based on three sections could negatively impact the production throughput. Another widely used approach is to segregate a potroom into sections based on clear physical separations such as road crossings. The plant managers experience in addition to the physical plant layout properties usually lead to a section scheme.

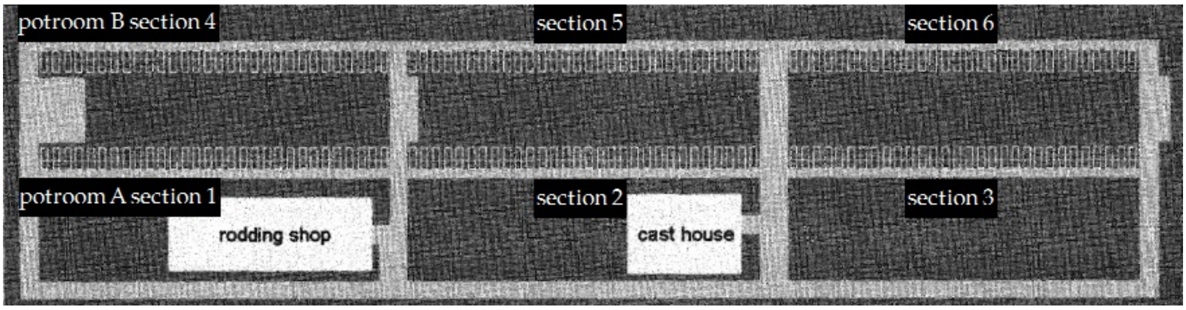


FIGURE 2.13: Example of a section layout containing two potrooms with three sections each. Adapted from Eick, Vogelsang, and Behrens (2001).

Plant managers sometimes decide to adjust their section schemes based on new findings. Especially when occasions such as holidays or weekends occur, it might be convenient to follow a different section scheme. This requires a proper way of managing the section activities.

Thus, the size and layout of the plant play a major role in the section distribution but also the plant managers' experience and impact on the production should be considered when deciding how to arrange the sections. It is a model requirement to incorporate the versatility in approaches to designate sections. Insights could be obtained by studying alternative section schemes.

2.2.3.2 Shift-based Schedule

Primary aluminium smelters operate based on shifts. Usually, each day is divided into three shifts of 8 hours. In the weekend, it is common to have two shifts of 12 hours each. Recall that the following three different activities are identified:

1. Anode changing;
2. Metal tapping;
3. Pot tending.

Before we explain these activities in detail, some more elaboration about the shift-based planning approach is necessary. Multiple teams work during a shift to finish the operations on-time. An operating team exists of machines, vehicles, and equipment needed to perform its tasks. However, for example, the AGAPTVs needed for the anode changing activity, might be shared among teams. This may happen, for example, when the tasks in one section are completed earlier. Figure 2.14 illustrates the shift-based planning approach using the example smelter layout we used before in Figure 2.13. So, the planned activities are based on a repetitive scheme.

Remark that there are also smelters that base their shifts on two activities only (anode changing and metal tapping). Pot tending activities are then integrated within the anode changing and metal tapping activities. Time window differentiation of the three activities can then provide an outcome to still maintain the three shift division. An example of this often used approach, is changing anodes and tapping metal every 8 hours but perform the pot tending activities every 2 hours. This will require a more sophisticated working approach then having three sections per potroom with non-overlapping activities, because more equipment is blocking pathways and traffic density increases in sections. On the other hand, this may increase the overall production output. An appropriate coordination is required to handle multiple activities that must be performed at the same cells within (almost) the same time window.

In the sequel, we respectively discuss the three aforementioned activities (anode changing, metal tapping, and pot tending). Thereafter, Subsection 2.3 focuses on the internal anode transportation, which is indispensable for the anode changing activity. Subsection 2.4 presents typical factory layouts.

Anode Changing

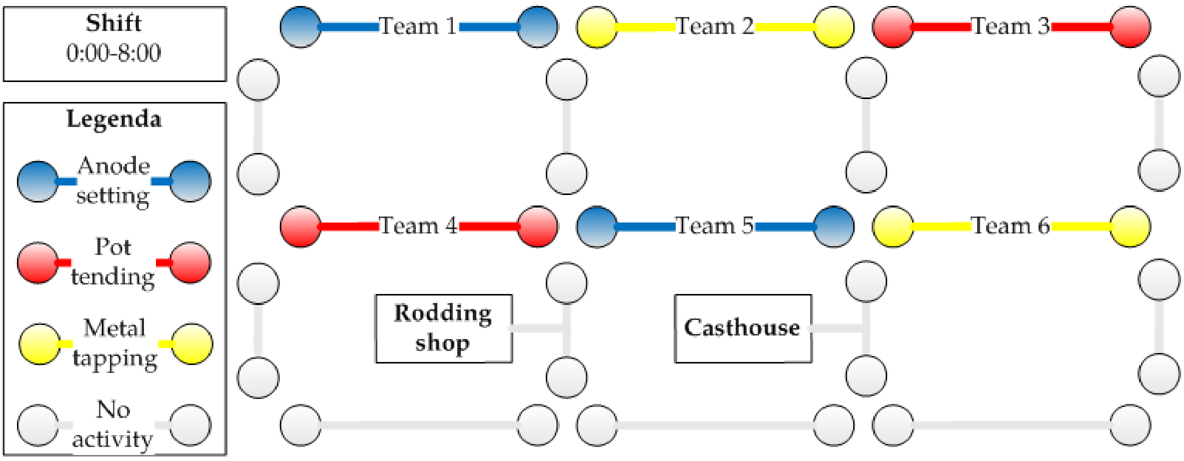
Anode changing activities are initialized by the shift scheme. That is, during the anode changing process, all electrolytic-cells in the concerning section that require anode replenishment are considered. The process of anode changing may be carried out by various team compositions. Often used team compositions are:

- one Pot-Tending Crane (PTM) (tools are swapped, which is a time-consuming task);
- two PTMs;
- one PTM and one Anode Changing Vehicle (ACV);
- one PTM and one Cavity Cleaner (CCL);
- one ACV and one CCL.

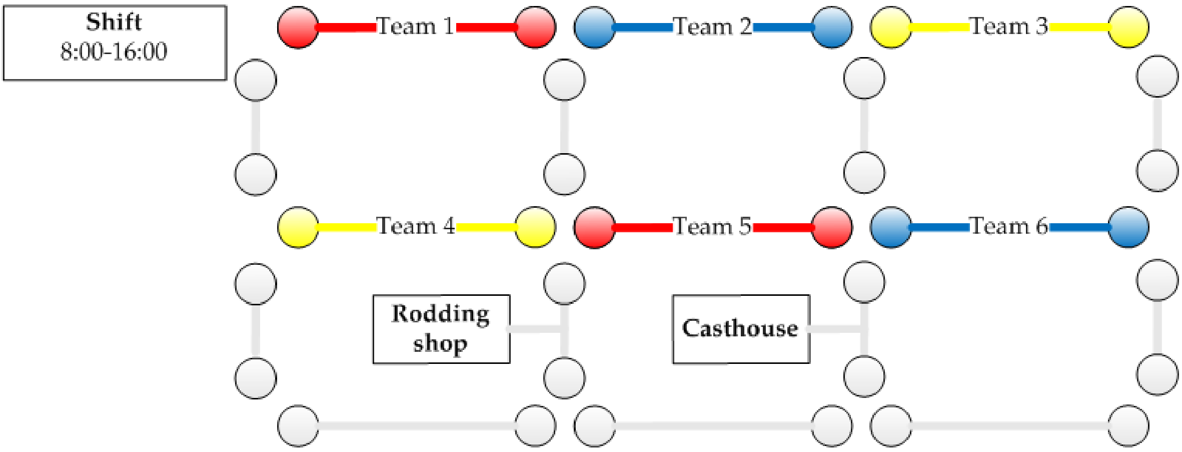
The process of changing one anode takes approximately 10 to 20 minutes (excluding the tool swapping task when having only one PTM) and consists of the following activities:

1. Break the crust to release the anode.
2. Take the old anode (anode butt) out and place it on an (empty) anode pallet position. An example of an used anode is shown in Figure 1.5a.
3. Clean the cell and put the bath material in an empty bucket.
4. Take a new anode from an anode pallet. An example of a new anode is shown in Figure 1.5.
5. Place the new anode on the correct height inside the cell.
6. Cover the anode with fresh bath material.

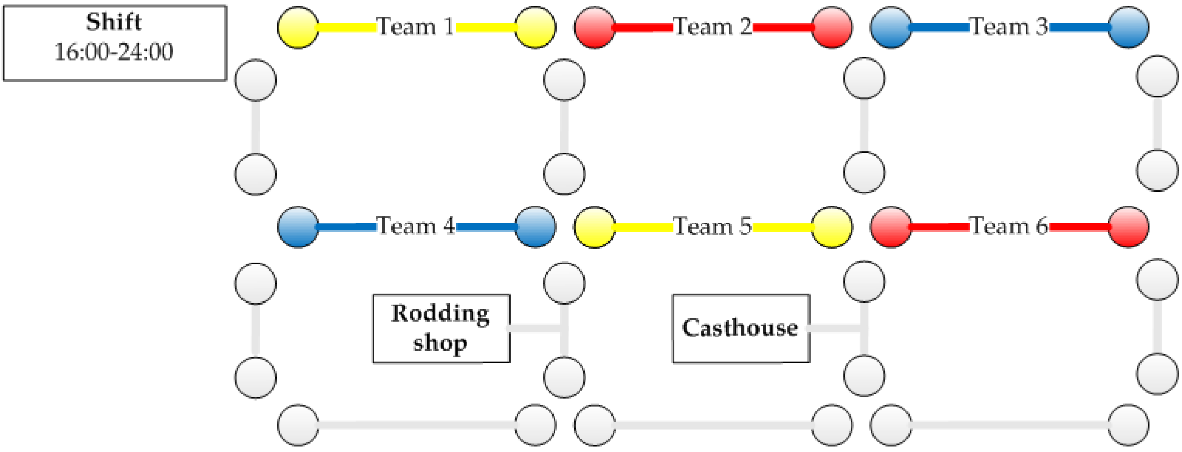
The Automated Guided Anode Pallet Transport Vehicle (AGAPTV) provides a supportive role by assisting those operations. Pallets filled with new anodes are delivered to nearby the cell and empty pallets or pallets with burned anodes are picked-up. The drop-off of pallets with new anodes may already start before the actual anode shift starts. The goal for the anode changing team is to start swapping anodes as soon as the anode changing shift starts. Cranes get their anodes from the pallets



(A) Shift 0:00-8:00.



(B) Shift 8:00-16:00.



(C) Shift 16:00-24:00.

FIGURE 2.14: A simplified example of the shift-based working routine. The scheme is representing the smelter layout from Figure 2.13 and depicts two potrooms including three sections each. Arcs denote lanes and nodes lane crossings. The daily working routine consists of three shifts with the same timespan. One activity (i.e., either anode setting, pot tending or metal tapping) takes place in each section during such a shift. After a shift has been ended, the successive activity in that shift will start.

and likewise drops them off in the pallets. In addition to the team compositions, there might be some other supportive machinery/vehicles involved as well (e.g., forklifts, hammer crust breakers, drumfeeders, etc.). However, detailed movements of these are not considered in this thesis.

Let us explain the commonly used anode changing approach in sections using an example. We consider a section containing 20 electrolytic-cells in total thus 10 cells on each side. There are no intersecting aisles and the cells are positioned in an end-to-end layout. Each cell holds 13 anodes on both sides, so 26 in total (see Figure 2.15). Anodes can only be reached from one side, either the center aisle or the back aisle. Recall that anodes must be replenished as soon as (or slightly before) the setting cycle is elapsed. We consider a setting cycle of 28 days for all anodes in this example. Suppose the repetitive changing scheme for cells is determined such that one anode is changed daily per cell starting on day one. Then, on the 26^{th} day, the last anodes have been interchanged. As we consider a similar changing scheme for each cell, there are two days left in which no anodes are changed (the so-called anode free days).

As introduced with the simplified example above, the repetitive anode changing pattern depends on the number of cells in a section, number of anodes per cell, and setting cycle. A larger number of cells or more anodes per cell, require more anodes to be transported. An increased setting cycle, results in requiring less anodes because anodes can sustain longer in cells. The sequence in which anodes are interchanged may differ inside a cell and is based on information from the Manufacturing Execution System (MES). Likewise, the setting cycle may be initialized on different moments per cell. That is, for example, an anode in the first cell of the section should be replaced on the first day, but the one in the second cell should not be replaced on that day. So, this results in fluctuating anode demand per shift. An appropriate modeling technique should be used to cover a variety of possible anode changing schemes.

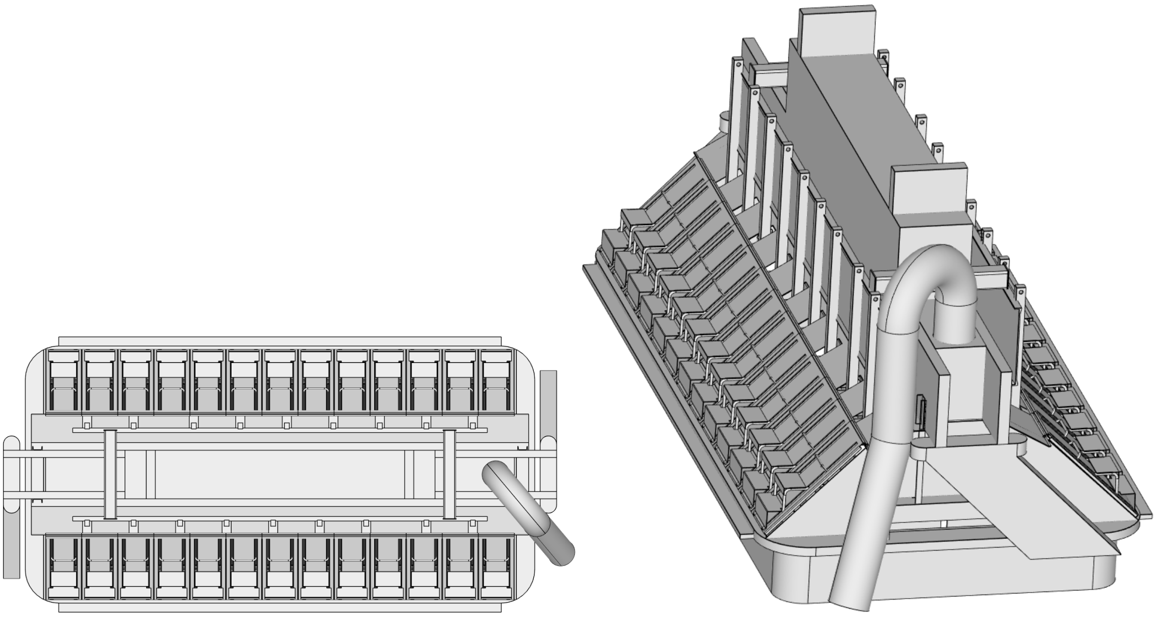

(A) Top view of an electrolytic-cell. (B) Top-right view of an electrolytic-cell.

FIGURE 2.15: Electrolytic-cell orientations. This cell contains 13 anodes on each side, so 26 in total.

Metal Tapping

Metal tapping comprises the process of tapping liquid aluminium from an electrolytic-cell and the logistics involved. Tapping could be done by a crane holding a vacuum crucible (e.g., see Figure 2.4) or metal tapping vehicles (e.g., see Figure 1.1a).

The time it takes to (practically) empty one cell depends on several factors like the size of the cell, the number of anodes, the used equipment, and the desired residual amount. Crucibles are usually full after a certain amount of taps and are then placed in main passages for transport. Crucible transporters transport the load to the casthouse. Empty crucibles are likewise transported by means of the crucible transporters. Tapping duration, tapping quantity, and crucible capacity are client specific.

When the metal tapping is in progress, it is desired to not have any other vehicles, machines, and equipment, which are not strictly necessary for this smelter process, in the corresponding section. Aluminium tapping involves special attention as the liquid aluminium is intense heat and therefore additional security measures should be considered. For that reason, it is common to block entire sections where the tapping process is ongoing.

Pot Tending
Pot tending activities are initiated by cell characteristics and are not always necessary. Pot tending activities include activities like bath leveling and beam raising (e.g., see Table B.1). Recall that bath leveling compensates a difference in bath material occurred due to processes going on in the electrolytic-cell (see Subsection 2.1.3). A commonly used approach in practice is to perform bath leveling activities a few hours after the cell is being tapped. During bath leveling, no other vehicles, machines, and equipment can pass the corresponding aisle in a similar manner as during the tapping activities.

Beam raising involves repositioning the anode in a cell. Typically, smelters are arranged such that one anode should be realigned in a cell on a daily basis (see Figure 2.3a). The same blocking properties hold for beam raising as for bath leveling.

2.2.3.3 Continuous-based Schedule

Although smelters typically use the shift-based planning approach, there is a growing tendency in achieving a planning approach that is not bounded to the shift and section way of working. For example, in the shift-based planning approach, it is possible that a shift ends earlier than expected. Consequently, the corresponding workforce has to wait until the next shift starts while it may be more efficient to already start with other cells in the next section. A better understanding of aluminium production processes and technological advances, such as the establishment of AGVs in aluminium smelters, contribute to the development of a production environment that enables a 24/7 operation.

One step further towards this development, is providing insights into the impact different planning approaches have on the aluminium smelter's performance. Modifications to section and shift-based working schemes would already be valuable. In the model we develop, we could examine the impact of various section, shift and anode demand distributions.

In this study, we mainly cover the shift-based scheduling approach because this approach is generally used in practice. However, by means of models parametrizations concerning the section- and shift-based working approach, we aim to provide insights into different ways of working.

2.3 Internal Anode Transportation

In this section, we successively describe the internal logistic processes of anode transportation and the specification of transportation jobs that should be carried out by the anode transport vehicles.

2.3.1 Anode Transportation Processes

The anode hauling process starts with a transport request generated by the MES. Each transport request is restricted by an earliest- and latest delivery time of an anode pallet. Also, the transport request has a pick-up and delivery place. Furthermore, the front of the anode pallet must be placed according to a certain orientation (North, West, South or East), which depends on the destination location. This subsection commences with presenting some typology and a base layout of the potrooms. Next, pallet orientation and placement restrictions with respect to the cells are addressed. After that, driving blockades and safety measures of the AGAPTV are discussed.

2.3.1.1 Typology and Base Layout

In the aluminium smelters we consider, electrolytic-cells are positioned following the end-to-end layout. That is, the shortest sides of the cells are placed next to each other (e.g., see Figure 2.6a). Figure 2.16 illustrates a layout including the AGV guide-paths. In general, the width of the center aisle is sufficient large to cover two parallel paths in which the AGAPTV can travel. In the center aisle, the cells are positioned in series facing the front ends to the same side side (see Figure 2.7a). The back side of the cell (see Figure 2.7b) is reachable via the back aisle. The back aisle is typically smaller than the center aisle and therefore at most one AGAPTV can travel on that side. As shown in the figure, the aisles intersect on crossings.

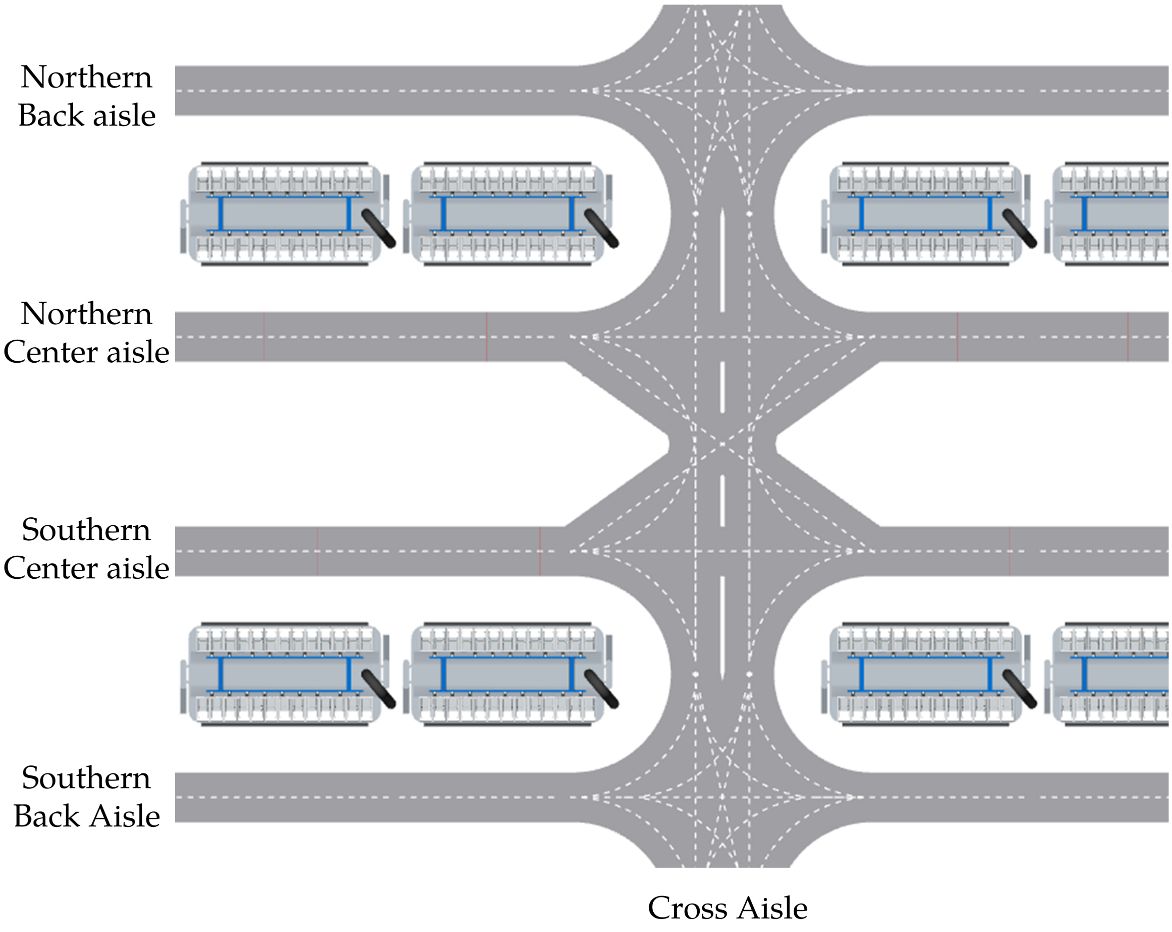


FIGURE 2.16: Smelter layout base typology within a segment.

As there are often multiple potrooms, the crossings may lead towards another potroom or to another segment. Cells are clustered in a segment and these segments are physically separated from other segments by means of cross aisles as well. Figure 2.17 shows the used typology to classify potrooms and segments throughout this thesis.

A modern smelter roughly contains around 300 to 700 pots covering a total length of approximately 1 kilometer. The length of a potroom and the physical placement of the different support systems play a crucial role in the time duration of a trip carried out by the AGAPTV. Imagine that the AGV must travel 1 kilometer with a driving speed of 5 kilometer per hour, then a round trip would already results in a duration of 40 minutes solely by driving.

2.3.1.2 Pallet Orientation and Pallet Placement Restrictions

Each cell is reachable from two opposite sides, however, the pallets may not be placed on the back side of the potrooms because of the narrowness of the path. As addressed before, pallets are not symmetrical because the anodes require a certain orientation in the cell. Anodes have a cove on the width side of the block (see Figure 2.12) and these need to be pointed to the electrolytic-cell. The pallet's orientation is essential during delivery of full buckets to the potroom. As shown in Figure 2.18, the southern parts of the cell require a similar orientation. The same holds for the northern parts of the cell. So, arising demand from either the northern or southern of the cell could potentially be combined in an anode pallet.

The pallet should not be stored in the section too far away from the cells where the anodes are actually needed. Disobedience of the latter could undermine an efficient workflow because the transportation time within a section then increases. So, before the AGAPTV delivers the pallet, the route,

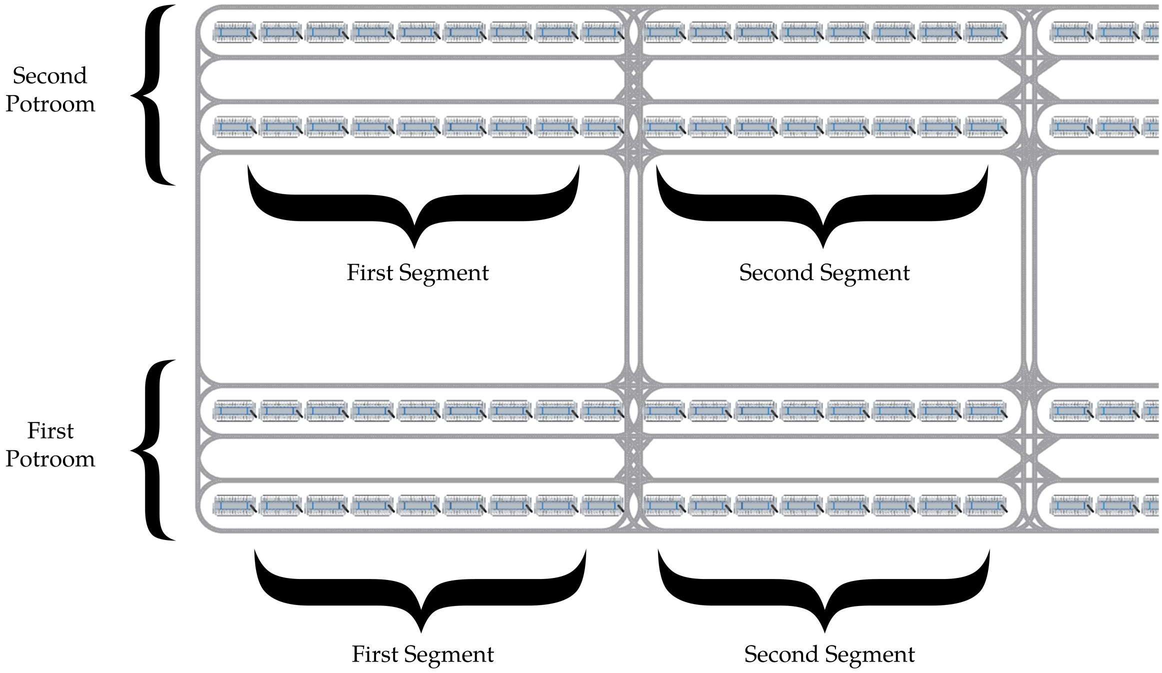


FIGURE 2.17: Smelter layout base typology within a smelter. A potroom contains two potlines with parallel series of electrolytic-cells. The cells are connected in series and lined-up in an end-to-end position. Cross aisles designate a physical separation between a series of cells. The area covering two parallel series of cells in one potrooms separated by cross aisles, is defined as a segment.

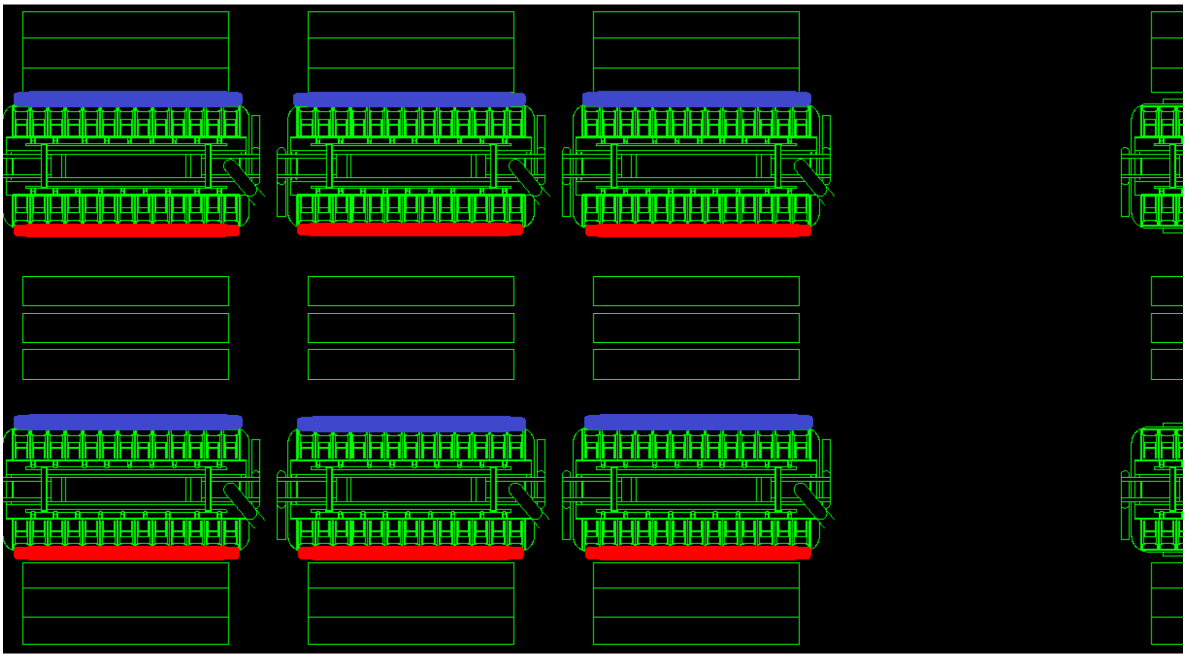


FIGURE 2.18: Anode pallet orientation in the potroom. Anodes positioned near the segments' northern back aisle and southern center aisle should be fulfilled through pallets located at the northern center aisle (indicated blue). Pallets at the southern center aisle fulfill anode demand from the southern parts of the cells (indicated red).

driving direction, and storage location should be determined. Likewise, the sequence in which anodes are replaced by the workforce should be taken into consideration as this influences the pick-up and delivery scheme.

The anode placement time plays an important role in the aluminium production process and requires on-time availability of anodes on nearby pallets that are reachable by anode changing equipment. New anode pallets are picked-up from the rodding shop or anode bake plant. On the one hand, when new anodes arrive too early at their destination, the anode placing equipment does not need them which could consequently lead to unnecessary stacks. On the other hand, a too late delivery affects the electrolytic process in the cell and could disturb an efficient aluminium production process.

Pallet orientation is less important when pallets are dropped-off at the rodding shop. Empty pallets and pallets with spent anodes can be dropped-off and picked-up from both sides. Hence, the pick-up orientation is then not an issue. Likewise, dropping pallets at the rodding shop requires no special pallet orientation.

2.3.1.3 Driving Blockades and Safety Measures

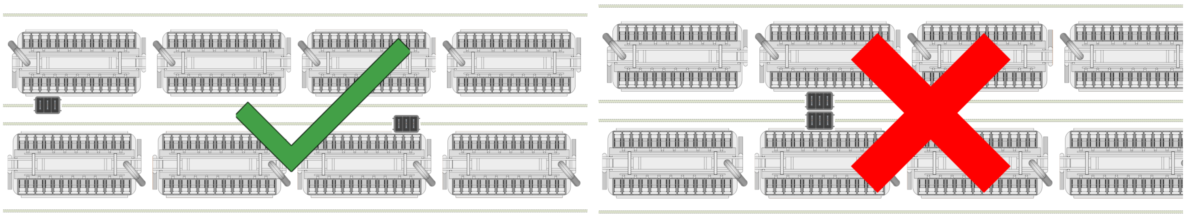
Besides that (parts of) driving lanes are blocked for the AGAPTV when smelter or pot tending operations are in progress (see Subsection 2.3), there are some other limitations that affect driving through by this vehicle as well. The AGAPTV is not only equipped with a safety scanner that detects possible physical obstacles within an observable range, but also with a control system that communicates with other vehicles and machines. This technology enables AGAPTVs to avoid obstacles and taking into account driving restrictions when determining safe routes. Possible blockades, driving restrictions, and safety measurements which are generally applicable within smelters we consider include:

- Possible vehicle collisions should be avoided by restricting a minimum distance between AGAPTVs (see Appendix C);
- For safety reasons (to avoid electrical short cut) and to enable other trucks to drive through, a minimum distance between pallets placed on different sides of the center aisle must be maintained (see Figure 2.19a and Figure 2.19b);
- It is allowed to drop pallets or park vehicles close near each others if they are placed on the same side of the center aisle (see Figure 2.19c). Other vehicles and equipment can then traverse the lane via the other lane of the center aisle;
- Limited space within the main aisle(s), restrictions concerning properties of the AGAPTV (e.g., size, length, turning angle, etc.), and securities measures to prevent possible accidents and deadlocks (e.g., tipped pallets, deployed maneuvers which are intermediately blocked, etc.) impose a few restrictions that should be considered. Firstly, the AGAPTV cannot turn to change driving directions once an aisle has been entered (see Figure 2.19d). Thus, it is not possible to change driving directions from, for example, heading north to heading south when driving in a lane. However, the AGAPTV could change its driving direction from forwards to backwards or visa versa on each path. Also, at crossings the AGAPTV may change driving directions. At these locations, the vehicle can change aisle directions by performing, for example, two 90 degree curves. Secondly, the AGAPTV may not easily make a turn in case of pallets standing in the outer parts of the segments. As illustrated in Figure 2.19e and Figure 2.19f it is desirable to not place pallets directly in the outer parts of the segment. This to avoid possible collisions by turning vehicles and preclude complex driving maneuvers for the AGAPTV.

Additionally, two approaches for rescheduling routes based on the occurrence of blocking restrictions are commonly used in practice. The first approach is acting in a reactive manner once a blocking occurs. once a job is dispatched to a vehicle, the route is determined only in the beginning (with considering blocking restrictions). As soon as a blocking restriction occurs, the vehicle could not drive further and the route will then be rescheduled. The other considered approach is a proactive rescheduling approach in which affected routes are adjusted immediately based on information about blocking restrictions. We decide to incorporate both approaches such that we can expose differences in achieved performance. For an brief explanation about differences in the rescheduling approaches, we refer to the literature review in Chapter 3.

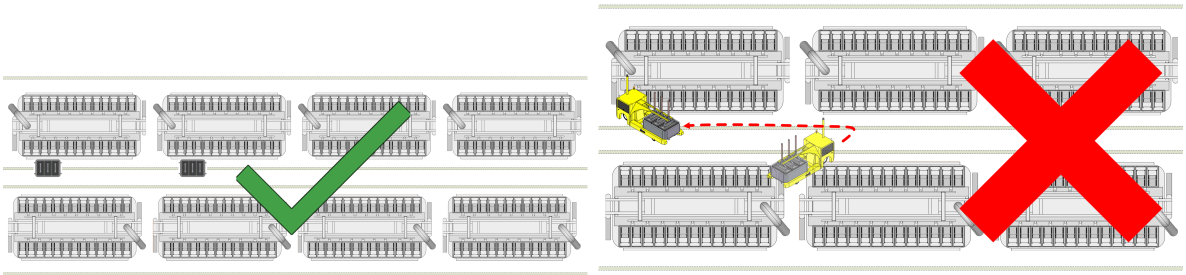
2.3.2 Types of Transportation Jobs for the Automated Guided Anode Pallet Transport Vehicles

The pick-up and delivery of anode pallets should be thoroughly planned. Considering the driving blockades and safety measurements addressed in the previous section, the AGAPTV transport orders



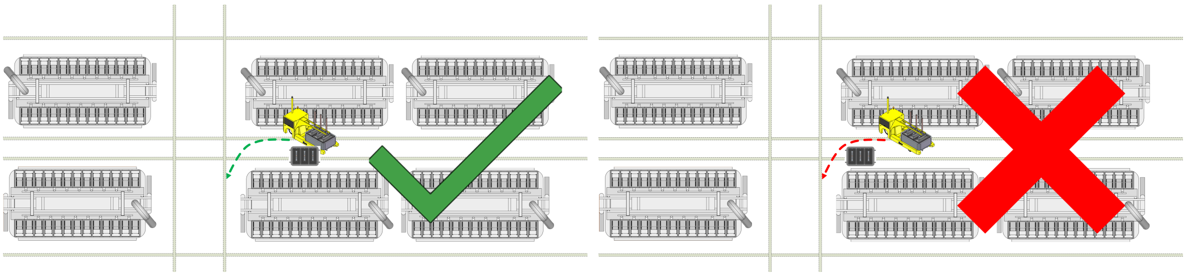
(A) A minimum distance between placed obstacles on each side of the center aisle must be maintained to enable vehicles and equipment to pass through. For example, one could consider a minimum distance of at least 2 times the pot length.

(B) Large vehicles should be able to pass anode pallets or vehicles in a safe way.



(C) Equipment may be parked with less than one pot length between them if they are placed on the same side of the center aisle.

(D) Performing a U-turn within section aisles is not possible. Simply a change in the driving direction of the AGAPTV is possible because the vehicle can drive both forwards and backwards.



(E) Anode pallets should be placed with an appropriate distance from the cross aisle, otherwise it may cause dangerous situations.

(F) Anode pallets should be placed with an appropriate distance from the cross aisle, otherwise it may cause dangerous situations

FIGURE 2.19: Various driving blockades, driving restrictions, and safety measurements concerning anode pallets and AGAPTVs. The rules are general applicable to the primary aluminium smelters with end-to-end positioned electrolytic-cells.

should be carried out in an adequate manner. A wrong transport decision made may disturb the aluminium production process significantly. Therefore, usually, upfront of the change of anodes, the pick-up and delivery sequence should be known. Otherwise, the transport may result in deadlocks and aluminium process disturbances. Thus, the sequence of completing transport orders should be tailored to the production process and visa versa.

As customers may use different anode changing schemes, which often deviates from day-to-day, it is important to cover a variety of approaches that are realistic in practice. Typically, an order list is received from the MES with transportation jobs to be carried out by the AGAPTV. MES should provide information concerning the type of transport, the pick-up and delivery location, and the job release time. A goal of MES is to provide the required anode transports appropriately such that the workforce can start working immediately once the anode changing shift starts. The following transportation jobs can be specified:

- Pick-up an anode pallet with fresh anodes from a storage location such as a rodding shop or conveyor belt, and transport it to an electrolytic-cell;
- Pick-up an anode pallet without anodes from a storage location and transport it to an electrolytic-cell;
- Pick-up a pallet full with spent anodes from an electrolytic-cell and transport it to a storage location;

- Pick-up an empty pallet from an electrolytic-cell and transport it to a storage location;
- Pick-up an anode pallet with some fresh anodes left from an electrolytic-cell and transport it to an intermediate storage location or other cell.

MES should not only consider the release of transport jobs based on the required fresh anodes, but also the imposed pallet placement restrictions and the sequence in which a workforce is replacing the anodes. One should consider the transition from anode demand to anode pallet demand. From thereon, the pick-up and delivery sequence should be determined in close collaboration with the team responsible for changing the anodes.

2.4 Typical Factory Layouts

Numerous different layouts exist for primary aluminium smelter layouts. Basically, every smelter is unique and capturing any possible setting to the highest degree of granularity in a model would be a lifelong work in itself. Despite the huge variety of imaginable smelter layouts, there are common elements to be found in most smelters (see Section 2.2). Furthermore, multiple layout characteristics that influence the path AGAPTVs may take can be pinpointed. The model to be developed should be suitable to comprise a representative client base. To this end, we determine a set of model parametrizations that need to be comprised in the model. Typical factory layouts are then covered under variants of the parametrizations. The requirements complement the elements already described in the previous sections. In this section, we address successively variations in plant size, sections and shifts, and rodding shop locations. We finalize this section, with providing a list of process inputs that we can derive from this chapter.

2.4.1 Plant Size

The size of the plants is different from customer to customer. The layout is characterized by potrooms, segments, and electrolytic-cells. A potroom is connected to other potrooms by means of pathways in main roads. Potrooms contain a certain number of segments. Usually, the potrooms are structured in a triangular shape. Hence, the first potrooms are longer than the subsequent potrooms or visa versa. Plant extensions during the years are a cause of this. For a representative model of aluminium smelters, the model must be able to appropriately incorporate different plant parametrizations:

1. Multiple potrooms with a varying number of cell segments. The distance from potroom to potroom is of importance, as well as the distance from segment to segment.
2. The number of cells per segment may deviate. Also, the size of cells should be modifiable. Likewise, a varying distance between cells must be incorporated.
3. Vehicle properties may influence the development of the guide-path and could impose other blocking restrictions that should be included.
4. The ability to (permanently) block individual paths.
5. Different locations of the rodding shops or conveyor belts.
6. Different locations of electricity charging areas.

The model's flexibility to include this can be demonstrated by implementing a few exemplary models. In Chapter 5, we devote some time in conducting experiments with different plant parametrizations.

2.4.2 Sections and Shifts

In general, plants use different sections and shifts distributions. There is no general consensus about how sections and shifts are arranged in smelters (see discussion in Section 2.2.3). However, as discussed before, two approaches are widely used for defining sections. The first approach is to classify three sections per potroom. The second approach is to classify sections based on physical separations such as road crossing and an approximately equal workload per section. To adequately model the majority of the client base, at least these two section distribution approaches should be included in this study to cover working schemes used by a large client base.

Concerning the shift-based working approach, the prevalent approach is to perform the three type of operations (anode changing, metal tapping, and pot tending) sequentially per shift per section. So, metal tapping operations are carried out in the shift posterior to the anode changing activities and pot tending operations after the metal tapping, etc. Typically, the duration of one shift is eight hours, which is equal for each activity type. This results in a repetitive scheme every day in which the same activities per section are performed during the same time frame. Notice that in the weekends, the duration of a shift is typically twelve hours. However, the model should be able to incorporate different durations of shifts. This because the shift scheme is closely related to how sections are designated.

Primary aluminium facility managers are eager to investigate different section- and shift distributions. By considering variations in section allocations and shift durations, interesting variations could be investigated.

2.4.3 Rodding Shop Location

The location of the rodding shop often differs per smelter. Rodding shops are important because the anode pallets are picked-up and dropped-off at this location. Usually, plants have multiple locations where anode pallets could be stored but their main storage area is (nearby) the rodding shop. Typically, the rodding shop is direct reachable via the main road and located on one of the the longitudinal sides of the plant. Figure 2.20 illustrates this by using an example of one potroom with five cell segments.

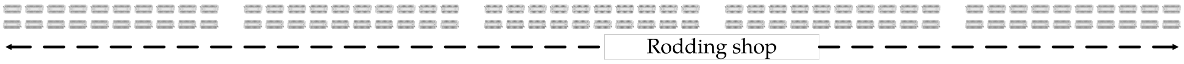


FIGURE 2.20: Variations in locations of the rodding shop. The rodding shop is usually direct reachable from the main road and positioned on the longitudinal side of the plant. The rodding shop could be placed anywhere on the dashed line.

2.4.4 Input Elements

In this subsection, we describe some of the input elements found so far:

- Anode demand characteristics:
  - Anode changing scheme (specified per cell)
- Transport job characteristics:
  - Origin
  - Destination
  - Anode pallet release time (job release time before the shift starts)
  - Time-window length
  - Pallet orientation
- AGV characteristics:
  - Battery capacity, battery charging and usage parameters (see Appendix C)
  - Loading and unloading time
  - Size properties (see Appendix C)
  - Driving properties such as speed, acceleration, deceleration, etc. (see Appendix C)
  - Capacity
- Network structure:
  - Number of potrooms
  - Number of segments per potroom
  - Number of electrolytic-cells per segment
  - Number of anodes per cell
  - Vertical and horizontal distances between potrooms, segments, and electrolytic-cells.
  - Rodding shop position(s)
  - Blocked paths
  - Distances between nodes in the network
- Shift and section characteristics:

  - Section allocation
  - Shift scheme (activity type, timespan, and degree of occurrence in case of pot tending activity)
- Rodding shop:
  - Location(s)
  - Pick-up and drop-off time
- Charging station:
  - Location(s)
  - Charging parameters (recharging time per AGAPTV)
  - Coupling/decoupling time
  - Vehicle capacity
- Parking areas:
  - Location(s)
  - Vehicle capacity

2.5 Conclusion

This chapter covered the context analysis of typical clients of Hencon active in the primary aluminium industry. We first gathered insights into the aluminium production and manufacturing process. Five steps are identified, starting with mining bauxite ore and ending with recycling aluminium. We highlighted that the anode blocks play an essential role in primary aluminium smelters and require an appropriate planning approach.

AGAPTVs should not only be on-time for anode changing operations but also properly deal with changing circumstances such as changing shifts and section, and their imposed restrictions. Besides that, cranes, vehicles, and other equipment interfere with the AGAPTV.

Afterward, we confined ourselves to common characteristics of the factory layouts. Electrolytic-cells can be positioned in an end-to-end or side-by-side layout. The focus of our study is on the former. The introduction of AGVs requires special attention as the pallets should be positioned according to cell properties, anode orientation, and section requirements. Moreover, blocking restrictions and adequate interference with other moveable objects should be included in the AGV control system.

Thereafter we discussed the shift- and section-based way of working. Potrooms are divided into sections and within each section, one type of activity (either anode changing, metal tapping, or pot tending) is performed during a time frame. When the shift ends, the subsequent activity is initiated.

This chapter proceeded with addressing the internal anode transportation. The base layout is characterized by cells lining up in series and positioned in segments. A potroom contains two lines of cells with two center aisles in-between them and one back aisle on each of the other sides. Road crossings allow the passage through next segments. Anode placement is subject to driving restrictions inside the section and segment. This is caused by the narrowness of aisles, safety rules, and vehicle size properties.

Finally, we considered typical factory layouts. Typically, smelters vary in size, use different section and shift distributions, and the location of, for example, the rodding shops differs. The layout characteristics are considerable unique for each primary aluminium smelter and parametrization of these factors would provide a comprehensive manner in covering a representative client base.

Chapter 3

Literature Review

This chapter provides a literature study of various topics covered in this thesis. Literature used will not only be limited to manufacturing systems, but will also cover a wider scope of application areas of AGVs such as warehousing, transshipment, and other transportation systems. Section 3.1 commences with outlining AGV system design approaches in manufacturing environments. Section 3.2 provides a literature study about dynamic scheduling approaches in manufacturing environments. Next, Section 3.3 introduces multi-agent system technology. After that, a brief literature study of closely-related operations research (OR) applications in the primary aluminium industry or comparable flexible manufacturing systems (such as the steel industry) is conducted in Section 3.4. Section 3.5 advocates the uniqueness of this thesis by combining the AGV system, dynamic scheduling and the MAS control approach. This chapter is concluded in Section 3.6.

3.1 Autonomous Guided Vehicle System Design

This section gives a brief overview of AGV system design approaches. Subsection 3.1.1 starts with introducing some terminology and functionalities of AGV systems. Subsection 3.1.2 describes conventional approaches of designing and controlling AGV systems. Subsection 3.1.3 motivates the methodology we will follow throughout this thesis for developing the AGV system. Finally, Subsection 3.1.4 concludes this section.

3.1.1 Terminology

We first give a definition of an AGV. After that, we introduce the essentials of an AGV system.

3.1.1.1 Automated Guided Vehicle

In general, an Automated Guided Vehicle (AGV) is a driverless transport system used for horizontal movement of material (Vis, 2006). Since their introduction in 1955 (Muller, 1983), the use of AGVs have found widespread industrial applications and can be found in many types of industries. AGVs can be used in inside and outside environments, such as manufacturing (where AGVs are traditionally used to transport materials related to the manufacturing process), distribution, transshipment, and (external) transportation areas (Vis, 2006). AGVs are one of the most efficient ways for material handling due to better routing flexibility, space utilization, product quality, and safety (Erol et al., 2012). For an overview of the history of AGVs, we refer to Ullrich (2015).

Clearly, the specifications of AGVs differ per environment. As AGVs are capable of transporting one or more loads at the same time, the so-called *unit load* has to be decided by the management. A unit load refers to a number of items arranged in such a way that they can be transported as a single object (Vis, 2006). A container or pallet are examples of a unit load. Furthermore, it has to be decided if the AGVs are capable of handling *single-load* or *multiple-loads*.

3.1.1.2 AGV Control System

An AGV control system receives transport requests generated by client systems such as an Enterprise Resource Planning (ERP) system, and assigns incoming transport tasks to appropriate AGVs (Weyns and Holvoet, 2008; Erol et al., 2012). According to Erol et al. (2012), an AGV system should be properly controlled and managed to reduce material handling costs, in-process inventories and overall operational cost. The AGV control system can be seen as the heart of the AGV operations and has to deal with all kind of dynamic and changing operating conditions (e.g., irregular and unpredictable transport streams, disturbances such as delay in goods, temporarily closed or blocked roads, AGV failures, avoiding collisions and deadlocks, maintaining the AGVs' batteries, etc.), while it should (under these conditions) still provide an efficient and robust operation (Weyns et al., 2008).

In an AGV system, several parts can be distinguished (see Figure 3.1), namely the vehicles, the transportation network, the physical interface between the production/storage system and the control system (Vis, 2006). Clearly, the specifications of an AGV system may differ per environment and the AGV system itself might be part of a larger system such as an intelligent flexible manufacturing system. Vis (2006) describes that the role of the transportation network is to connect all stationary installations (e.g., machines, buffers, etc.) in the center. At stations, pick-up and delivery points are installed that operate as interfaces between the production/storage system and the transportation system of the center. At these points, a load is transferred by, for example, a conveyor or crane from the station to the AGV and vice versa. AGVs travel between pick-up and delivery points on fixed or free paths. Guidepaths are determined by, for example, anchoring points in the floor or wires in the ground. More recent technologies allow AGVs to operate without physical guidepaths, which are so-called free-ranging AGVs (Le-Anh and Koster, 2006). For this type of AGVs systems, tracks are software programmed and can be changed relatively easy when new stations or flows are added.

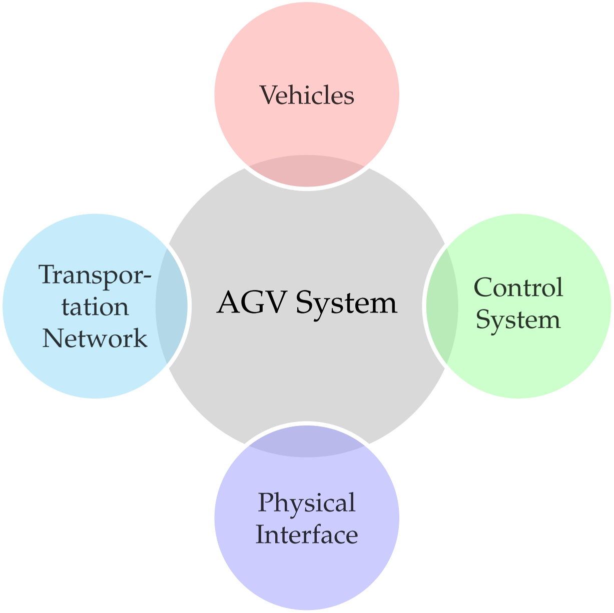


FIGURE 3.1: Automated Guided Vehicle (AGV) System. Adapted from Vis (2006).

An AGV system's purpose is mainly to manage the execution of transports appropriately. The main objective of an AGV system could be different per system, and likewise, performance indicators might differ. The objective of an AGV system can, for example, be to maximize throughput of the system or to minimize total costs of AGV movements. In general, the main functionalities that an AGV system should be able to execute are (Weyns et al., 2008): (1) transport assignment, (2) routing, (3) gathering traffic information, (4) collision avoidance and (5) deadlock avoidance. The subsequent subsection explains the purpose of these functionalities in relation to various design issues.

3.1.2 Automated Guided Vehicle Control & Design Methodologies

The design and implementation process of an AGV system comprises many decision variables on the strategic, tactical and operational level. Decisions at the strategic level have a strong effect on decisions at other levels. The procedure of designing an AGV system is a complicated process as the impact of decisions on mutual interactions and performance between and within every stage, cannot be considered separately and might be difficult to predict. Vis (2006) discussed that at least the tactical and operational issues, as explained below, have to be addressed in designing and controlling an AGV system. Notice that we discuss these issues only concisely and refer the reader to Le-Anh and Koster (2006) and Vis (2006) for an extensive overview of design and control approaches for AGV systems.

3.1.2.1 Guidepath Layout

Guidepath layout design is often seen as an important aspect in the development of an AGV system. The guidepath depends greatly on the allocation of shop-floor space, the layout of storage zones, and the arrangement of handling stations (Le-Anh and Koster, 2006). A guidepath layout connects machines, processing centers, stations and other fixed structures along aisles (Vis, 2006). It is common to represent such a layout of aisle intersections, pick-up and delivery (P/D) locations as nodes on a graph connected by a set of arcs. The arcs represent the paths that vehicles can follow when moving from node to node.

Guidepath layouts can be designed in various ways. Vis (2006) categorizes these methodologies as follows:

- Determine simultaneously the layout of the facility, the layout of the guidepath and the location of P/D-points;
- Consider the layout of the facility as an input factor, and determine the design of the guidepath and the position of P/D-locations;
- Consider the layout of the facility and the locations of P/D-points as input factors, and determine the guidepath design.

3.1.2.2 Traffic Management: Prediction and Avoidance of Collisions and Deadlocks

Collisions and deadlock situations in which vehicles are blocked completely, should be avoided. AGVs should have the ability to avoid obstacles and the ability to return to their original path without any collisions (Vis, 2006). AGVs cannot cross the same intersection at the same time, however, safety measures are also necessary when AGVs pass each other on closely located paths (Weyns et al., 2008). Deadlocks could not only occur when AGVs moving in opposite direction are forced to stop in front of each other but, for example, also at buffer areas of P/D-locations (Vis, 2006). If a load is available for transport at a P/D-location and a loaded AGV is the first in line before an empty AGV, then the loaded AGV cannot be unloaded and the new load cannot be transported since AGVs are relatively constrained in their movements.

According to Vis (2006), detection and resolution of deadlocks, instead of avoidance and prevention of deadlocks, results in a lower performance of the system. For that reason, considerable effort has been made and methods have been developed to tackle the deadlock problem by means of avoidance and prevention approaches. Vis (2006) divides the literature into three design categories:

- Design the guidepath in such a way that collisions and deadlocks are avoided;
- Divide the traffic area into several non-overlapping control zones. This approach is often denoted as the zone control modelling approach;
- Develop routing strategies to prevent collisions and deadlocks.

Le-Anh and Koster (2006) mention several ways to avoid deadlocks in AGV systems. They discuss the following solution approaches:

- Better routing algorithms (e.g., single loop, tandem or segmented flow topology);
- Prediction of collisions through forward sensing and consequently avoiding these through vehicle backtracking and/or rerouting;
- Imposing zone control and extensive route pre-planning.

3.1.2.3 Location of Pick-up and Delivery Points

In the design of the layout of an AGV system, the locations and number of P/D-points are of importance. P/D-points are the terminals that connect the AGV network to, for example, machines and places of storage. Furthermore, P/D-points can be used as a transfer station from one material handling network to another (Vis, 2006). Vis (2006) mentions several publications that address designing approaches for choosing the P/D-points.

3.1.2.4 Vehicle Requirements

Many decisions should be taken to determine a sufficient number of vehicles required to ensure that all tasks are performed within time. For example, decisions regarding the unit load of AGVs and whether AGVs should carry one or multiple loads. On the one hand, too few AGVs in the system leads to operational deficiencies. On the other hand, too many AGVs in the system lead to more congestion. To determine an optimal balance in AGV fleet size, that yields an economically attractive approach, many factors have to be taken into account. Some factors pinpointed by Vis (2006) are:

- Number of units to be transported;
- Points in time at which units can be or need to be transported;
- Speed of the AGV;
- Costs of the system;
- Layout of the system and guidepath;
- Vehicle dispatching strategies.

A collection of deterministic, stochastic, and simulation models to determine AGV fleet sizes in different type of environments is reported by Vis (2006) and Le-Anh and Koster (2006).

3.1.2.5 Control Policy

AGVs should route efficiently through the facility when executing their transports. Furthermore, AGVs must be able to carry out their transport requests without the occurrence of deadlocks and collisions. Therefore, a policy should be designed that controls the system in an appropriate manner. According to Vis (2006) at least the following activities need to be supported by such a system:

- **Vehicle dispatching**. A dispatching rule denotes a procedure to select a vehicle to execute a transportation demand. A dispatching decision is made when (1) a vehicle drops off a load, (2) a vehicle reaches its parking location, or (3) a new load arrives (Le-Anh and Koster, 2006);
- **Routing and scheduling of AGVs**. The control policy should decide when, where and how a vehicle should act to perform tasks, including the route it should take (Le-Anh and Koster, 2006). In the book from Fazlollahtabar and Saidi-Mehrabad (2015b) a series of papers are presented in which scheduling and routing models for AGVs are discussed;
- **Positioning of idle vehicles**. Vehicle idleness is unavoidable in AGV systems. When an AGV is idle, it can park at a free park location.

Dispatching, routing, scheduling, and positioning of idle vehicles can be decided simultaneously or separately, and offline or online. If all tasks are known prior to the planning period, the scheduling problem can be solved offline (Le-Anh and Koster, 2006). However, in practice, environments are usually stochastic (e.g., temporarily closed or blocked roads, change in driving times, AGV failures, fluctuation in loading and unloading times, etc.). Consequently, an event may impact the offline schedule such that its performance drastically decreases or even turn infeasible. Alternative control policies are online scheduling or dispatching approaches. Attention is given to these type of approaches in Section 3.2, where we also discuss the so-called pick-up and delivery problem with time windows (PDPTW). The PDPTW is similar to the problem studied in this thesis, and covers constructing routes such that transportation requests requiring pick-up and delivery are met.

3.1.2.6 Battery Management

AGVs have a limited battery capacity and therefore have to charge their battery at the available charging stations. McHaney (1995) presents an overview of three types of charging schemes:

1. **Automatic charging**. An AGV recharges when its available energy reaches a certain level and then the scheduler assigns this AGV for charging.
2. **Opportunity charging**. The AGV follows a pre-defined battery charge plan and uses the natural idle time in an AGV's cycle to replenish batteries.
3. **Combination system**, which is a combination of the previous two schemes.

Other technical options are suggested in the literature as well. For example, Ebben (2001) developed control rules to take battery constraints into account. Besides various battery replenishment strategies, Ebben (2001) conducted a simulation study to compare the performance and costs for systems in which batteries are charged during traveling (via charge-rials) and systems where batteries are replaced (battery swaps).

3.1.2.7 Failure Management

Until now, limited attention is given in the literature about the impact of equipment failures on the AGV system. Vis (2006) suggests that in case only a few AGVs are used, failures have little effect on the occurrence of congestion in the system and that in case a large number of AGVs are used, congestion may occur more often. We argue that it is debatable whether and to which degree AGV failures effect the occurrence of congestion in environments. Once the system is relatively small with a few AGVs, the failure of only a couple of AGVs could already affect the occurrence of congestion and deadlocks significantly. Considering a relatively large system, one could argue that there is more slack in dealing effectively with congestions and deadlocks. Nevertheless, counter arguments may be given as well.

3.1.3 Selection of an AGV System Design Approach

Recall from the previous subsection that designing an AGV system is a complicated process which involves a myriad number of decision variables. As addressed in the previous subsection, there are many interdependencies and interactions between and even within the design stages. Since we start almost completely from scratch, a thorough AGV system design methodology is desirable in which the design elements are combined.

As discussed in the previous subsection, the survey of Vis (2006) covers tactical and operational elements that have to be addressed when building an AGV system. However, this survey does not include a structural approach for developing an AGV system that can be easily followed. Many other papers are concentrated on limited parts of the designing problem only. For example, on approaches to construct design guide-path networks (e.g., Lim et al., 2002; Ko and Egbelu, 2003), conflict-free routes (e.g., Sarker and Gurav, 2005; Guan and Dai, 2009; Ho and Liao, 2009), or scheduling or routing issues (e.g., Langevin, Lauzon, and Riopel, 1996a; Qiu et al., 2002; Duinkerken, Ottjes, and Lodewijks, 2006; Corréa, Langevin, and Rousseau, 2007; Singh, Sarngadharan, and Pal, 2011). Le-Anh and Koster (2006) proposed a decision framework for the design and implementation of AGV systems. This framework, as shown in Figure 3.2, provides a holistic approach that depicts interdependencies among design problems adequately. Furthermore, it sketches boundaries of an AGV system and includes a hierarchical structure. Decisions at a higher level set the boundaries for decisions at a lower hierarchical level. The hierarchical structure is particularly applicable to the purpose of our thesis, since the aim of our thesis (see Subsection 1.3.2) is to develop a decision support model for, on the one hand, operational planning and control of AGVs, and, on the other hand, an evaluation model about the impact of more tactically and strategically framed decisions. For these reasons, we choose to use the framework from Le-Anh and Koster (2006) as a guideline for the design of the AGV system. Papers that address individual or multiple design problems are of importance as well and will be used to complement the framework if necessary.

The design process of the AGV control system, as discussed by Le-Anh and Koster (2006), starts with establishing the system requirements and gathering input data, such as facility layout, P/D locations, material flows, load characteristics, and type of vehicles and guidance. The first step is designing the guide-path system, which takes place at the strategic level. After this, design issues on a tactical level are considered, which include estimating the number of required vehicles, determining the vehicle scheduling approach, deciding the parking policy, and decisions regarding battery management. On the tactical level, decisions influence each other and should be considered simultaneously. Also, tactical decisions may influence the guide-path design decisions (represented by dashed arrows in Figure 3.2). Arrows in the framework indicate interdependencies between decisions and represent a strong influence (thick arrow), less strong influence (thin arrow) or possible less strong influence (dash arrow). At an operational level, decisions are made with regards to guiding vehicles in a conflict-free way to their destination.

Section 3.5 describes how the AGV control and design framework can be combined within the design approach used in this thesis. In the model design chapter (Chapter 4), arguments are given for appropriate design approaches with respect to the used framework.

3.1.4 Conclusion

This subsection covered the scope of AGV control and design approaches that are potentially applicable to our research. We first took a wide perspective, introducing AGV terminology. An AGV

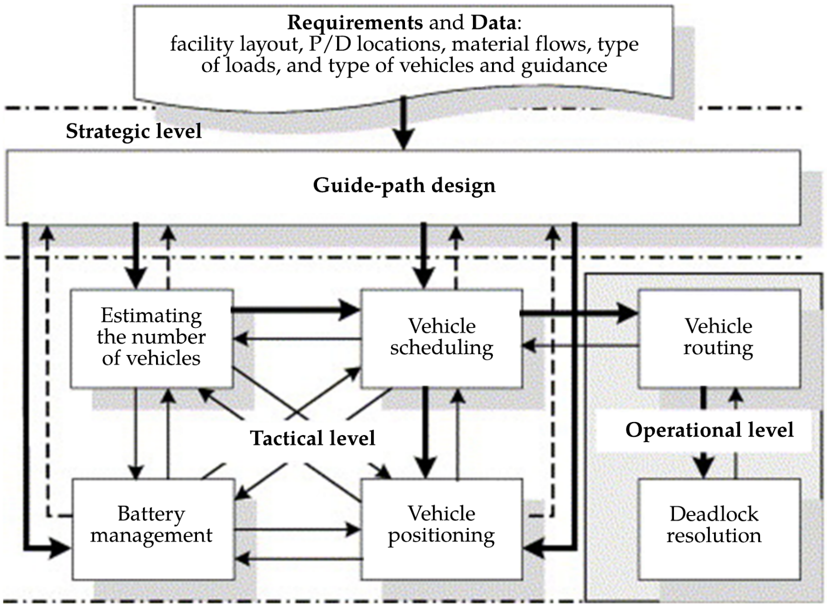


FIGURE 3.2: Decision Framework for Design and Control of an AGV System (Le-Anh and Koster, 2006).

system's main purpose is to manage the execution of transport tasks. Afterward, we confined ourselves to design and control methodologies of AGV systems. The process of designing an AGV system is complicated since the impact of decisions on mutual interactions cannot be considered separately and might be difficult to predict. Finally, we concluded that in this thesis a comprehensive approach will be followed in which the design issues are tackled. The framework as proposed by Le-Anh and Koster (2006) will be used to guide us through the AGV system design.

3.2 Dynamic Scheduling in Manufacturing Environments

This section provides an overview of dynamic scheduling approaches in manufacturing environments. Dynamic scheduling is introduced in Subsection 3.2.1. Next, Subsection 3.2.2 gives a classification of dynamic scheduling techniques and designates various solution techniques used to solve dynamic scheduling problems. Subsection 3.2.3 continues with providing an introduction to the so-called pick-up and delivery problem with time windows (PDPTW), as our problem is well known in the area of vehicle routing problems (VRPs). In the light of the PDPTW introduction and the problem context as discussed in Chapter 2, Subsection 3.2.4 compares solution approaches and addresses suitable approaches within this thesis. Subsection 3.2.5 concludes this section.

Notice that in the context of this section, key references are the extensive literature studies as reported in Ouelhadj (2003), Ouelhadj and Petrovic (2009) and Chaari et al. (2014).

3.2.1 Terminology

Companies are facing increasingly complex challenges nowadays. These challenges often comprise decision-making within complex environments. In transportation, production, and distribution environments as well as service industries, scheduling plays an important role in supporting the decision-making process. Scheduling is the process of deciding what happens, when, and where (Parunak, 1991). Commonly, scheduling is defined as the allocation of resources to tasks over time periods and its goal is to optimize one or more objectives (Pinedo, 2012). Static scheduling approaches implicitly assume a static environment without failures of any kind. For literature reviews on static scheduling we refer to Jain and Meeran (1999), Pinedo (2008), Pinedo (2012), and Pinedo (2016).

Manufacturing and production environments have to deal with rapidly changing and often unpredictable real-time events. Rescheduling plays an important role in such environments, as real-time events may cause a significant change in scheduled plans and may render them infeasible or inefficient. The dynamic nature of the aluminium production process is subject to various disruptions and together with the complexity of the process itself, finding coherent schedules is a challenging process. In addition, technological advances in this capital and energy intensive industry underline the importance of effective planning and scheduling. For the successful implementation of real-world scheduling systems, it is desirable to invoke real-time rescheduling in which the schedule modifications are executed concurrently with production.

Dynamic scheduling can be defined as the process of rescheduling or updating an existing production schedule in response to disruptions (Vieira, Herrmann, and Lin, 2003). Disruptions that could occur, denoted as real-time events, could be categorized into roughly two directions (Ouelhadj and Petrovic, 2009):

- **Resource-related:** machine breakdown, operator illness, unavailability or tool failures, loading limits, delay in the arrival or shortage of materials, defective material (material with wrong specification), etc.
- **Job-related:** rush jobs, job cancellation, due date changes, early or late arrival jobs, change in job priority, changes in job processing time, etc.

Notice that a resource that becomes available or a job that has just arrived is also an event that could affect the schedule. Depending on definitions and used algorithms, a distinction can be made, for example, between predictable and less predictable events. In the next subsection, we will outline several classification schemes for scheduling approaches.

3.2.2 Dynamic Scheduling Techniques

The typology discussed by Ouelhadj and Petrovic (2009) provides appropriate guidelines for the organization and categorization of dynamic scheduling in manufacturing systems in the literature. The paper gives a comprehensive typology, integrating the various kinds of dynamic scheduling problems in manufacturing systems as they appear in the literature. They categorized dynamic scheduling approaches in three divisions (see Figure 3.3): completely reactive scheduling, predictive-reactive scheduling, and robust pro-active scheduling. Although Ouelhadj and Petrovic (2009) exhaustively covered the existing literature at that time, the classification scheme used in this study might be outdated and may not encompass new kind of scheduling algorithms. Chaari et al. (2014) proposed an improved classification scheme as shown in Figure 3.4. Their classification is more general and constructed independently of problems and domains. Chaari et al. (2014) classify scheduling approaches in the three main directions: proactive, reactive or hybrid. Hybrid approaches can be separated in proactive-reactive and predictive-reactive approaches. The difference with the classification scheme from Ouelhadj and Petrovic (2009) is that Chaari et al. (2014) identifies pro-active reactive approaches as well. We will now briefly discuss the classification of Chaari et al. (2014).

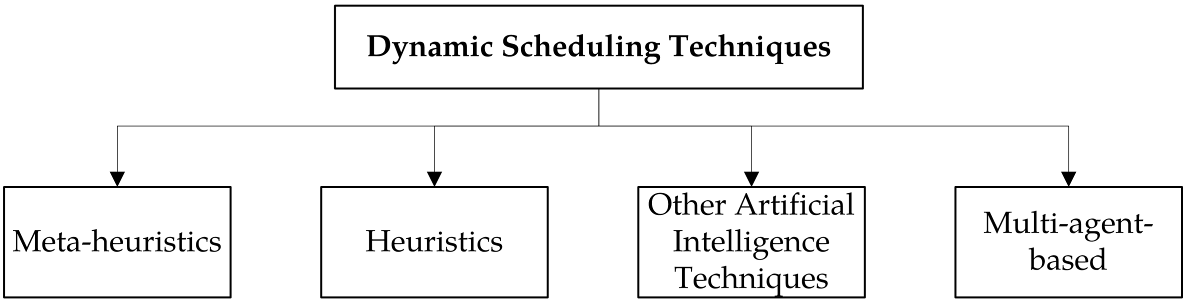


FIGURE 3.3: Dynamic Scheduling Categorization, as report by Ouelhadj and Petrovic (2009).

3.2.2.1 Pro-active Scheduling

Pro-active scheduling is the process of constructing predictive schedules which satisfy performance requirements predictably in a dynamic environment (Ouelhadj and Petrovic, 2009). The determination of predictability measures is often seen as a complicated task. Proactive (also known as robust) scheduling approaches take uncertainty, such as disruptive events, into account when designing

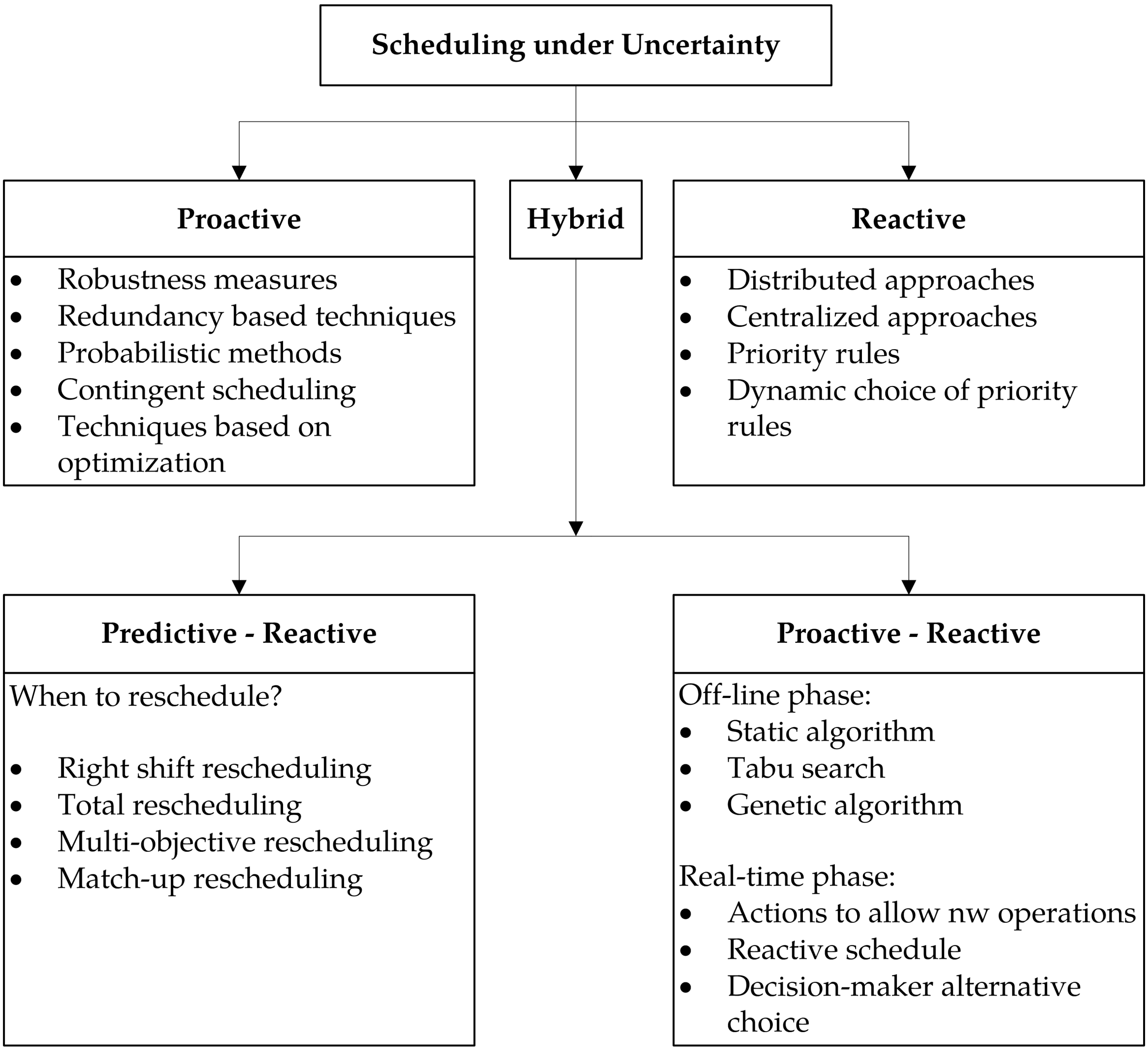


FIGURE 3.4: Approaches for Scheduling under Uncertainty, as report by Chaari et al. (2014).

schedules (Chaari et al., 2014). During the generation of the initial schedule, possible future disruptions are taken into consideration. Proactive approaches attempt to construct a schedule (or a series of schedules) that is relatively insensitive to uncertainty.

As shown in Figure 3.4, proactive scheduling techniques can be further classified in five solution approaches. For now, we refer the reader to consult the survey of Chaari et al. (2014) for more details about these solution methods.

3.2.2.2 Reactive Scheduling

According to Ouelhadj and Petrovic (2009), in reactive scheduling no firm schedule is generated in advance and decisions are made locally in real-time. Reactive scheduling approaches are often used in highly perturbed environments, where the uncertainties are both frequent and large (Chaari et al., 2014). In most practical environments, scheduling is an ongoing process where evolving and changing circumstances continually force reconsideration and revision of pre-established schedules. A frequently used approach in reactive scheduling is using dispatching rules. A dispatching rule is a rule used to select a vehicle to execute a transportation task. Basically, dispatching rules can be divided into two categories, namely *workcentre initiated dispatching* and *vehicle initiated dispatching* (Egbelu and Tanchoco, 1984). A workcentre is a station that requires and provides goods to be transported. When a workcentre initiated dispatching rule is used, a vehicle has to be selected from a set of idle vehicles to transport a load. So, when a load becomes available for transport, the tasks is assigned to an idling vehicle. In vehicle initiated dispatching rules, an idling AGV selects a load from a set of transportation jobs. Dispatching rule selects the next job or vehicle with the highest priority based on dispatching heuristics.

3.2.2.3 Predictive-reactive Scheduling

Predictive-reactive scheduling approaches are often referred in the literature to support risk (Chaari et al., 2014). Predictive-reactive is a process in which schedules are revised in response to real-time events. Ouelhadj and Petrovic (2009) state that most of the predictive-reactive scheduling strategies are based on simple schedule adjustments which consider only shop efficiency. Usually, predictive-reactive approaches consist of two phases (Chaari et al., 2014):

1. Constructing a deterministic offline schedule. For this schedule predictable events are considered. For example, the jobs which are to be scheduled are all available initially and process times are known and deterministic.
2. Online adaption of the schedule. When disturbances occur during execution, the predictive schedule is adapted in real-time.

Ouelhadj and Petrovic (2009) argue that it is important to generate these schedules robustly. A new schedule may namely deviate significantly from the original schedule and affect the performance tremendously since other planning activities are based on this original schedule. Schedules can be repaired locally or a complete reschedule strategy can be followed to react to the real-time events.

3.2.2.4 Proactive-reactive Scheduling

In proactive-reactive scheduling approaches, no online scheduling is done (Chaari et al., 2014). Instead, one out of many pre-established schedule solutions is chosen. Proactive-reactive scheduling approaches are able to built a set of static schedules of which one schedule can be selected that is (the most) suitable in case of certain real-time events. An example of a scheduling approach that can be used in a proactive-reactive setting, is the genetic algorithm. Genetic algorithms generate solutions based on perturbations (e.g., mutations) to a set of solutions. Suppose one generates a set of solutions with this algorithm based on a certain event that is expected to occur soon. Once the event occurs, the decision-maker selects an appropriate solution out of the offline generated solution set.

3.2.2.5 Combination of Scheduling Techniques

Combinations of techniques are gaining increasing interest. Wu, Brown, and Beck (2009) combine a proactive approach with a reactive approach to deal with the precedence of uncertain events. The proactive method constructs a robust baseline schedule with built-in flexibility used for the reactive scheduling approach.

3.2.3 Pick-up and Delivery Problem with Time Windows

The transportation problem, as addressed in Chapter 2, concerns a pickup and delivery problem with time-windows (PDPTW). PDPTW is part of the dynamic scheduling approach this thesis attempts to provides an answer for. Below, we first provide a brief introduction into the PDPTW. After which we consecutively discuss common applications, characteristics, and solution approaches.

3.2.3.1 PDPTW Introduction

An extensive number of publications are available that cover the PDPTW. In the PDPTW, transportation jobs are defined by a pickup location, a delivery location, and time-window restrictions at the pickup location and/or the delivery location (Cordeau et al., 2007). PDPTW is a problem in the field of combinatorial optimization and is a generalization of the well-known vehicle routing problem with time-windows (VRPTW). The difference between VRPTW and PDPTW is that in the PDPTW, transportation requests do not only have a defined delivery location, but also a pick-up location. This pick-up location typically differs from the depot. Since the PDPTW is a generalization of the VRPTW, it is at least as complex as the latter (Savelsbergh, 1985). Hence, the problem domain belongs to a class of optimization problems that are intrinsically hard to solve. In practical situations where the problem size is large, it is often difficult to find reasonable solutions within a short computational time. As a result, research on PDPTW has mainly concentrated on finding efficient heuristic computational procedures for different variations of the problem. For reviews of the PDPTW literature we refer to Berbeglia et al. (2007), Cordeau et al. (2007), Berbeglia, Cordeau, and Laporte (2010), and Pillac et al. (2013).

In contrast to their static counterparts, dynamic variants of the PDPTW involve the aspect that some if the input data are revealed or updated during the period of time in which operations take place. Dynamic routing problems require making decisions in an online approach, which often compromises reactiveness with decision quality (Pillac et al., 2013). In other words, computational time invested in finding a better solution comes at the price of a lower reactiveness to input changes. A frequently studied variant of the dynamic PDPTW is the so-called dial-a-ride problem (DARP). DARP consist of constructing vehicle routes and schedules for users who specify pick-up and delivery requests between origins and destinations. The goal of DARP is to develop a set of minimum cost vehicle routes, under a set of (service level) constraints. A commonly used example is door-to-door transportation for eldery or disabled people. A recent survey dedicated to the DARP can be found in Berbeglia, Cordeau, and Laporte (2010).

3.2.3.2 PDPTW Applications

The PDPTW has numerous applications in operational planning problems. Common examples are freight transportation, maritime shipping, urban courier services, and door-to-door passenger transport (Battarra, Cordeau, and Iori, 2014). PDPTW situations arise when vehicles must travel to a variety of places to deliver and/or pick-up goods, or to provide services. We refer to the literature surveys as discussed in this section for a variety of other examples.

3.2.3.3 PDPTW Characteristics

The PDPTW is concerned with determining a set of routes and corresponding schedules for a fleet of vehicles in order to serve these transportation requests (Savelsbergh, 1985). A solution consists of an ordered sequence of locations for each vehicle route (routing) and the arrival and departure times for all locations of each route (scheduling). The scheduling problem in an AGV system is similar to the PDPTW. However, the AGV system has some properties differing from the PDPTW, such as a higher traffic density, higher routing variation, shorter planning horizon due to stochastic arrivals, and battery charging issues (Le-Anh and Koster, 2006).

In literature, a wide variety of objective functions is presented. Also, solution approaches are typically subject to a set of constraints such as that each route starts at the corresponding vehicle's embarking position and that all time windows should be satisfied (e.g., see Liakos, Angelidis, and Delis, 2016). Examples of objective functions related to single- or multiple vehicles involved pick-up and delivery problems are (Savelsbergh and Sol, 1995):

- Minimize duration;
- Minimize completion time;
- Minimize travel time;
- Minimize route length;
- Minimize client inconvenience;
- Minimize the number of vehicles;
- Multiple objectives in an profit function.

3.2.3.4 Dynamic Scheduling Solution Approaches

Several formulations and solution approaches are proposed in literature for the PDPTW (e.g., see Ropke and Pisinger, 2006; Bianchessi and Righini, 2007; Ropke, Cordeau, and Laporte, 2007; Parragh, Doerner, and Hartl, 2008; Baldacci, Bartolini, and Mingozzi, 2011; Toth and Vigo, 2014). The reader is referred to the work of Berbeglia et al. (2007), Cordeau et al. (2007), and Toth and Vigo (2014), which exhaustively review solution approaches to variants of the PDPTW.

In addition to these surveys, there are some literature reviews carried out specifically aimed at AGV scheduling and routing problems (e.g., see Qiu et al., 2002; Fazlollahtabar and Saidi-Mehrabad, 2015a). These studies discuss different approaches to optimize AGV systems for scheduling and routing problems at manufacturing, distribution, transshipment, and transportation systems. Fazlollahtabar and Saidi-Mehrabad (2015a) categorize related literature to different methodologies based on (1) scheduling and (2) routing. Within this categorization, the authors distinguish the following optimization techniques (see Figure 3.5): mathematical methods (exact and heuristics), simulation studies, meta-heuristics and artificial intelligent approaches.

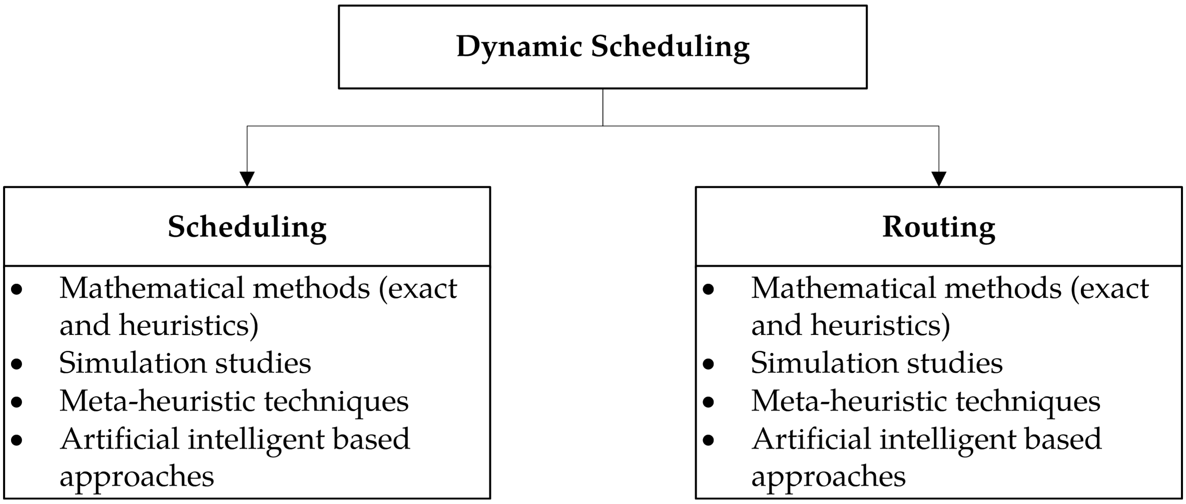


FIGURE 3.5: Dynamic Scheduling Classification Framework. Adapted from Fazlollahtabar and Saidi-Mehrabad (2015a).

Various models concerning the scheduling and routing of AGV systems in these environments are addressed. For example, Nishi, Hiranaka, and Grossmann (2011) proposed a bilevel decomposition algorithm for solving simultaneous scheduling and conflict-free routing problems for AGVs. Taghaboni-Dutta and Tanchoco (1995) developed a dynamic routing approach to route AGVs in both unidirectional and bidirectional path networks. However, their algorithm may not yield an optimal route and correctly predict the delays in some cases. Langevin, Lauzon, and Riopel (1996b) propose a dynamic programming approach that results in an optimal integrated solution for planning the dispatching, conflict-free routing, and scheduling of AGVs in a manufacturing system. Even with a relative small number of AGVs in the system the number of possible states could explode and therefore additional effort has to be made, to achieve a good solution within an acceptable time. Qiu and Hsu (2001) proposed an algorithm to route large number of AGVs in a conflict-free manner over a bidirectional guidepath while minimizing travel times. Limited literature focuses on approaches to detect and recover from deadlocks, which are causes by the interaction between the AGV system and other handling equipment. However, Lehmann, Grunow, and Günther (2006) studied two different methods for the detection in an automated container terminal where resources are affected by blocking situations. Furthermore, they presented three different procedures to resolve deadlock situations. These resolutions aim to modify the sequence of handling operations or to assign them to alternative resources to resolve conflicts between concurrent processes.

In a broader sense several techniques can be identified to solve dynamic scheduling problems. Ouelhadj and Petrovic (2009) discusses several approaches used to solve dynamic scheduling problems (see Figure 3.3): heuristics, meta-heuristics, multi-agent-based techniques, and other artificial intelligence techniques. *Heuristics* do not guarantee to find an optimal schedule, but have the ability to find reasonably good solutions in a relative short time (Ouelhadj and Petrovic, 2009). *Meta-heuristics* are high level heuristics which guide local search heuristics to escape from local optima. Examples are tabu search, simulated annealing and genetic algorithms. Ouelhadj and Petrovic (2009) state that limited research has been carried out that apply a meta-heuristic as dynamic scheduling approach. *Multi-agent-based scheduling approaches* apply the technology as discussed in Section 3.3 to solve scheduling problems. A collection of other approaches are classified as *artificial intelligence techniques*. Examples of these techniques are (Ouelhadj and Petrovic, 2009): knowledge-based systems, neural networks, case-based reasoning, fuzzy logic, Petri nets, etc.

3.2.4 Comparison of Dynamic Scheduling Solution Techniques

There is a large variety of possible solution techniques that could be applicable to our case. PDPTW is well-studied in the literature and an appropriate solution approach should be used during the model design phase. It is important to not exclude important solution techniques beforehand because this could potentially undermine the quality of the solution approach. Moreover, the dynamic scheduling approach must be appropriately positioned within the methodologies used for the AGV control (Section 3.1) and Multi-agent System (Section 3.3). For these reasons, we demarcate the scope of solution techniques further in Section 3.5 and ultimately select appropriate approaches during the model design phase (Chapter 4).

3.2.5 Conclusion

Dynamic scheduling is the process of rescheduling or updating an existing production schedule in response to disruptions. These disruptions are events that could occur in manufacturing environments, such as machine breakdowns or task arrivals. Dynamic scheduling approaches can be classified into three major directions: proactive, reactive and hybrid. Hybrid approaches cover predictive-reactive and proactive-reactive scheduling techniques. The scheduling and routing problem concerned with our thesis is known in the literature as the pickup and delivery problem with time windows (PDPTW). This thesis requires a solution approach that handles real-time events in the highly dynamic environment of primary aluminium manufacturing. Depending on the overall solution methodology followed within this thesis, a comprehensive approach is required in which appropriate dynamic scheduling techniques are applied.

3.3 Multi-agent Systems

This section provides an introduction to Multi-agent Systems (MAS). Subsection 3.3.1 introduces MAS. We highlight some applications of MAS in Subsection 3.3.2, with a focus on applications related to the subject of this thesis. In Subsection 3.3.3, we provide arguments for using MAS as part of this thesis and discuss some alternatives. Subsection 3.3.4 describes methodologies to support the development of MAS. We also address some of the pitfalls associated with agent-oriented development in that section. Based on this review, we determine the methodology we use for developing our MAS. Subsection 3.3.5 concludes this section.

3.3.1 Terminology

We commence with introducing MAS by discussing its origin. After that, we provide definitions and characteristics of MAS.

3.3.1.1 Emergence of Multi-agent Systems

Multi-agent Systems (MAS) have seen a growing number of applications in the last few years and is yet to receive intense attention from practitioners. Although MAS is a relative young research area, the paradigm of MAS has been studied as a field in their own right since about 1980. This field gained widespread recognition in the mid-1990s and consequently contributed to the emergence of research, design, modeling, analysis and programming fields of MAS. The field of MAS is nowadays highly interdisciplinary. Despite this rapid development of MAS to date, there are five continuing trends observable in computer science that contributed to this (Wooldridge, 2009):

- ubiquity;
- interconnection;
- intelligence;
- delegation;
- human-orientation.

Wooldridge (2009) describes *ubiquity* as introducing processing power into places and devices where it would have been uneconomic or unimaginable until now, due to a continual reduction in cost of computational capabilities. These advancements of computational power lead to new and innovative applications, and drives society to an omnipresence of technology. An example that enhances this omnipresence is the availability of data at increasing levels of granularity, as we see with large open-data projects.

Nowadays, computer systems are *interconnected* and collaborate and exchange information through large distributed systems (Wooldridge, 2009). The growth of the internet and modernized distribution networks such as internet-of-things are observable means of this phenomena. The increasing large-scale interconnections provide new technological opportunities for both practitioners and academics.

The trend of being capable of automating and delegating complex tasks to computers has grown steadily (Wooldridge, 2009). This increasing *intelligence* of systems allows us to better understand the way computer systems are capable of performing tasks in this increasingly complex world. Systems that we analyze and model are becoming more complex in terms of their interdependencies (for instance among infrastructures such as the power grid). In the earlier years, many assumptions were often made to analytically and computationally cope with the complexity of problems. Our increased understanding provides opportunities to relax assumptions and therefore make a more realistic view of occurring problems (Macal and North, 2005).

The fourth trend Wooldridge (2009) highlights, is the increasing *delegation* to computer systems. Delegation implies that we give control rather to computer systems instead of performing it by ourselves. An example is climate control software, which acts on behalf of the user in order to manage conditions within an environment (e.g., car, house, swimming pool, etc.).

Lastly, Wooldridge (2009) hints on the trend of moving towards concepts and metaphors that more closely reflect the human-interaction with computers instead of a machine-oriented view. In the early days, computer developers and programmers had to conceptualize and implement software in terms of low-level - more machine-oriented - abstractions (e.g., raw machine codes, no graphical user interface, etc.). We nowadays grow towards a more *human-oriented* perspective with high-level abstractions (e.g., object-oriented programming, abstract data types, etc.).

The five discussed trends have contributed to the emergence of a relatively new approach to deal with our increasingly complex world: MAS. For a more extensive elaboration about the emergence of MAS, we refer to Jennings, Sycara, and Wooldridge (1998) and Wooldridge (2009).

3.3.1.2 Definitions and Characteristics

We first define agents and a multi-agent systems. After that, we give characteristics of agents. Finally, we briefly discuss control perspectives of a MAS.

Agents
Basically, an agent can be described as a computer system (piece of software) that is situated in some environment, and that is capable of independent action in this environment in order to meet its design objectives (Wooldridge and Jennings, 1995a). This autonomous action can be fulfilled on behalf of its user or owner.

Multi-agent System
MAS can be described as a group of intelligent agents which coordinate and plan their capacities in order to achieve (local or global) goals (Wooldridge, 1999). Agents are dependent on each other and require agent interaction. In order for those agents to successfully interact, they require the ability to: *cooperate* (working together to achieve a common objective), *coordinate* (arranging for related activities to be performed in a coherent manner), and *negotiate* with each other (a process by which a group of agents comes to a mutually acceptable agreement on some matter) (Jennings et al., 2001).

Discussion of Definitions
Although several authors (e.g., see Bankes, 2002; Leitão, 2009; Macal and North, 2010; Niazi and Hussain, 2011) indicate that there is some debate among researchers about the exact definition of agents and closely related terminologies, such as agent-based modeling, the concept of an agent is already quite established. We suspect that differences in definitions are likely to be caused by the evolution of agents in a broad base of application domains (e.g., biology, social sciences, network theory, etc.). For the purpose of this thesis, we use the definitions of Wooldridge and Jennings (1995a) and Wooldridge

(1999) as mentioned above. Therefore, we do not further elaborate in this thesis, upon possible confusion regarding the exact semantics of various terms used in literature.

Agent Characteristics
The capabilities that we can expect from intelligent agents are (Wooldridge and Jennings, 1995b):

- **Reactive**. Intelligent agents should be able to perceive their environment, and respond in a timely fashion to changes that occur in it in order to satisfy their design objectives;
- **Proactive**. Intelligent agents should be able to exhibit goal-directed behavior by taking the initiative in order to satisfy their design objectives;
- **Social ability**. Intelligent agents should be capable of interacting with other agents (and possibly humans) in order to satisfy their design objectives.

In addition to the characteristics of agents as pointed out above, we can address three other characteristics which are of importance later on:

- **Situated**. Agents exists in a challenging environment and should be able to act based on dynamic, unpredictable and unreliable behavior (Padgham and Winikoff, 2005).
- **Robust**. Agents should be able to recover from failure of actions or plans (Padgham and Winikoff, 2005). Robustness can be achieved to be flexible such that there are multiple ways of achieving goals.
- **Flexible**. Agent design and architecture should consider different environmental states and act appropriately in different situations (Farahvash and Boucher, 2004). By having a range of ways of achieving a given goal, the agent has alternatives that can be used in case an action or plan fails (Padgham and Winikoff, 2005).

Centralized versus Decentralized Control System
There are two extreme system control perspectives: fully centralized and fully decentralized. In a *centralized* approach, a global system (or agent) computes the actions for all other agents. This agent also handles the task allocation and coordination of agents. Agents need to share information with the system in order to achieve a good overall performance. A disadvantage of this approach is that computing the overall best solution usually takes a tremendous amount of time (Dewan and Joshi, 2000). Also, the solution quality will degrade with an increasing problem size. Moreover, as discussed by Nwana (1996) and Ferber (1999), this centralized approach is contrary to the assumptions of MAS. It namely presumes that one entity has a global view of the entire agency in many domains, which is an unrealistic assumption.

In a *decentralized* approach, which is often used in a MAS, each agent acts on its own and has incomplete information or capabilities for solving the problem (Jennings, Sycara, and Wooldridge, 1998). Thus each agent has limited viewpoints. Generally speaking: data are decentralized, there is no global system control, and computation is asynchronous. An advantage of decentralized control over centralized control is that there is limited communication between the agents and system controllers. This results in lower computational requirements and faster control. However, this advantage will typically lead to a decreased overall system performance in comparison to using a completely centralized control system. For an extensive overview of pros and cons of centralized versus decentralized control approaches, we refer to Ong (2003) and Leitão (2009).

Notice that there are also system approaches possible with a partly decentralized system control, where some cooperation, communication, and perhaps negotiation among control agents may take place.

3.3.2 Applications of Multi-agent Systems

Agents have nowadays found applications in numerous different domains. Agent technology can, for instance, be found in workflow and business process management, information retrieval and management, and e-commerce (Wooldridge, 2009). We see MAS also applied in environments such as air traffic control, taxi agents negotiating taxi rides (e.g., see Seow, Dang, and Lee, 2007), simulating panicky crowds to test building design safety (e.g., see Ren, Yang, and Jin, 2009), and the gaming and education industry. Application domains that are likely to benefit from MAS are typically characterized by (Sierra, 2004):

- Very fast interactions;

- Interactions are repeated with either (a) high communication overheads, or (b) a limited domain so that learning done by the agent about user behaviour is effective;
- Each trade is of relatively small value;
- The process is repeated over long periods of time;
- The product traded is relatively easy to specify.

Likewise, the characteristics of autonomous, collaborative, and reactive agents are appealing for supply chain networks that can contain millions of interacting intelligent entities that need to be controlled. In supply chains, which consists of many collaborating entities, such as vehicles, machines or distribution centers, and uncertainties, MAS is attractive because agents enable us to tackle a broad class of coordination and negotiation issues (Jiao, You, and Kumar, 2006; Monostori, Váncza, and Kumara, 2006). We mention a few examples of applications in this field. Warehouses and cross docking facilities are examples of distribution areas where MAS can be used (e.g., see Ito and Mousavi Jahan Abadi, 2002; Guizzo, 2008; Gerrits, Mes, and Schuur, 2016). Gambardella, Rizzoli, and Funk (2002) developed a combined rail, road and terminal transport planning system where an agent-based planner organizes transport plans for dispatching intermodal transport units. Their simulation system verifies the feasibility of these plans and measures their performance. Roorda et al. (2010) constructed a conceptual framework for agent-based modeling of logistic services in the freight system. Frayret et al. (2007) and Forget, D'Amours, and Frayret (2008) employ a combination of agent-based modeling and classical operations research tools to develop a decision support tool for supply chain coordination in the forest industry. An agent-based approach for a reliable and flexible AGV system for a bakery, is developed by Mes, Heijden, and Harten (2007). Mes, Heijden, and Harten (2007) used simulation to evaluate several alternative agent architectures. Douma, Hillegersberg, and Schuur (2012) considers an agent-based approach to model the barge handling problem, which is the problem to align barge and terminal operations in a port. They demonstrated their MAS design in the Port of Rotterdam through a distributed planning game. Gath, Herzog, and Edelkamp (2014) demonstrated the usage of agent-technology to optimize the allocation of orders to transport facilities. For more examples of applications of agent-technology, we refer to Uhrmacher and Weyns (2009) and Barbati, Bruno, and Genovese (2012), in which the latter one discusses several contributions in the field of scheduling problems, transportation and logistics, supply chain planning, and other optimization problems are discussed.

MAS applications for AGV systems are emerging in literature as well. A number of articles have appeared in literature that model various types of AGV transportation networks by means of agent-technology. Wallace (2001) uses agent-technology to develop an AGV controller for large complex guide-paths. This study models agents as traffic managers that handle the coordination of AGVs on a guide-path. Erol et al. (2012) uses an agent-approach for scheduling AGVs and machines within a manufacturing system. Their proposed approach works under a real-time environment and generates feasible schedules using negotiation/bidding mechanisms between agents. Bazzan, Amarante, and Da Costa (2012) use an agent-based approach to manage a fleet of automated guided personal rapid transit vehicles. A generic automated planning and control system for pick-up and docking of semi-trailers by means of AGV has been developed by Gerrits, Mes, and Schuur (2016). Their designed agent-based simulation model could be used to evaluate the performance impact when varying the number of AGVs under various scenarios.

Literature studies conducted by Chen and Cheng (2010), and Bazzan and Klügl (2014), discussed that the deployment and applications of agent-based modeling techniques in realistic scenarios where scalability design is of importance, is still a major issue. Bazzan and Klügl (2014) further reports that there are new traffic and transportation challenges rising due to the development of AGVs. However, they state that especially applications of agents in autonomous driving technologies are scarce and most papers still lie on the conceptual model level or are quite restricted prototypes. The issue that most papers stay at the level of a conceptual agent model and sometimes draw conclusions about the (expected) performance of the model without presenting experimental results was already discussed by a survey on existing research on agent-based approaches in transport logistics by Davidsson et al. (2005). A survey conducted by Leitão (2009) about agent-based manufacturing approaches concludes that although approaches and architectures are reported in literature, real implementations are extremely rare in manufacturing systems.

To conclude, we see agent-based technology used more often, especially in environments where uncertainty in decision-making plays an important role. MAS applications of AGV systems are also growing towards a mature level. However, there are still challenges to overcome in the design and control of AGV systems. In this thesis, we contribute to the design and development of a MAS model for planning and control of AGVs in the primary aluminium industry. Our contribution is to show how MAS technology can be used in this environment.

3.3.3 Motivation for using Multi-agent System Technology

Most logistical planning systems are of a centralized nature. Classical (exact and heuristic) optimization techniques dominated for a long time the available approaches to solve different types of decision-making problems. However, centralized approaches face difficulties because of their inability to cope with a high degree of complexity and change, which requires the solution to be robust to disruption and configurable when necessary (Marik and McFarlane, 2005). Marik and McFarlane (2005) specifically mention three possible characteristics that make a centralized approach inappropriate, and hence make an agent-based approach attractive:

- **Centralized solution's (theoretical) infeasibility**. At any time, each possible decision-making node has only a limited part of the information required to make the decision;
- **Impracticality**. Even if all information is potentially available to each decision-making node, practical constraints (e.g., time, costs, and quality) could hinder a centrally based decision;
- **Inadvisability**. Even if centralized decision making is feasible and practical, it might still be inadvisable owing to: (1) a single decision-making node's susceptibility to disruptions, and (2) the complexity of making system reconfigurations and long-term changes under a centralized regime.

Agent-based computing can provide some other advantages of which some we already addressed previously. Advantages include reduced computational times, thanks to their ability to divide problems into several sub-problems, and tend to be preferable when the size of the problem is large, the domain is modular in nature, and the structure of the domain changes frequently (i.e., high changeability) (Davidsson, Persson, and Holmgren, 2007). Furthermore, several comparisons between centralized and agent-based approaches show that a system based on agent-technology outperform centralized approaches in terms of robustness to fluctuations in for example processing times (e.g., see Liu, Gruver, and Kotak, 2002) service levels (e.g., see Mes, Heijden, and Harten, 2007) or demand rates (e.g., see Nourinejad and Roorda, 2016). However, these computational advantages can be offset by several drawbacks by which classical optimization techniques are preferable. Davidsson, Persson, and Holmgren (2007) highlight that when the computational requirements and times are costly and the quality of the solution is important, traditional approaches tend to outperform agent-based approaches. In addition to these drawbacks, the design and implementation of agent-based applications are often inherent to several pitfalls as discussed in, for example Jennings, Sycara, and Wooldridge (1998), Weyns and Holvoet (2008), and Wooldridge (2009).

Approaches based on multi-agent technology should not be seen as a separate artifact. Mes, Heijden, and Harten (2007) and Pokahr et al. (2008) for example, plead to make simulation an integral part of a MAS design in order to compare different alternative designs. This integration allows them to conduct experiments easily. Davidsson, Persson, and Holmgren (2007) discussed that agent-based approaches and optimization techniques can complement each other.

Marik and McFarlane (2005) specifically points out that transportation and material-handling systems typically exhibit one or more of the just described characteristics. Agents can, for example, represent the transportation paths (conveyers, pipelines, automatic guided vehicles, etc.) and their sensing and switching elements (diverters, valves, tag readers, pressure sensors, etc.). Furthermore, the problem characteristics in the field of transportation and material-handling systems tend to closely match those of an ideal MAS, as discussed by Davidsson et al. (2005). One of the early adopters of MAS in a transportation planning problem identified four main reasons why agent technologies are appealing in this area (Fischer, Müller, and Pischel, 1996):

- The domain is inherently distributed. It is natural that trucks and jobs maintain a level of autonomy as agents do have;
- There is a high degree of dynamics in the process of planning (new orders can be given to the system asynchronously) and execution (unforeseen events may occur, such as traffic jams). MAS are capable to act in dynamic environments;
- The task of centrally maintaining and processing information in classical methods for transport planning is complex. Modeling entities as independent and autonomous units seems an acceptable way to proceed;

- The existence of a high level of negotiation and cooperation in performing transportation tasks. Cooperative processes in transportation business, such as task decomposition, task allocation, decentralized planning, and negotiation, could be included in MAS.

We argue that applying an agent-based approach to our problem seems to provide an appealing and promising added value. Dynamic processes within the primary aluminium smelter require rapid decision making by individual entities. The dynamic and interactive nature of aluminium production suits the purpose of MAS technology. Moreover, our problem scope is currently quite limited and consequently, the potential of the system to grow rapidly in terms of adding new features and covering a wider scope could be limited when using solely centralized optimization techniques. A minor extension to the optimization models could already increase the problem size and complexity tremendously and turn the solution infeasible. Although centralized optimization techniques regularly outperform MAS with respect to achieving a better overall solution value, under computation time limitations there is often no guarantee a feasible/optimal solution can be found. Furthermore, the growing number of MAS applications used to model AGVs in production environments indicates that MAS technology is a suitable candidate for the problem comprised in this thesis. In particular, the usage of AGVs requires an adequate communication and cooperation manner to perform the transportation tasks properly. MAS is a suitable candidate in fulfilling this. Lastly, similar studies have been performed in comparable industries such as the steel industry, which suggest that research on MAS reached a high enough level of maturity.

By providing a solution based on agent-technology, the ability to provide a robust and efficient solution with a long-term focus is likely to be achieved. As pointed out previously, several literature studies highlight the rising opportunities to built agent-based applications in realistic scenarios (e.g., see Leitão, 2009; Chen and Cheng, 2010; Bazzan and Klügl, 2014). This thesis further contributes to this line of research.

3.3.4 Multi-agent System Design Methodologies

Designing and building a MAS where multiple agents act simultaneously in the same environment, can be a complicated and iterative process. Agents must be able to react to external changes, caused by the actions of other agents. A clear understanding of the system in terms of functional and non-functional (e.g., reusability, testing, easiness to extend, maintainability, etc.) requirements is critical for the successes of the model. Essential is that our model is generic and thus enables a whole range of potential types of system to be built, by using parametrizations or model extensions. The model's requirements and design decisions partly depend on the real-life test cases in order to satisfactory design the MAS. According to Park and Sugumaran (2005) it is imperative that a systematic analysis and architecture design are developed to create an appropriate agent-based system. As it is not the intention of this thesis to extensively review available MAS design methodologies or to develop a methodology ourselves, we make us of an existing methodology to structurally guide us through the development and implementation of the model. This methodology should not only be able to provide specifications of the system on a high-level, but also detailed (practical) guidelines to explain how to specify, design and build the MAS.

In the remainder of this section, we briefly discuss some of the methodologies used throughout the literature to develop a MAS and advocate the MAS design approach used in this thesis. We restrict ourselves to one of most recent agent-based analysis and design methodology overviews as discussed by Wooldridge (2009). Methodologies for the development of agent-based systems can be broadly originated from two groups:

- methodologies that were developed that extend or adapt existing object-oriented approaches, with agent-oriented features.
- approaches based on knowledge engineering principles or other techniques.

Several methodologies are included in the book from Wooldridge (2009), including AAII, Gaia, Tropos, Prometheus, Agent UML, and Agents in Z. Although there are commonalities between MAS design methods and standard object-oriented methods are able to support a MAS design, many approaches generally lack the essential support for specific agent-oriented functions. For example, the notion of agents to proactively generate actions or dynamically react to changes in their environment is a major problem in many standard object-oriented methodologies. Likewise, not all methodologies include an approach to let agents effectively cooperate and negotiate with other self-interested agents. For a discussion and comparison of agent-oriented methodologies, the interested reader is encouraged to consult the publications describing the various methodologies and the comparisons between methodologies (e.g., see Sturm, Dori, and Shehory, 2003; Bauer and Müller, 2004; Padgham and Winikoff, 2005; Park and Sugumaran, 2005; Tran and Low, 2005; Mes, Heijden, and Hillegersberg, 2008; Wooldridge, 2009). Roughly speaking, most agent-based design methodologies consist of the following steps (Mes, Heijden, and Hillegersberg, 2008):

1. Decomposition of the system into multiple functionalities;
2. Allocation of functionalities to agents;
3. Establishing interaction protocols between agents;
4. Designing the decision-making capabilities of agent.

It appears that the Prometheus methodology (see Figure 3.6) is specifically designed to support the development of agent-based systems, through a rich collection of models and detailed guidelines (Padgham and Winikoff, 2005). Unlike other methods, Prometheus supports the development of intelligent agents, provides "start-to-end" support, evolved out of practical industrial and pedagogical experience, and above all, is detailed and comprehensive. Prometheus offers a set of detailed guidelines that includes examples, heuristics and industrial standards like Unified Modeling Language (UML) sequence diagrams, AUML (itself an extension of UML) and Rational Unified Process (RUP). Furthermore, there is an expressive and usable development tool available, the Prometheus Design Tool (PDT), which enables us to define various models/architectures and to achieve automatic model transformation to a high degree. Besides that, Prometheus has been used commonly in the literature for designing agent-based solutions specifically for AGVs (e.g., see Mes, Heijden, and Hillegersberg, 2008; Erol et al., 2012; Xing et al., 2012; Kaplanoğlu et al., 2015). For these reasons, we select in this thesis the Prometheus methodology and the PDT for designing the MAS.

In short, the Prometheus Method as depicted in Figure 3.6 consists of three phases:

1. The *system specification* phase focuses on identifying the goals and basic functionalities of the system, along with inputs (percepts) and outputs (actions).
2. The *architectural design* phase uses the outputs from the previous phase to determine which agent types the system will contain and how they will interact.
3. The *detailed design* phase looks at the internals of each agent and how it will accomplish its tasks within the overall system (Padgham and Winikoff, 2005).

The last phase is implementation. Padgham and Winikoff (2005) omitted this because its details depend on the chosen implementation platform. Chapter 4 describes the overall structure of the methodology in detail.

3.3.5 Conclusion

This section served three main purposes. First, we introduced MAS and described its characteristics. The concisely conducted literature study indicated the increasing research attention on using agent-technology in the field of transportation and related areas. A number of agent-based applications have already been reported in the literature and different approaches demonstrate the (promising) potential of using agent-based technology. However, MAS applications in the primary aluminium industry are still immature, which underlines the importance as part of our study. Second, we advocated the use of MAS technology as an integral part of this thesis. Finally, we discussed the purpose of using a proper MAS design methodology. We concluded that Prometheus is a practical, comprehensive and easy to understand methodology that will be used in this thesis.

3.4 Operations Research Applications in the Primary Aluminium Industry

Production planning in the primary aluminium industry is a challenging task, due to imbalances among production and fabrication steps comprised. Only a minor mistake, like inferior anode placement and postponed metal tapping, may negatively impact the performance of a potroom. Unexpected variations in the process could result in temporary shutdowns of (parts of) the system (e.g.,

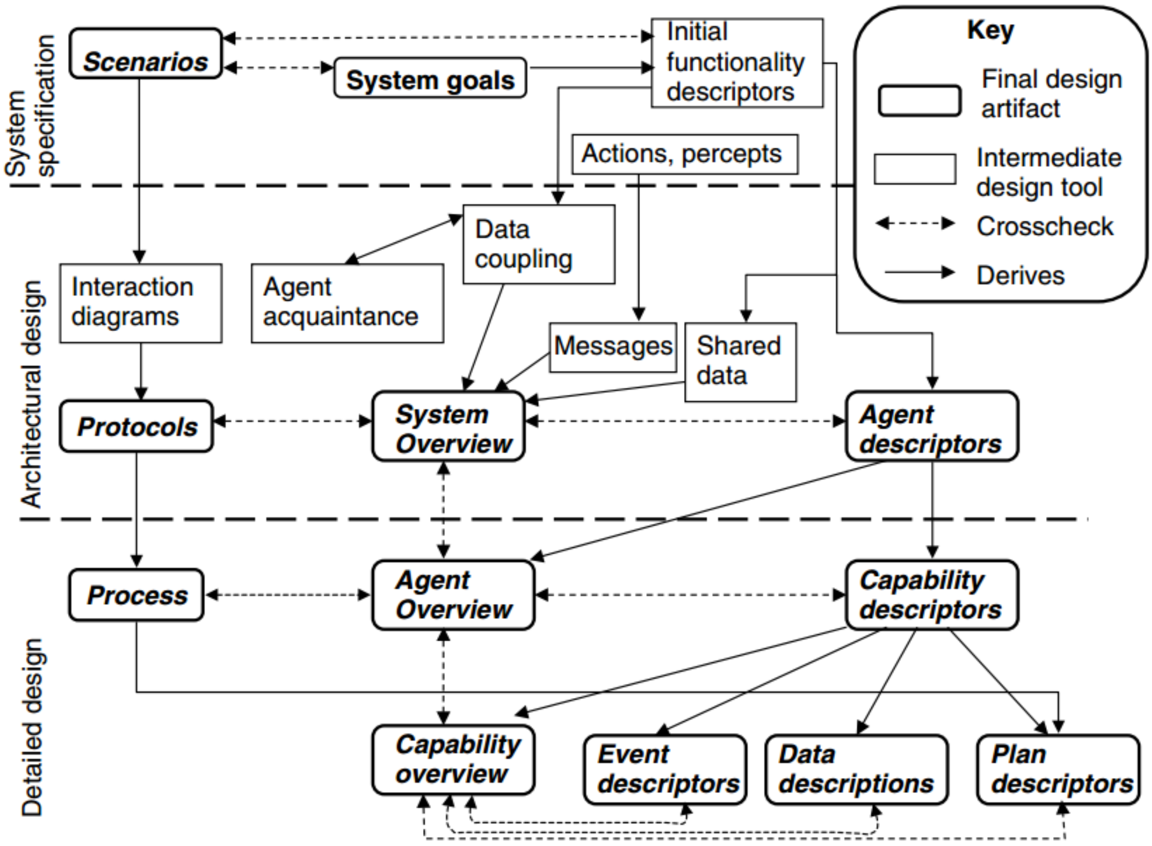


FIGURE 3.6: Prometheus MAS Design Methodology (Padgham and Winikoff, 2005)

disruptive electrolytic-cells) and ultimately negatively impact the throughput to the casthouse. Consequently, it may take a considerable amount of time for a cell to recover from such a disruption and get back to its most productive stage again (Meijer, 2015).

An adequate logistics planning for distributing anodes is essential for stable production in primary aluminium plants. Meijer (2011) highlights that anode changing is an important parameter that influences the stability of a cell and that optimizing this material flow can create a more efficient overall performance and higher productivity of the smelter. Anodes that arrive too early at their destination could lead to stacks blocking the passage for other equipment or bottlenecks, while a delayed anode delivery could affect the electrolytic process that takes place in the cell. Moreover, with the even growing number of cells used in modern smelters (see Figure 3.7), the need for sophisticated applications of analytic methods to help make better decisions regarding logistics planning of anode, is of substantial value. Furthermore, as the aluminium industry is a capital intensive industry, only a marginal improvement with the application of analytic approaches can lead to significant reduction in costs realized by aluminium companies. Thus, improving the decision-making of smelter operations, with a focus on logistics involved in anode changing activities, represents a promising opportunity in reducing process variation and operational expenses.

There is a significant stream of studies taking analytical methods for aluminium smelters into consideration. The Light Metals series (e.g., see Grandfield, 2014; Hyland, 2015; Williams, 2016) contain a collection of articles covering the value chain from bauxite to final products and alloys. Technological advances have contributed to various alternative production and manufacturing processes. Research findings and reviews over the last five decades, in the field of aluminium production and related light metals technologies, are bundled as well (see The Minerals, Metals & Materials Society, 2013). Dutta, Apujani, and Gupta (2016) performed a concise survey of operations research (OR) approaches applied to the aluminium industry. Similar techniques have been studied in other industries such as the steel industry (e.g., see Dutta and Fourer, 2001; Ouelhadj and Petrovic, 2009).

Winkelmann et al. (2016) developed a dynamic discrete-event simulation model to support planning processes in downstream manufacturing processes. They mapped the material flow of rolling mills and extrusion plants by the configuration of generic simulation models. In their models, they

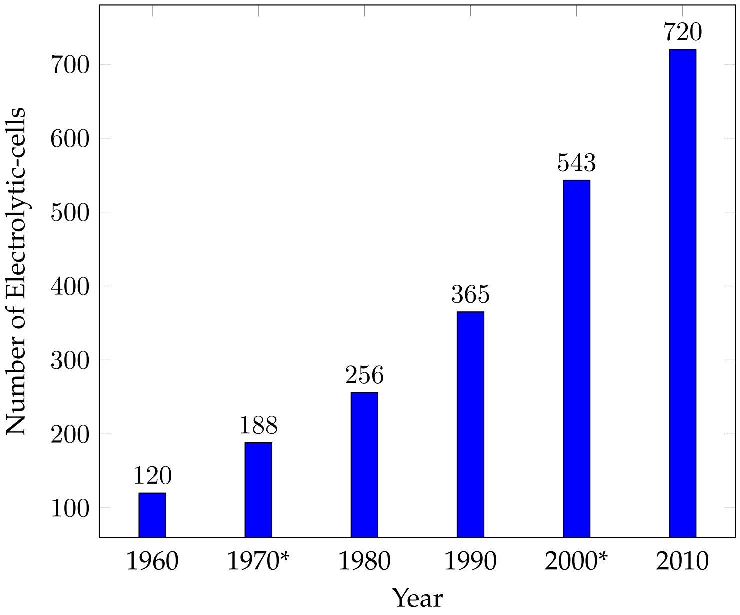


FIGURE 3.7: Typical Number of Electrolytic-cells in Modern Aluminium Smelter Facilities. Adopted from (*Simulating Pot Room Logistics in Aluminium Smelters*). The *-sign indicates that linear interpolation of the depicted direct neighbor years is used to estimate the number.

included handling equipment and production facilities under consideration of process models. Their work mainly differs from ours because we do not focus on operations in the secondary aluminium process (e.g., rolling mills, extrusions plants, etc.). We focus on the primary aluminium process and the anode transportations that is thus limited covered by Winkelmann et al. (2016).

Pablo, Racca, and Bustelo (2012) consider a simulation model to identify the main bottlenecks in the process of liquid aluminium transportation. They analyzed dynamic system behavior, apply heuristics balancing algorithms and validate possible solutions for increasing casting capacity. The focus of their study is investigating the impact of the logistics of liquid metal transportation taking into account a desired production of rods. The difference with our study is that we primarily consider anode transportation instead of liquid aluminium. Eick, Vogelsang, and Behrens (2001) developed a discrete-event simulation model of a smelter based on high-level Petri nets. Their model incorporates features such as operation scheduling, collision detection, and material handling processes. Also, they explicitly modeled the anode and butt transport as part of their Petri net. Although both models presented in Eick, Vogelsang, and Behrens (2001) and Pablo, Racca, and Bustelo (2012) can be used to gather insights into the logistical performance in aluminium smelters, both publications do not focus on the impact of tactical and operational decisions on their anode transportation approach.

Steinrücke (2015) considers a Mixed-Integer Linear Programming (MILP) model of a so-called multi-stage production, shipping, and distribution scheduling problem in the aluminium industry. The used relax-and-fix decomposition method aims to connect the material flows of the adjacent subsystems including bauxites mines, aluminium oxide refineries, and the aluminium smelters. The main distinction with our study is that we provide an operational strategy for determining how to manage the internal logistics in the aluminium smelter and thereby support the material flows on a network-wide scale. Steinrücke (2015) simplified operational decisions made on sites and only considered the planning of production and shipping quantities.

An interesting and closely related line of research comes from Nicholls and co-authors. Nicholls and Hedditch (1993) present an integrated mathematical model of an aluminium smelter incorporating the raw materials feed, carbon bake, rodding, potrooms and ingot mill-areas, including non-linear feedback loops. Besides evaluating the impact of technological, organizational and financial changes, such as capacity variations and electric current variations, on the strategic planning level within an aluminium manufacturing facility, their model takes into account the anode setting cycle. Optimizing the throughput of an ingot mill in an aluminium smelter is discussed by Nicholls (1994). Their MILP model optimizes the throughput under varying percentage time availability of furnaces, troughs, and casters. Other examples can be found in Nicholls (1995a), Nicholls (1995b), Nicholls (1997), Nicholls and Cargill (2008), and Dutta, Apujani, and Gupta (2016). The main differences of our thesis compared to work of Nicholls are: (1) we focus on tactical and operational decisions for the material transport of anodes to support the electrolytic process; and (2) the mathematical models developed by Nicholls are mainly based on a Portland Aluminium Smelter, Australia, while we provide a model that is generically applicable to many modern smelters.

Similar OR applications can be found in other industries. For example, Hamoen and Moens (2002) developed a simulation tool to simulate steel plants. Their tool can be used to assist decisions makers in steel production plants to obtain insights into the influence of lay-out changes, process and speed parameters, length of production runs, and changes in planning and type of products that are being produced. Another example is the modeling and simulation of an engine production logistics distribution system as discussed by Song, Jin, and Tang (2016). Besides that their application domains are differently than ours, their models seem in their infancy in terms of setting up a sophisticated level of detail regarding the scheduling and routing of vehicles.

To conclude, we observed a myriad number of publications involved in the primary aluminium industry. However, a limited number of papers include anode transport. Some research covers activities related to the transport of anodes but the planning and control of inbound logistics are then often given limited attention (Pablo, Racca, and Bustelo, 2012; Dutta, Apujani, and Gupta, 2016). Integral planning approaches are proposed in similar industries. Generally, these approaches cannot easily be applied for the purpose of this thesis because the application domain is different and the transportation tasks are not modeled in sufficient detail.

3.5 Integration of Solution Techniques

The introduction of AGVs to transport anodes requires a thorough approach by which the AGV control system and the Manufacturing Execution System (MES) are interconnected. The new system must be able to respond rapidly to continuously changing circumstances under the presence of multiple manufacturing and execution constraints. Besides that, a model must be developed in this thesis that is able to evaluate the logistical performance of various realistic scenarios. In this section, attention is given to the combination and integration aspects of the methodologies followed within this thesis to establish the aforementioned goals.

We discussed the design of the AGV control system and MAS by appropriate methodologies. This allows us to develop the software architecture of the transportation applications and to obtain the required functionalities of the system. The nature of the problem embodied in this thesis, its interdependencies and the possibility of using autonomous planning entities, lead us to use a multi-agent approach. An agent-based approach allows considering aspects which do not appear in classical PDPTW approaches, such as different strategies of requests acceptation by different vehicles or communication among vehicles. A MAS solution is capable of adapting quickly to changing circumstances and provides an efficient approach to integrating entities of distributed and interactive systems. Moreover, MAS is capable of integrating the AGV control system with the dynamic scheduling approach.

Continuing this line of reasoning, the following overall design methodology, as depicted in Figure 3.8, will be used for the model development. The two fundamental building blocks are the design of the AGV system, whereby the decision framework from Le-Anh and Koster (2006) will be used, and the MAS, that is build based on the Prometheus methodology (see Padgham and Winikoff, 2005). These two fundamentals interact with each other and require information about appropriate dynamic scheduling techniques. Consequently, the conceptual model can be built. This model functions as a blueprint of the evaluation tool and input for the implementation plan. In addition to the conceptual model, the openTCS will be part of the implementation plan as well. Our design approach is inspired by the work of Gerrits, Mes, and Schuur (2016).

3.6 Conclusion

This chapter served five purposes. First, we studied AGV control and design approaches. The framework as discussed by Le-Anh and Koster (2006) will be used to guide us through the design of the AGV system. Second, dynamic scheduling approaches in manufacturing environments were examined. Our problem can be characterized as a PDPTW and requires a solution approach that can operate adequately in a dynamic environment. Third, we discussed that the Prometheus methodology (see Padgham and Winikoff, 2005) will be used to design the MAS. Fourth, we studied closely-related OR applications and advocated the importance of this thesis. Fifth, we presented an overall methodology to guide us through the model development.

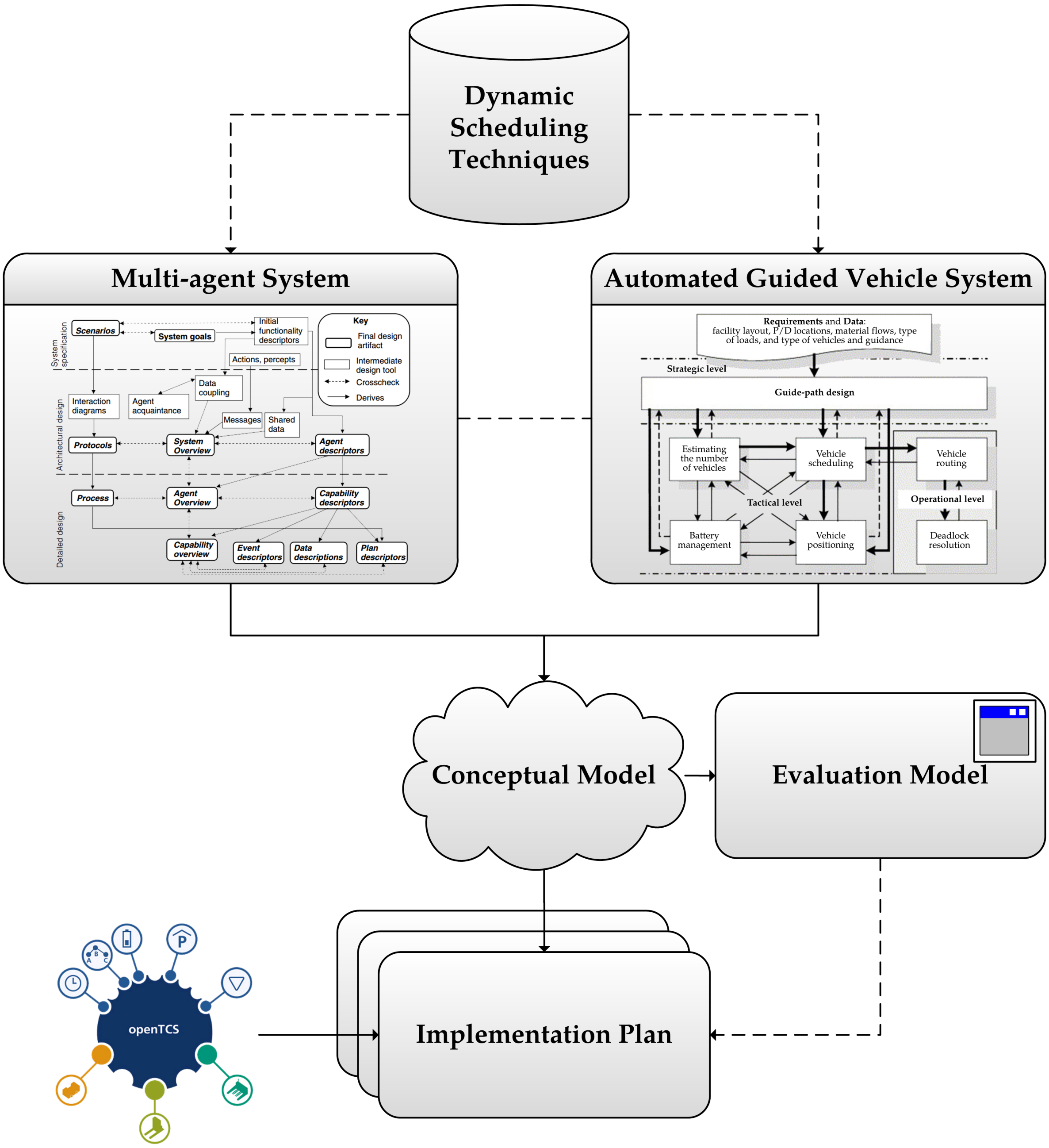


FIGURE 3.8: Overall Model Design Methodology

Chapter 4

Model Design: Multi-agent System

This chapter describes the design of the MAS. The MAS supports the AGV system and functions as a planning and control system. The three phases of the Prometheus methodology (Padgham and Winikoff, 2005), system specification, architectural design, and detailed design, are subsequently described in the subsections below. Intermediate design decisions are advocated in these subsections as well. Finally, Section 7.4 presents concluding remarks.

4.1 System Specification

In the system specification phase, we first describe the system goals in Subsection 4.1.1. Next, Subsection 4.1.2 contains the system functionalities. Then, Subsection 4.1.3 outlines the development of scenarios. After that, Subsection 4.1.4 discusses alternative scenarios. Finally, Subsection 4.1.5 describes the interface description. The process of system specification is conducted in an iterative manner.

4.1.1 System Goals

Systems goals describe on a high level what the system needs to be able to do (Padgham and Winikoff, 2005). Specification of goals, subgoals, and the relationship between those, help in addressing requirements specification and facilitating a mapping into later detailed design and implementation. The following system goal is defined:

System Goal: *A* ***generic planning and control model*** *based on agent technology for the* ***pick-up and delivery*** *of anode buckets in the primary aluminium production. The model must* ***interact with a given metal transport model****, facilitate anode transportation in a* ***collision- and conflict free environment*** *carried out by* ***AGVs****, and provide* ***insight into the logistic performance****.*

The goal specification continues with decomposing the goal into multiple sub-goals. By grouping similar goals and adding sub-goals, a network of connected goals can be made. The work as presented in (Gerrits, 2016) is to a large extent comparable to our work, therefore we used his proposed network as a basis and tailored it to our case. Figure 4.1 depicts the system goal overview we constructed with the aid of PDT. Two major distinctions can be made from the work of Gerrits, Mes, and Schuur (2016). First, we included a shift management goal. The aim of this goal is to incorporate the shift-based planning approach. This approach influences sub-goals of the demand management and the collision avoidance. There is a need to incorporate this goal, because of the boundaries of our study (i.e., modeling the currently used production approach) and the scope demarcation by simplifying some activities that take place during daily operations (e.g., crane, pot tending, and metal tapping tasks). Second, the orientation of anode buckets must be taken into account as this influences further decisions. Recall that cranes require anodes to be placed according to a certain orientation before they can handle them properly.

Remark that the actual AGV controller is not part of the MAS we develop. The ultimate goal of carrying out physical vehicle movements is not incorporated as these are obvious and could be assigned to the AGV controller for an actual implementation.

4.1.2 System Functionalities

Next, we have to declare system functionalities. A functionality describes a chunk of behavior, consisting of decisions and actions, as well as relevant triggers and data (Padgham and Winikoff, 2005).

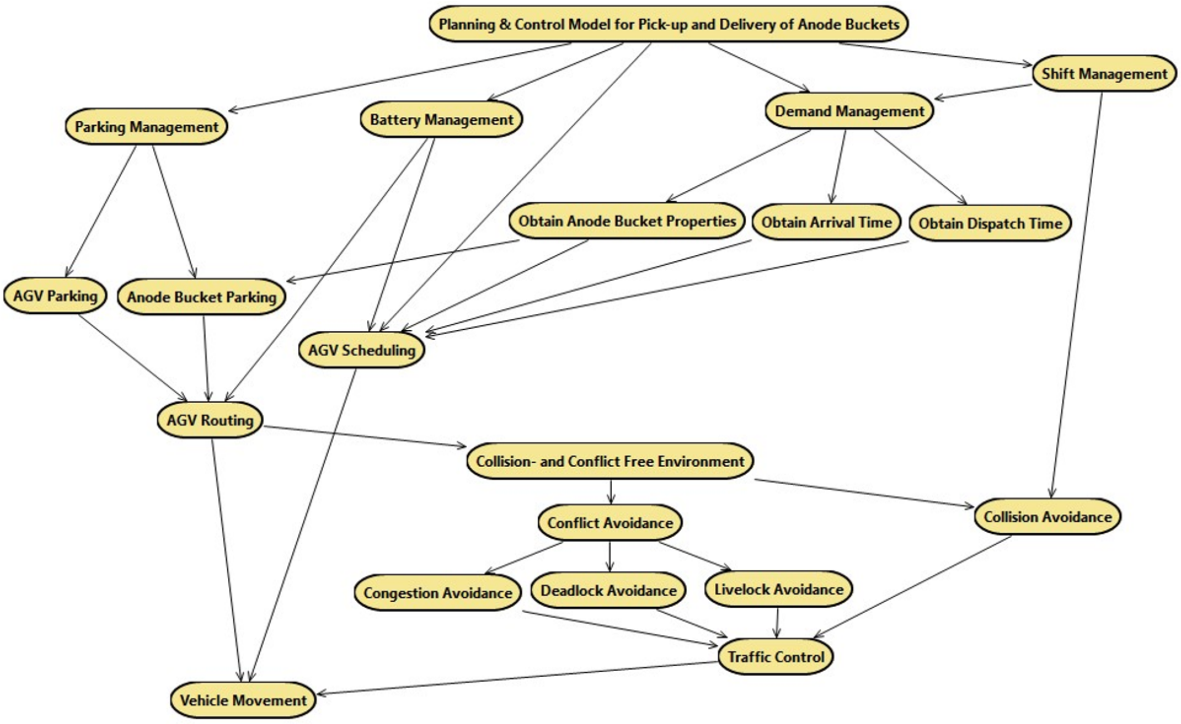


FIGURE 4.1: MAS system goal overview. Adopted from Gerrits (2016).

Functionalities are identified by a top-down process of goal development and provide a bottom-up approach for determining the agent types and their responsibilities (see Architectural Design phase).

We grouped the goals in almost the same functionalities as Gerrits, Mes, and Schuur (2016) did, except that we separated a more general park management into a section management functionality and an AGV parking management functionality, and framed the functionalities to the context of our study.

1. **Demand Management (DM)**. This functionality monitors in- and outgoing anode pallets based on the working schema. It obtains information about (expected) arrival and (expected) dispatch times, and anode pallet specifications (e.g., orientation, anode type, amount of anodes, etc.).
2. **Section Management (SM)**. This functionality monitors anode pallet positioning and sequencing in a section of cells. It assigns pick-up and drop-off locations to anode pallets and takes care of avoiding collisions due to other ongoing potroom activities in the section.
3. **AGV Parking Management (PM)**. This functionality assigns parking locations to AGVs.
4. **Vehicle Scheduling (VS)**. This functionality determines when, where, and which AGV should pick-up or drop-off the anode pallet.
5. **Vehicle Routing (VR)**. This functionality determines the route an AGV should take.
6. **Conflict Resolution (CR)**. This functionality monitors AGV movements, takes care of collision avoidance and resolves conflicts (e.g., deadlocks and congestions).
7. **Battery Management (BM)**. This functionality determines when and where AGVs should be recharged.

Based on the identified functionalities, functionality descriptors are defined. This description provide an adequate prescription about the required functional behavior of agents in terms of goals, actions, triggers, information used, and information produced. A trigger represents an event or situation that will cause an activity to be initiated within this functionality (Padgham and Winikoff, 2005). An example of the functionality descriptor for *Demand Management* is given in Table 4.1. For the other descriptors we refer to Appendix E.

4.1.3 Scenario Development

The next step is scenario development. Scenarios illustrate the normal running of the system. Scenarios are complementary to goals as they show the sequences of possible steps that take place within

TABLE 4.1: Example of the functionality descriptor for Demand Management

Demand Management Functionality

Description	This functionality monitors in- and outgoing anode pallets based on the working schema. It obtains information about (expect) arrival and (expected) dispatch times, and anode pallet specifications (e.g., orientation, anode type, amount of anodes, etc.)
Goals	Obtain (expected) arrival time, Obtain departure time, Obtain anode specifications
Actions	Log (expected) anode pallets arrival, Log anode pallets departure, Log anode pallet specifications
Triggers	Anode pallet arrival, Anode pallet departure
Information used	Potroom and cell demand characteristics, Shift schema, Anode pallet arrival time, Anode pallet dispatch time, Anode pallet specifications, Anode and anode pallet database
Information produced	Arrived anode pallets, Dispatched anode pallets, Delayed anode pallets, Anode and anode pallet database

the system (Padgham and Winikoff, 2005). Steps that could be described in scenarios are: achieving a *GOAL*, performing an *ACTION*, receiving a *PERCEPT* (i.e., need for information from the environment), or referring to another use case *SCENARIO*. In addition, the step type *OTHER* may be used to represent unusual steps such as waiting for a response. Each step is performed by a functionality and includes information that is used and information that is produced/written.

A scenario can be used to illustrate an interaction or the execution of a use case instance (Rumbaugh, Jacobson, and Booch, 2004). A complete set of scenarios should describe everything the system is intended to do. However, it is impractical to enumerate an endless number of possible scenarios and fully define them. We attempt to describe a scenario for at least one variant of each important process within the system. We consider the following scenarios:

Scenario 1: Shift begins. This scenario describes which functionality does what when a new shift starts.

Scenario 2: Anode butt arrival from a cell. This scenario considers the arrival of burned anodes from cells. The starting situation in this scenario is that an empty pallet is available nearby the cell.

Scenario 3: Anode pallet transport request. This scenario occurs when new anodes need to be placed and there is no pallet holding new anodes in front of the cell.

Scenario 4: AGV becomes idle. This scenario considers an idling AGV while there are no anode transport jobs left.

Scenario 5: AGV reaches low battery status. This scenario considers the situation of an AGV having a low battery status and thus need to be recharged.

Scenario 6: AGV conflict expected. This scenario could occur when a deadlock or a collision between two vehicles is predicted.

Scenarios interact with each other and scenarios may take place multiple times during a time horizon. Below we discuss the scenario of the initialization of a shift (scenario 1) and the anode pallet transport request (scenario 3). Table 4.2 and Table 4.3 provide the scenarios, which we explain in more detail below. The other scenarios can be found in Appendix F. Remark that the reported scenarios are use case instances only and thus not fully represent all imaginable scenarios.

The first scenario (see Table 4.2) starts every time a new shift occurs. The *Demand Management* (DM) functionality prescribes which electrolytic-cells require anodes to be changed in the shift. DM determines the number of anode pallets to be transported to sections during the shift. It takes into account the current state of cells and pallet orientation. This scenario ends with the request of an anode pallet transportation.

TABLE 4.2: MAS Scenario: Shift initiated

Key for functionality and data abbreviations:

DM	Demand Management
A.D. Scheme	Anode Demand Schema
A.P.D. Scheme	Anode Pallet Demand Schema

	Step type	Step	Funct.	Data used and Data produced
1	PERCEPT:	*New shift initiated*		
2	GOAL:	*Obtain anode changing schema*	DM	Shift Schema A.D. Schema
3	GOAL:	*Determine pallet demand schema*	DM	A.D. Schema Cell Specifications Pallet Specifications A.P.D. Schema
4	ACTION:	*Request anode pallet transportation*	DM	A.P.D. Schema
5	SCENARIO:	*New anode pallet transport request (via DM)*		A.P.D. Schema

Subsequently, we consider the scenario that follows-up logically, namely a transportation request for a new anode pallet (as a trigger from the environment). Table 4.3 illustrates a scenario that starts with the percept of a new anode pallet transport need. In this scenario, the transport need could be originated from the shift initialization scenario (scenario 1). Properties of the cells, anodes, and the pallet are obtained first (e.g., required pallet orientation, the number of anodes, destination, delivery time window, etc.). This is done by the DM.

The anode pallets will be placed in front of the electrolytic-cells and thus partly block the driving path for AGVs (and other vehicles). Although the AGVs we consider could drive both forwards and backward, delivering the pallets in an inappropriate manner could disturb the aluminium process, block the passage of other vehicles, or lead to deadlock situations. For that reason, a *Section Management* (SM) functionality is introduced, which determines the drop-off and pick-up sequence within a section and releases transportation jobs if necessary. This functionality consumes cell-specific information (e.g., delivery time-windows, butt release times, etc.), section-specific information (e.g., available traffic, already blocked cells, butt pallets, etc.), but also information related to AGVs queuing in front of the section and AGVs en route. The aim of the SM functionality is to determine the drop-off and pick-up schedule inside a section and to pass new transport requests on to the *Vehicle Scheduling* (VS) functionality. Imagine the situation that an AGV is expected to be on-time at its destination but that the original PD-location is not reachable, for example, due to another AGV's delay. SM could then prioritize the on-time AGV and re-allocate transportation activities such that the on-time AGV swaps its job with the delayed AGV. Also, the Section Management could request the *Vehicle Routing* (VR) functionality to explore different routes and thus ultimately change the section handling schedule.

In parallel to the SM activities, the VS and VR functionalities conduct their MAS tasks. Transport requests are passed on to the VS functionality, which determines which AGV should pick-up the pallet. This functionality uses anode pallet information, pick-up and delivery time-windows, and the status of AGVs (e.g., location, whether it is idling, busy or charging, and when it is available for new transport requests). VR is responsible for determining the route an AGV should take once it is selected by the VS functionality. Depending on the anode pallet, the VR makes routes for transporting (full) anode pallets, butt anode pallets, and empty pallets. Also, routes for battery charging and parking locations are determined by VR. VR is likewise triggered when the SM functionality requests an adjusted destination location. VR uses, among other information, the guide-path design and blocked sections as input data.

Once an AGV and its corresponding route are selected for a transportation job, the *Conflict Resolution* (CR) functionality is introduced. CR monitors and updates AGV movements, takes care of collision avoidance, and resolves conflicts such as deadlocks and congestions. CR is, for example, able to handle with deadlocks for concurrently scheduled vehicles. This could occur when two or more vehicles moving in the same area run into a deadlock. CR decides which AGV to prioritize and what action has to be taken by them. Note that the AGV controller, responsible for actual physical movements of the AGV, is not incorporated in the scope of this thesis. Therefore, we finalize this scenario with communicating the driving actions to the controller.

TABLE 4.3: MAS Scenario: Fulfillment of new anode pallet transport request (shift initiated)

Key for functionality and data abbreviations:

CR	Conflict Resolution
DM	Demand Management
SM	Section Management
VR	Vehicle Routing
VS	Vehicle Scheduling
A.P. Specifications	Anode Pallet specifications
A.P.S.D.	Anode Pallet Storage Database
E.A.P.A.T.	Expected Anode Pallet Arrival Time
P.C.D.C.	Potroom and Cell Demand Characteristics

	Step type	**Step**	**Funct.**	**Data used and Data prod.**
1	PERCEPT:	*New anode pallet transport request*		
2	GOAL:	*Obtain transport properties*	DM	P.C.D.C. Shift Schema A.P. Specifications
3	ACTION:	*Request anode pallet storage location*	SM	A.P. Specifications A.P.S.D. Section Properties
4	GOAL:	*Assign anode pallet storage location*	SM	A.P. Specifications A.P.S.D. Section properties A.P.S.D. Transport Request
5	GOAL:	*Determine anode pallet arrival time*	SM	A.P. Specifications A.P.S.D. Guide-path Design Section Properties Transport Proposal E.A.P.A.T.
6	ACTION:	*Request pick-up*	VS	A.P. Specifications E.A.P.A.T. Transport Request
7	GOAL:	*Determine AGV schedule*	VS	Transport request AGV Status AGV Schedule
8	ACTION:	*Request route*	VR	AGV Schedule
9	GOAL:	*Determine AGV route*	VR	Guide-path Design AGV Schedule AGV Status AGV Route
10	GOAL:	*Update AGV status*	CR	AGV Status AGV Status
11	ACTION:	*Send info to AGV controller*	VR	AGV Schedule AGV Route
12	OTHER:	*Wait for AGV to be at the section*		

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Table 4.3 – continued from previous page

Step type	Step	Funct.	Data used and Data produced
13 SCENARIO:	*AGV possible collision detected*		AGV Routing AGV Status AGV Routing
14 PERCEPT:	*Collision is avoided*		
15 SCENARIO:	*AGV deadlock expected*		AGV Routing AGV Status AGV Routing
16 PERCEPT:	*Deadlock is avoided*		
17 OTHER:	*Wait for AGV to be at the section*		
18 PERCEPT:	*AGV arrives at section and drops-off the pallet*		
19 GOAL:	*Update AGV status*	VS	AGV Status AGV Status
20 GOAL:	*Update anode pallet database*	DM	A.P.S.D. A.P.S.D.

4.1.4 Alternative Scenarios

An almost endless number of alternative scenarios could be captured. It is not the intention of the scenario development to discuss all exceptional instances that could occur. However, as our MAS should be built generically, it is required that the system can cope with a variety of scenarios. Below we discus some examples of modifications to the scenarios by which we show that is is easy to modify, delete and create new scenarios. Additionally, the management made a design choice regarding the process flow and demand characteristics, which influences the further MAS en AGV system design.

An example of a modification to the discussed *shift initialization* scenario would be to make use of a continuous way of working and omit the shift schema. For example, one could have a continuous anode transport demand (24/7) for the production facility. As a consequence, another scenario could be considered where different triggers than shift start moments lead to transport requests. Another example is to modify the *AGV becomes idle* scenario such that (expected) future transport tasks are taken into account or parking strategies are combined with battery charging strategies.

Various modifications regarding the process flow and demand can be made which we aim to capture in the MAS and AGV system. One modification is already highlighted in the examples above, namely deviation in the process flow. Two process deviations are considered in the design: shift & section-based working and continuous-based working. Additionally, we capture two demand variations, cyclic/repetitive arrival and random arrival. Table 4.4 shows the alternative designs we cover. In the sequel of the MAS and AGV system design, we focus on addressing the first two options as depicted in the table, because the continuous-based working approach is to the best of our knowledge not used in practice yet. Therefore, we discuss the continuous based-working approach in the scenario evaluation (Chapter 6) in more detail.

TABLE 4.4: Alternative scenarios captured in the model design

	Process Flow		**Demand**	
Option	Shifts & Sections	Continuous	Cyclic	Random
1	✓	✗	✓	✗
2	✓	✗	✗	✓
3	✗	✓	✓	✗
4	✗	✓	✗	✓

4.1.5 Interface Description

An important aspects of a MAS is the interaction with its environment. Agent systems are typically situated in a changing environment that can be affected by the MAS. Environments may be influenced by the MAS but not totally controlled by it. For that reason, it is important to define what the system should do to interact with and affect the environment. Interaction protocols from the environment to the MAS (*percept*) and from the MAS to the environment (*action*) must be included.

Data exchange should be made possible when developing the system. In the system specification phase, data that are external to the agent system as well as additional interaction with any other software should be specified. Below, we discuss a few important interface descriptions. Other descriptions are more explicitly covered in the Architectural Design, lower design levels and implementation plan (see Chapter 8).

The MAS should interact with the environment in several ways. An important interaction protocol should be established for the communication between the MES and MAS. Transportation jobs are originated from the MES. MES requires anode pallets to be at a certain place at a certain time. The MAS should be informed about whether a pallet can be transported. Therefore, data related to the expected arrival and departure times are an important source for the system to function properly. Furthermore, the AGV is equipped with physical sensing devices of which some are useful for the MAS. These sensors should be incorporated in the MAS, for example, to be able to detect possible collisions.

4.2 Architectural Design

The architectural design phase builds upon the system goals, scenarios, and functionality descriptions as defined in the system specification phase. In the architectural design phase, we first decide on the agent types used. We continue with describing the interactions between agents.

4.2.1 Agent Types

The main design decision in the architectural design is deciding which agents the system will include (Padgham and Winikoff, 2005). To select proper functional groupings, we used the criteria *coupling* and *cohesion*. Coupling is described as the degree of communication between agents. It is a property of dependency among agents. Cohesion is the agent's level of uniformity of the functionalities.

After we have identified the agent's functionalities, we have to provide validity to the grouping of functionalities. To examine properties that lead to a desirable number of agents while maintaining an appropriate level of coupling and cohesion, we used the techniques as discussed by Padgham and Winikoff (2005): data coupling diagram, agent acquaintance diagram, and agent descriptors.

4.2.1.1 Data Coupling Diagram

Data coupling diagrams could be used to visualize which data are coupled to which (grouped) functionality (Padgham and Winikoff, 2005). To this end, we design a Data Coupling Diagram (DCD) which consists of the previous defined functionalities and data. In such a diagram, an arrow pointing towards the data indicates the data are produced or written by that functionality. An arrow pointing the other way around indicates the data are used by the functionality. A bidirectional arrow is used to show that the functionality both uses and produces the data. The designed DCD is displayed in Figure 4.2. The figure provides a high-level overview of the relations among grouped functionalities and data sources. Each group of functionalities is in accordance with the earlier defined agents. It does not show internal functionalities and data sources in detail, this because the model otherwise would become too complex.

The data coupling diagram uses the same agents as defined earlier but with an additional *AGV Control Management*. This newly introduced agent communicates with the AGV board computer and sensors. The communication with the AGV control computer is left out of scope within this study.

As addressed earlier, the MES is an important external information source for the MAS. MAS acquires data about the anode and anode pallet demand and section division from the MES. This client-specific information together with the guide-path design, form the two main external information sources.

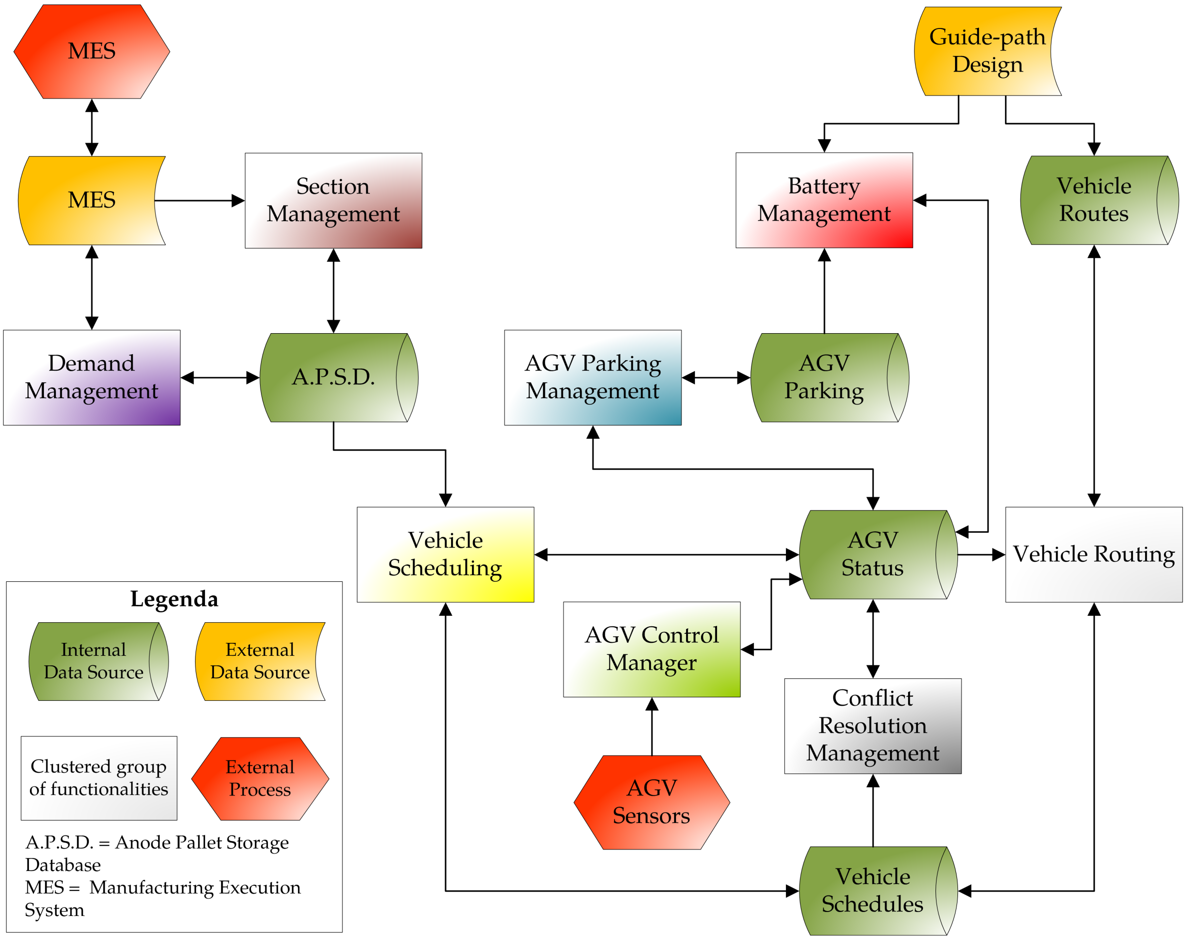


FIGURE 4.2: MAS Data Coupling Diagram.

4.2.1.2 Agent Acquaintance Diagram

In the design of a MAS, the *grouping* criterion can be evaluated using an Agent Acquaintance Diagram (AAD). The purpose of this technique is to design the agents such that they are as loosely coupled as possible. In such a diagram, each agent is linked with the other agents it interacts with. In addition, the cardinality of the relationship is given (e.g., one *Demand Manager* interacts with many *Section Managers*). These relationships and the cardinality are used to analyze the system.

The designed AAD as shown in Figure 4.3, can be analyzed in two ways: an analysis of the density of the links and a bottleneck analysis. The density of the links is measured with the ratio of the actual coupling to the maximal possible coupling. Our system has eight agents, then each agent could potentially be linked to a maximum of seven agents, resulting a theoretical maximum of ($\frac{8*(8-1)}{2}$ =) 28 non-directional links. Figure 4.3 contains in total 16 links. The link density is then ($\frac{16}{28}$=) 57%, which is moderately coupled. In terms of performance on the coupling criteria, one would ideally have this ratio as low as possible.

In our design, we observe that the *Vehicle Scheduling* and *AGV Control Manager* have six connections. Furthermore, we observe two agents with a cardinality of n, namely the *Section Manager* and *AGV Control Manager*. The *Section Manager* receives demand information and translates this to a specific transport request. Multiple *Section Managers* are used, because the plant is divided into sections and each section has its own characteristics. These cardinalities of n could lead to potential run-time bottlenecks if the number of *Section Managers* and *AGV Control Managers* are too high. However, not all connections are always necessary. For example, the *Section Manager* only communicates with the AGVs available in that section of cells. Furthermore, most of the links of the *AGV Control Managers* are directed towards the *AGV Control Managers*, which suggests that this agent uses more information instead of producing it.

The potential computational time deficiencies when dealing with a large number of *AGV Control Managers* and *Section Managers*, is expected to be limited. We do not expect that these numbers will be

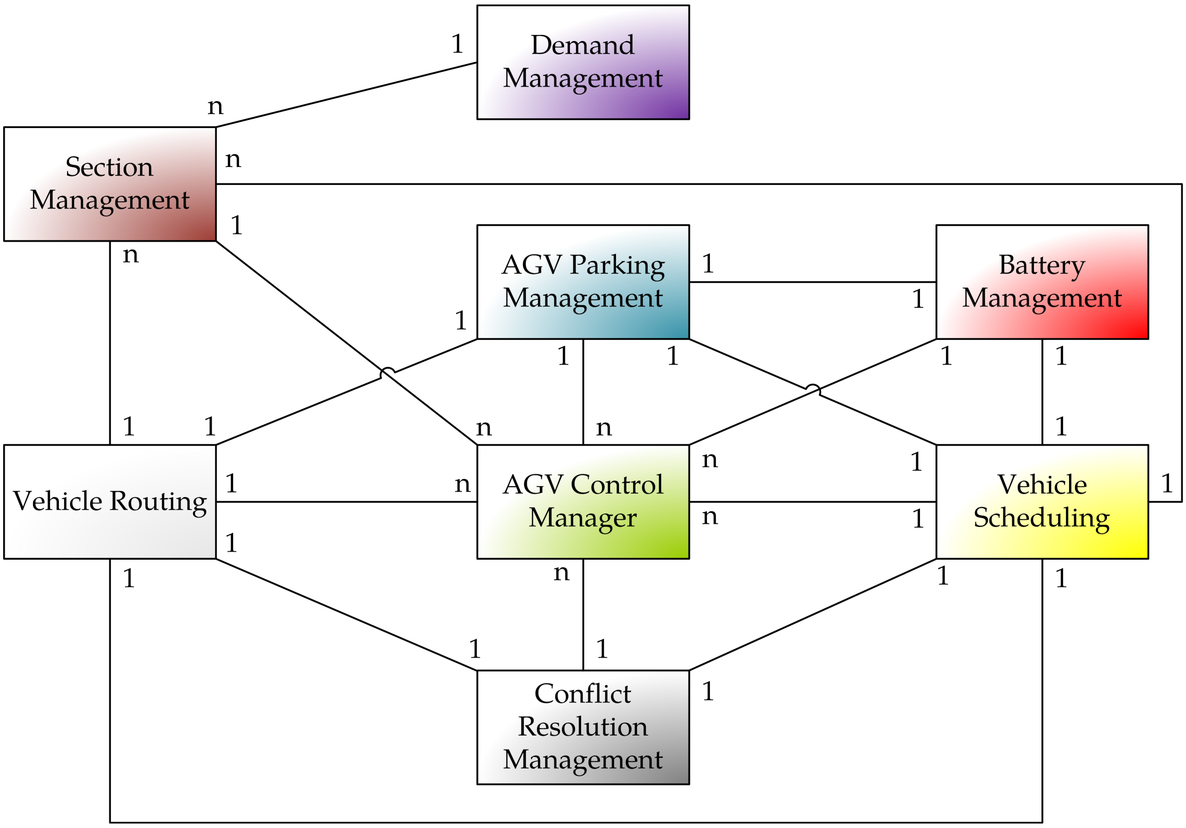


FIGURE 4.3: MAS Agent Acquaintance Diagram.

extremely high in most practical cases. Furthermore, the number of communication flows between Section Managers and other agents are limited to a small number of *Section Managers* due to the way the heuristics are arranged (see simulation model).

Some design decisions are made and one could debate about the proposed cardinalities. We choose to have one *Section Manager* dedicated for each section. This *Section Manager* is not only used in our design to arrange section activities appropriately but could also be used in potential model extensions where more sophisticated activities are included (like crane operations). One could also argue that the *Demand Management* and *Section Management* could be covered in, for example, a more centralized demand management. We decided to split the functionalities for these agents, to increase the generic applicability when having different demand characteristics. Additionally, the currently designed model could be used with minor modifications only when considering the continuous way of working (see Chapter 6).

4.2.1.3 Agent Descriptors

The next step is to incorporate the designs and analysis of the previous parts and provide a brief overview per agent. Besides the information from the previous subsections (such as functionalities, used and produced data, interactions with other agents, etc.), this agent descriptor contains information regarding the lifetime, initialization, demise (termination), and more. Table 4.5 shows the agent descriptor of the *Demand Management*.

We decide to not fully describe all agent descriptors because the high-level structure of our MAS is now sufficiently defined. During the implementation phase, it is likely that modifications need to be made to the agent descriptors. For example, specific IT-protocols have to be defined and additional information needs to be obtained to tailor the MAS to unique clients. We decide to not speculate about specific use cases and therefore leave the other architectural design phases (interaction diagrams and protocols) to further research. The design phases we skip aim to develop interaction diagrams from use case scenarios, generalize interaction diagrams to interaction protocols, develop protocol and message descriptors, and provide a system overview. To some degree, we discuss this in the AGV control system design and evaluation model. One should notice that for the actual implementation,

TABLE 4.5: MAS Agent Descriptor: Demand Management

Agent descriptor: Demand Management	
Name:	Demand Management
Description:	Monitors in- and outgoing anode pallets based on the working schema. It obtains information about (expect) arrival and (expected) dispatch times, and anode pallet specifications (e.g., orientation, anode type, amount of anodes, etc.).
Cardinality:	One per system
Lifetime:	Ongoing
Initialization:	Data from MES
Demise:	None
Percepts	Anode pallet arrival, Anode pallet departure
Actions:	Log (expected) anode pallets arrival, Log anode pallets departure, Log anode pallet specifications
Uses data:	Potroom and cell demand characteristics, Shift schema, Anode pallet arrival time, Anode pallet dispatch time, Anode pallet specifications, Anode and anode pallet database
Produces data:	Arrived anode pallets, Dispatched anode pallets, Delayed anode pallets, Anode and anode pallet database
Internal data:	Arrival DB, Dispatch DB, Delayed DB
Goals:	Obtain (expected) arrival time, Obtain departure time, Obtain anode specifications
Functionalities:	Demand Management
Protocols:	Arrival protocol, Dispatch protocol, Delayed protocol, Anode and anode pallet protocol

these architectural design steps are of importance because the established protocols and information availability are then accessed and validated. In the remainder of this chapter, we assume these missing steps are carried out appropriately (e.g., all data are available, accessible and pre-processed) for a proper system functioning. Nevertheless, for the MAS implementation we require some data acquisition and pre-processing as well. Insofar it is relevant, we document our used approach to make the information accessible for our simulation model.

4.3 Detailed Design

The detailed design phase of the Prometheus methodology aims to develop capability descriptions to specify the individual plans, beliefs, and events (Padgham and Winikoff, 2005). To a major extent, design elements of this MAS phase can be found in the sequel of this report. Therefore, we refer to the AGV system design and the evaluation model description for the detailed MAS design. These sections include how the MAS contribute to the control of the AGV system and discuss in more detail how the individual agents are specified in the system.

4.4 Conclusion

This chapter presented a MAS design to support anode transportation with AGVs in the primary aluminium industry. The model is able to interact with a given metal transport model and facilitates a collision- and conflict free environment. To this end, system functionalities are grouped in eight designated agents: demand management, section management, AGV parking management, vehicle scheduling, vehicle routing, conflict resolution, and battery management. The design will be further detailed in the AGV system design (Chapter 5) and evaluation model (Chapter 6).

Chapter 5

Model Design: Automated Guided Vehicle System

This chapter designates the AGV system design. Section 5.1 commences with specifying the system requirements and data for the AGV system. Next, the guide-path design is proposed in Section 5.2. After that, we discuss the tactical AGV system design elements, which includes estimating the number of vehicles (Section 5.3), vehicle scheduling (Section 5.4), vehicle parking (Section 5.5), and battery management (Section 5.6). Lastly, operational design issues including vehicle routing and conflict resolution are addressed in respectively Section 5.7 and Section 5.8 . Remark that elements from the MAS are interrelated with the AGV system and that certain MAS design choices are further motivated in this section. Section 5.9 concludes this chapter.

5.1 System Requirements and Data

Before we start the design process, we first specify system requirements and input data for the AGV system, this includes facility layouts (Subsection 5.1.1), pick-up and delivery locations (Subsection 5.1.2), and material flow characteristics (Subsection 5.1.3). Remark that the type of loads part of the AGV system design methodology is covered in the material flow part. Also, the type of AGVs is already discussed extensively in Chapter 2. Therefore we refer to that chapter for more details. We use input from Hencon's clients and literature as discussed in Chapter 2 for this part of the design. Finally, we discuss potroom blockade characteristics that should be considered because they may cause AGAPTV blocking restrictions in Subsection 5.1.4.

5.1.1 Production Facility Layout

The production facility is shaped in a rectangular form and the facilities we consider contain cells lined up in an end-to-end position. Cells are placed in one or more parallel lines down the center of the potroom. The size of the electrolytic-cells and distance between cells placed in line should be variable as the number of anodes per cell may deviate. Cells are clustered in a segment and these segments are physically separated from other segments by means of cross aisles. Segments are not overlapping between potrooms. Each potroom may contain multiple segments. A segment may exists of multiple sections and a section can be spread over multiple segments in the same potroom. We define a section as a number of consecutive electrolytic-cells lined-up in a potroom in which common activities are carried out.

The rodding shop is directly reachable from the cross aisle and positioned on the longitudinal side of the plant. Other areas such as the casthouse and repair and maintenance facility are considered beyond the scope of our research.

5.1.2 Pick-up and Delivery Locations

The production layout is characterized by some anode pallet placement restrictions. Due to the narrowness of the back aisles, it is not permitted to drop (and pick-up) any pallets on these sides of the layout. The demand arising from the anodes in cells positioned on the back aisles side should be fulfilled through the center aisles (overhead cranes can lift an anode from the center aisle to the back aisle over the cell). Furthermore, it is not desirable to pick-up or drop-off anode pallets within the cross aisle, as this is not convenient for other vehicle and machinery in the potroom. So, the anode pallets should all be placed in the center aisle. We consider that every cell has one unique location in front of it that functions as a pick-up and drop-off location for a pallet. However, as mentioned in Subsection 2.3.2, pallets may not be placed in front of the cells located directly near a crossing. This results in four places per cell segment in which no pallet may be stored.

Additionally, we have to consider the pallet orientation restriction. As it is not convenient to let pallets with the proper orientation be positioned directly in front of the cell (because the rods attached to the anodes may hinder crane operations), the required pallet should be placed on the opposite center aisle. Furthermore, the two parallel series of cells in a potline are identically oriented, which implies that the southern part of an electrolytic-cell in the northern segment requires a pallet orientation similar to the cell at the southern segment. Figure 5.1 illustrates how the pallet should be positioned and which anode demand can be fulfilled by it. Anodes positioned near the northern back aisle of a segment and southern center aisle should be fulfilled through pallets located at the northern center aisle (indicated blue in the figure). Demand arising from the southern part of the cells should be fulfilled through pallets in the southern center aisle (indicated red in the figure). In the remainder of this study, we define pallets positioned at the southern center aisle as southern pallets and pallets at the northern center aisle as northern pallets.

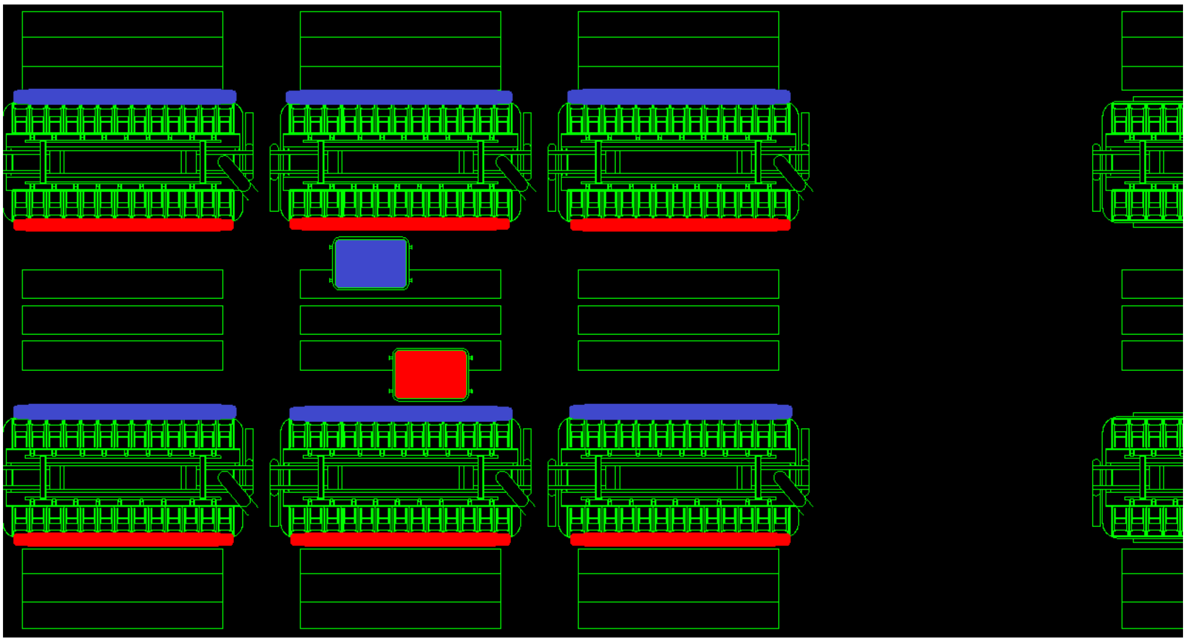


FIGURE 5.1: Anode pallet placement and demand fulfilled by it. Anodes positioned near the segments' northern back aisle and southern center aisle should be fulfilled through pallets located at the northern center aisle (indicated blue). Pallets at the southern center aisle fulfill anode demand from the southern parts of the cells (indicated red).

The rodding shop functions as a pick-up and drop-off location as well. Pallets containing fresh anodes are received from the rodding shop. Empty pallets and pallets with used anodes are retrieved by the rodding shop. We assume rodding shops have sufficient storage capacity to cover the arising pallet demand and the used anode pallets. Other (temporary) storage locations for anode pallets are not considered in the model.

5.1.3 Material Flow Characteristics

Anode pallet requests are generated by the MES and the behavior of that transport demand generating system needs to be captured appropriately in the model. For modeling the MES, we discuss design considerations that form the boundary in which this system operates. To this end, we first address some general material flow characteristics. After that, we highlight design considerations that are involved in decision making in the material flow process.

Before the actual anode changing begins, an appropriate number of pallets with fresh anodes should be transported to the section such that once the operators start their shift, the anodes are available. MES provides an anode pallet release time from whereon it is allowed to transport a pallet with new anodes to the section. We specify this start moment as the *fresh anode pallet release time*, which is expressed in time before the anode changing shift starts. The fresh anode pallet release time depends on when the anode changing shift starts and when the actual anodes of that pallet are needed. Considering a too early fresh anode pallet release time may cause unnecessary accumulations of pallets in a section and a too late fresh anode pallet release time may affect an efficient workflow in the potroom. Furthermore, a P/D-location nearby a rodding shop would require a lower release time than a pallet situated further away from it, because the AGAPTV travel time will be longer (in general). Likewise, the moment when the anodes are actually needed should be considered.

In addition to this fresh pallet release time, from whereon the fresh pallet transport tasks are introduced to the system, the pallets should be on-time at the destination. As the shifts are bounded by time-limits, there is a desire to have the pallets not too early and not too late at the destination. Therefore, we could make use of delivery time-windows as well. These delivery times should be interconnected with the fresh anode pallet release time because an inappropriate fit of these windows could disturb the AGV system. For example, if the anode pallet release time is 4 hours before the anode changing shift starts and the shift takes 8 hours, the pallet may then wait 12 hours before the anodes are actually needed in the most extreme case.

The anode pallet flow process embodied in the MES comprises making various decisions that require communication between, for example, operators, AGAPTVs, and cells. The behavior of and the decisions made by these entities should be incorporated in the demand generation. Firstly, anode demand arising from cells are combined into pallets and transported to dedicated places. The demand from individual cells must be translated to an integer number of pallets, because the pallet's capacity (in most cases) is more than the anodes required for one particular cell. A proper utilization of the pallets' capacity would limit the unnecessary rides. Secondly, the center aisle's width is often quite narrow such that only a limited number of AGAPTVs can traverse the aisle at the same time. This requires a satisfactory approach in handling blocking and deadlock situations. Thirdly, the movements and work procedure of the crane operators should not be neglected as this may have consequences for the pallet placements. Ideally, one would have the anode pallets as close as possible to the corresponding workforce team once it requires the anodes because the crane movements are then limited. However, this may not be always possible because of:

- pallet placement restrictions;
- anodes located on the back aisles that need to be moved by crane via the center aisle;
- pallet orientation that should be taken into account;
- conflicting pallet placement interests (e.g., where to position one pallet if two neighboring cells require one anode each and another cell a couple of meters further requires one anode?);
- any other vehicles, machinery, and operators involved for other smelter operations;
- possible workforce flow through different sections.

Based on this material flow process description and our already made design choices, we could deduce a few scheduling activities involved in planning anode logistics: (1) generation of anode demand, (2) transition from anode demand to anode pallet demand, (3) interaction with crane operators, and (4) interaction with other shifts. In Section 6 we describe our approach to incorporate these scheduling tasks and the specification of the release and delivery times in more detail.

5.1.4 Guide-path Blocking Restrictions

Smelter characteristics such as the narrowness of aisles and other ongoing activities, may limit the travel capabilities of AGAPTVs. As a consequence, paths may be (temporary) blocked which cannot be traversed anymore (for a while) by the AGAPTV. To describe the possible blocking restrictions in more detail, we discuss below two smelter characteristics that may affect the AGAPTV routing approach: (1) the narrowness of aisles and (2) the influence of shift activities.

One aspect that could cause AGAPTV blocking restrictions is the narrowness of the paths. In general, the back aisle width is not sufficient for more than one AGAPTV. The center aisles, on the other hand, are typically wider and could be driven by at most two vehicles in parallel lines. Besides that these layout characteristics influence the way guide-paths can be organized (see Section 5.2), it affects the pick-up and delivery procedure of the AGAPTV. To this end, the AGAPTV has to perform placement maneuvers. This maneuver is required to avoid blocking situations due to physical AGV properties. Figure 5.2 illustrates the drop-off of a pallet by performing a forward steering procedure. After the AGAPTV dropped the pallet, the AGAPTV moves forward or backward to perform its next task. Figure 5.3 depicts the situation where the pallet can only be dropped-off from one side by performing a backward steering maneuver (given the already placed pallet cannot be picked-up first). From the figure we can deduce the importance of managing the pallet pick-up and drop-off sequence properly.

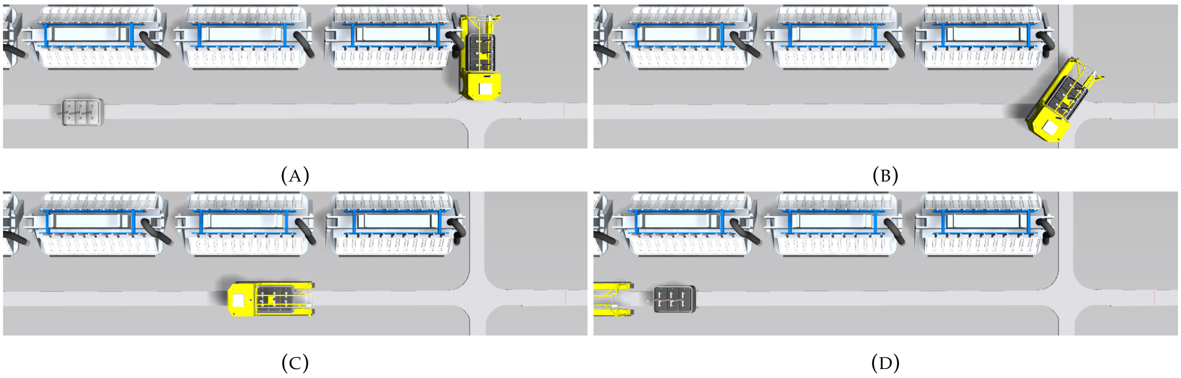

(A) (B) (C) (D)

FIGURE 5.2: Example of an anode pallet placement maneuver (1). The transparent pallet in (A) indicates the location where the pallet need to be positioned.

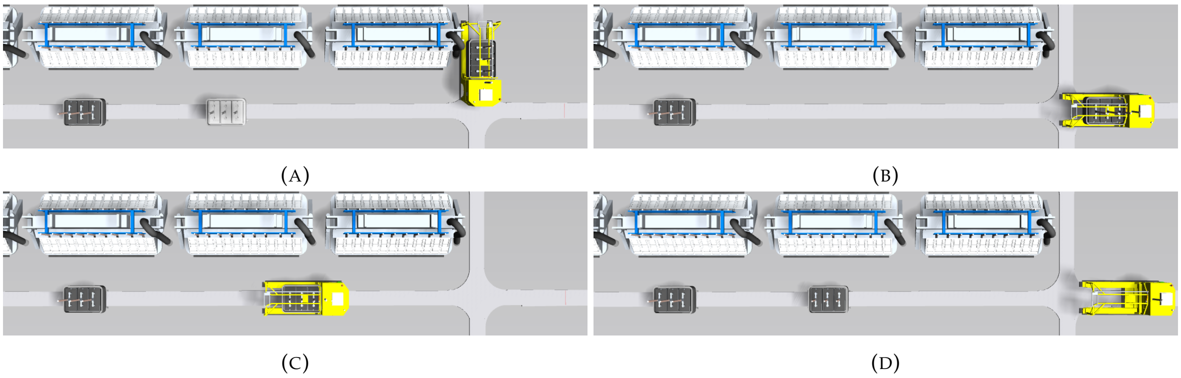

(A) (B) (C) (D)

FIGURE 5.3: Example of an anode pallet placement maneuver (2). The transparent pallet in (A) indicates the location where the pallet need to be positioned. The AGAPTV should drive backwards to drop-off the pallet.

The other smelter characteristics that result in blocking restrictions for the routing of AGAPTVs are shift associated operations. Operators, machines, equipment, and other vehicles limit the passage for AGAPTVs during specific shifts and operations. When a metal tapping activity is performed, it is common to close the entire lane for other vehicles not required for that activity type. In pot tending shifts, the AGAPTV blocking restrictions are limited to one side of the dedicated cell only because these activities are focused on a specific cell. In the anode changing shift, the resulting blocking restrictions require some more attention. Besides that an anode change blocks the passage in front of the corresponding side of the cell, the anode changing workforce (of which the crane in particular) affects the passage for the AGAPTV in multiple ways. That is, when anodes at the back aisle are being changed, the cell path on that back aisle is being blocked and the corresponding cell paths in the center aisle (see Figure 5.4). An anode change at the center aisle side only blocks the center aisle path of that electrolytic-cell.

5.2 Guide-path Design

The design of a guide-path is an important element in an AGV system. The guide-path depends on the allocation of shop-floor space, layout of storage zones, and the arrangement of handling stations (Le-Anh and Koster, 2006).

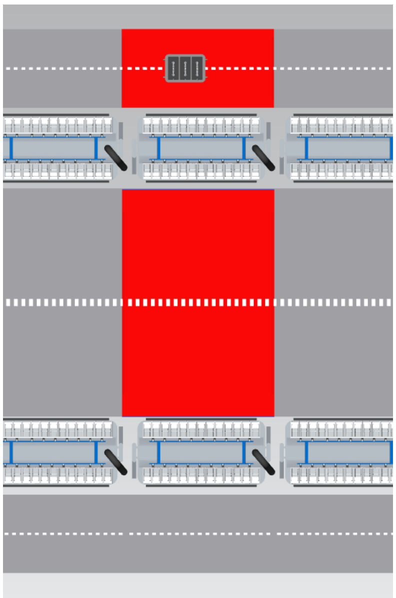


FIGURE 5.4: AGAPTV pathways blocked during anode changing process at the back aisle. During the anode changing process at the back aisle, the driving path near the corresponding cell is blocked as well as the center aisle path near that cell (depicted red). Notice that it is not permitted to place pallets on the back aisles.

In our case, the shop-floor space and the P/D locations are given. In addition, we face several restrictions regarding the guide-path design because of limitations imposed by physical factory properties. Therefore, we focus on considering the layout of the facility and the P/D-locations as input factors, and design the guide-path.

The road network can be described as the collection of paths and junctions on which the AGVs have to travel. A guide-path can be schematically represented by a graph consisting of a set of nodes (intersections and P/D-locations) and arcs (paths). Guide-paths can roughly be classified by the characteristics as shown in Table 5.1. A conventional flow topology consists of a network of roads and crossings. The conventional guide-path can be unidirectional or bidirectional (Le-Anh and Koster, 2006). Unidirectional paths allow vehicles to travel in only one direction, while bidirectional paths allow vehicles to travel in both directions. Unidirectional paths are easier to control (Vis, 2006) but using bidirectional paths can reduce the travel distance because AGVs can take shortcuts. In a single loop configuration, vehicles travel in only one loop without any shortcut or alternative routes (Le-Anh and Koster, 2006). Usually, these layouts are unidirectional, because in bidirectional traveling it is likely that vehicle interfere. In a tandem guide-path system, guide-paths are divided into several non-overlapping closed loops. Only one vehicle may travel in a zone and transfer stations are used to interface between zones. In a segmented guide-path configuration, the system has one or more zones, separated into non-overlapping segments which are served by a single vehicle. The guide-path topologies can be further specified in road segments that contain a single lane or multiple parallel lanes. Multiple parallel lanes require more space but may increase the throughput. Also, the combination of a mixed uni-bidirectional guide-path is possible.

TABLE 5.1: Characteristics of guide-paths (Le-Anh and Koster, 2006).

Flow topology	**Number of parallel lanes**	**Flow direction**
Conventional	Single lane	Unidirectional flow
Single loop	Multiple lanes	Bidirectional flow
Tandem		
Segmented		

In our case, the AGAPTV can travel both forwards and backwards, which enhances the flexibility of maneuvering efficiently through guide-paths. As the production facilities are typically long buildings with not that many crossings, it is not desirable to consider a single loop flow topology. Another reason to not consider this topology is that the cell sections may be blocked unexpectedly and that other vehicles may interfere with the AGV such that a single loop flow does not yield an efficient performance. A counter argument to include this configuration would be that the anode demand usually follows a predictable cyclic pattern and with the single loop configuration, the AGAPTV's driving route could then be arranged such that AGAPTVs perform their tasks appropriately. However, for the purpose of our generic model (applicability in many layouts), providing a robust solution for extensions to our model (e.g., including crucible transporters), and flexibility in driving courses, such a single loop approach is not desirable. A tandem configuration requires (intermediate) storage buffers at the end of each segment and additional time to transfer loads at buffers. Although a tandem and a segmented system seem promising as it can easily be expanded and is often used in manufacturing environments where workstations are grouped, we do not prefer this approach because of defining buffer areas, not all clients have additional storage space, and less tolerance to system failures. It would be interesting to investigate this approach in a further research. A conventional approach, on the other hand, provides flexibility in control and tolerance to system failures, which is of importance in capital intensive industries like the aluminium industry. Disadvantages of a conventional topology are that it is complicated to control, lead to congestion and interference problems, and face difficulties in expanding (Le-Anh and Koster, 2006). We argue that we could tackle or at least limit these potential deficiencies by our further AGV system design and incorporated MAS control strategy.

Discussions with the management have led to a base for the guide-path layout as shown in Figure 5.5. Limitations due to physical properties are taken into account and the P/D-points were considered as a guideline in this design. These physical properties include vehicle characteristics like AGAPTV width, length, and maneuvering capabilities, as well as general potroom characteristics like the typical center aisle width and cross aisle length. The management considered two crossroad designs. One design is using single bidirectional lanes that connect sections with each other. However, in general, there is sufficient space to let two AGAPTVs pass each other on the cross aisle. Therefore, we decide to include two parallel lanes in the cross aisle that are connected to the center and back aisles in the way as depicted in Figure 5.5. This would potentially increase the flexibility (for example, when possible collisions are detected). Lastly, as the AGAPTV can drive forwards and backwards, the direction of the path is by definition bidirectional. Interviews with the management of Hencon resulted in the following guide-path construction rules:

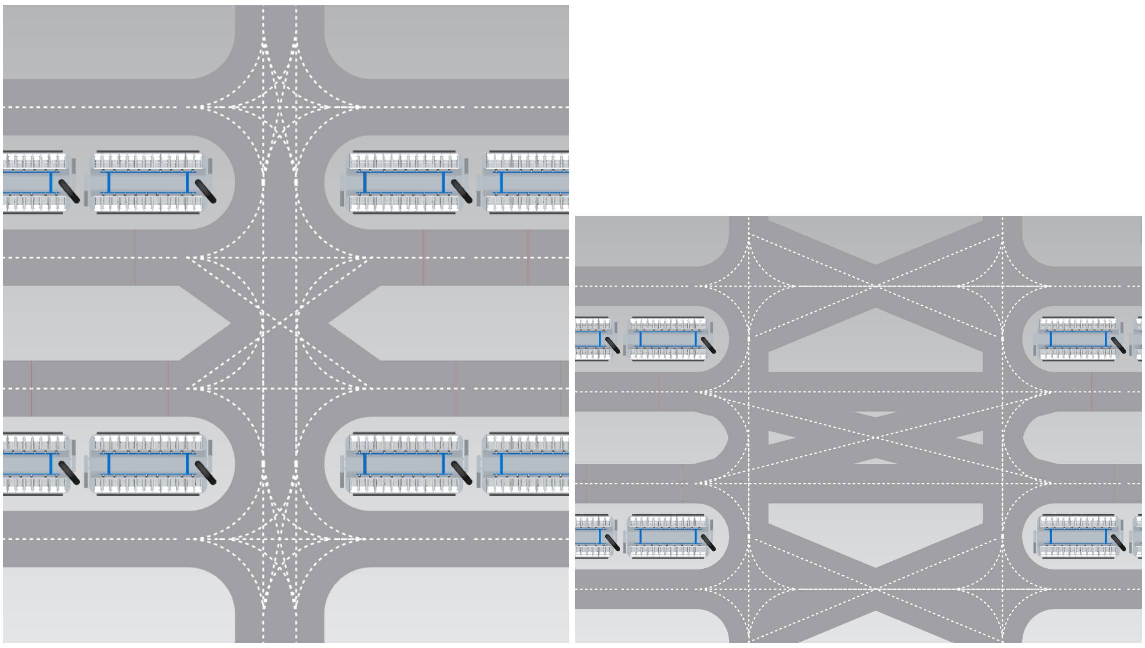
1. The back aisles consist of one single aisle that can be traversed by one AGAPTV.
2. The center aisle consists of two parallel center aisles in between the cells.
3. AGAPTVs can make a turn from the back aisle to the center aisle or the other back aisle.
4. Segments are linked together by means of horizontal paths and zigzag paths as shown in Figure 5.5. These diagonal paths allow AGAPTVs to change driving lanes.
5. Potrooms are linked together by means of vertical paths. Zigzag paths allow the AGAPTVs to change driving aisles.
6. Although zigzagging within the cell segment paths is generally feasible, the management decides to not incorporate this feature yet because the current guide-path provides plenty of possibilities to change directions.
7. All paths are bidirectional.

5.3 Estimating the Number of Vehicles

On the tactical design level, estimating the number of vehicles is important because the number of AGVs influences the performance of AGV systems significantly (Le-Anh and Koster, 2006). Three main factors affect the the required number of vehicles (Egbelu, 1987): guide-path layout, location of load transfer points, and vehicle dispatching strategies. Egbelu and Tanchoco (1984) proposes an analytical approximation for single-load capacity vehicles. We could use this estimation when using anode pallets as input. The estimation is given by:

$$N = \left[\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} D_{ij}}{V} + \left(\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} \right) \times (t_u + t_l) \right] \Big/ \ (60T - t) \tag{5.1}$$

In this formula, n is the number of P/D-locations, f_{ij} is the expected number of loaded trips required between location i and location j during a period or shift, D_{ij} is the estimated empty and loaded travel distance between locations i and j, T denotes the length or the period or shift during



(A) Guide-path layout including horizontal, vertical, diagonal, and curving paths.

(B) Similar as Figure I.1a but now with wider vertical paths in between the segments.

FIGURE 5.5: Guide-path base layout. Illustration of the cross aisle linking two segments within the same potroom together.

which the f_{ij} occurs, V is the average vehicle travel speed, t_l and t_u are respectively the mean time to load and unload a vehicle, t is the expected lost time by each vehicle during a time period of T due to battery change (Le-Anh and Koster, 2006).

This analytical approach provides an initial estimate of the required number of AGVs in the system. In the scenario analysis (Chapter 7), we use the result from this formula to determine an initial number of the required AGVs. We use simulation to further assess the impact of a varying number of AGVs in the system.

5.4 Vehicle Scheduling

The flexible characteristic of AGV systems makes the task of controlling AGVs challenging. In the design of an AGV system, issues regarding dispatching, vehicle routing, and vehicle scheduling have to be addressed. By using MAS, we can design communication schemes and protocols that can be used in controlling AGVs. In this subsection, we discuss our approach regarding vehicle scheduling and dispatching.

The transport orders are classified as:

1. A fresh pallet transport containing from rodding shop r to segment s cell c according to orientation o.
2. A butt pallet transport from segment s cell c according to orientation o to rodding shop r.
3. An empty transport from rodding shop r to segment s cell c according to orientation o.
4. An empty transport from segment s cell c according to orientation o to rodding shop r.

Each *AGV Control Manager* maintains its own schedule which consists of a sequence of actions to be executed. The actions considered in such a schedule are: (1) travel with a load from position i to j, (2) travel empty from position i to j or (3) wait at node j until time t (Mes, Heijden, and Harten, 2007). The latter one also includes vehicle idling or charging.

In the AGV system design, we consider applying dispatching rules for scheduling AGVs. The use of dispatching rules is a reactive scheduling technique in which decisions are based on triggers within the potroom and requires information exchanges among the defined agents. We decide to investigate the allocation of two integrated dispatching functionalities for the system: vehicle-initiated and workcenter-initiated. Below we first address the motivation for using this approach, after which we discuss the considered approach in our AGV system.

5.4.1 Motivation For Using Dispatching Rules

As addressed in the literature review chapter, scheduling vehicles (among other vehicle control activities) can be decided upon simultaneously or separately, and offline or online. We decide to use relatively simplistic dispatch rules for handling vehicle scheduling. An advantage of using these kind of rules is that it is easy to understand approach. Also, the computational effort in this strategy is relatively limited in comparison to, for example, more centralized hierarchical approaches. As we aim to hold a satisfactory degree of scalability and genericness under various stochastic circumstances (e.g., job arrivals, job density, pathway blockades, etc.), we favor using dispatching strategies.

A drawback of using these rules is that the collection of defined rules may not yield or guarantee an optimal result in every aluminium manufacturing facility and, therefore, lack in providing an integral approach that takes into account arising demand over an extended time-horizon. Despite these drawbacks, basic dispatch rules can easily be extended by, for example, considering dynamic variants, look-ahead periods, vehicle reassignments or other modifications. For the aforementioned reasons, a clear explanation to clients, and re-usability of the model for various manufacturing layouts, the use of dispatching rules seems to provide an appropriate solution.

5.4.2 Vehicle Scheduling Solution Approach

An approach solely based on workcenter- or vehicle-initiated dispatch rules is not sufficient. A workcenter-initiated dispatching strategy does namely not check whether there is a new transport job when an AGV has dropped-off a pallet. It may occur that orders are waiting to be transported, but that the workcenter-initiated dispatching rule will not take these orders into account because AGAPTVs could become available in the system one at a time. In particular, if the system load is high and the number of AGAPTVs is relatively low, the AGAPTVs then can form the bottleneck in the system. Likewise, a pure vehicle-initiated dispatching approach is not appropriate because if all AGAPTVs are idling at the moment a transport job becomes available, there is no initiator of the job assignment. This would often occur in systems where the load on the system is low and multiple AGAPTVs are available to transport orders.

For these reasons, the incorporated vehicle scheduling approach includes triggers and rules from both type of strategies. A consequence is that the load on the system may influence the system performance because different dispatch rules are used. The following triggers are identified:

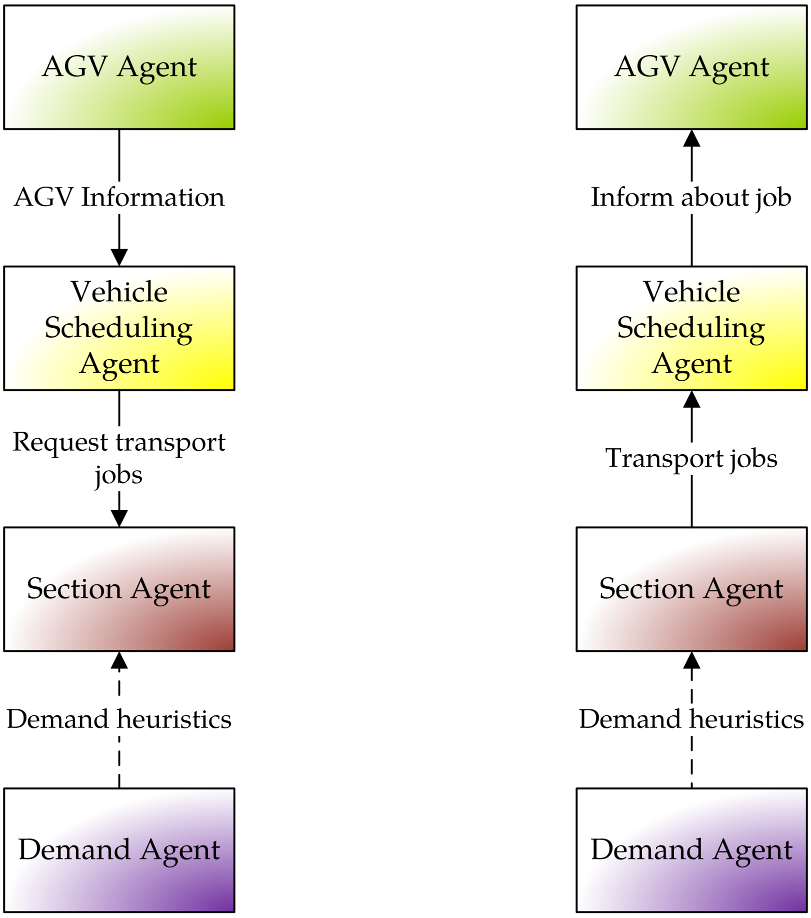
- **Workcenter-initiated**: Pallet transport job initiated;
- **Vehicle-initiated**: AGAPTV dropped-off a pallet;
- **Vehicle-initiated**: AGAPTV that is charging its battery reached the plateau level b_{plat} (see Subsection 5.6.1 for the definition).

So, both allocation strategies are considered in the model. Below we subsequently address the vehicle- and workcenter-initiated dispatching rules.

5.4.2.1 Vehicle-initiated Dispatching

Vehicle-initiated dispatching includes the assignment of jobs based on triggers from the *AGV Control Agent*. Whenever an AGAPTV becomes idle, the *AGV Control Manager* informs the *Vehicle Scheduler* about its position (see Figure 5.6a). We decide to let the *Vehicle Scheduler* send a request to all *Section Managers* to submit their transport job characteristics (i.e, load type, earliest and latest delivery and release time, P/D-locations). Based on these characteristics, the *Vehicle Scheduler* selects the most suitable transport job candidate and informs the *AGV Control Manager* about the course of actions (see Figure 5.6b). The considered dispatching rules are discussed below.

In this vehicle-initiated dispatching approach, the *Section Managers* keep track of a list of transport jobs that should be carried out within their group of cells. Transport orders containing fresh anode pallet requests are generated by the *Demand Management* and send to the *Section Management*. The butt pallet requests are generated by the *Section Management*. The *Section Management* retains information about both fresh anode pallet transport requests and butt pallet transport requests. The considered vehicle-initiated dispatch rules are shown in Table 5.2.



(A) Information flow from the *AGV Control Agent* to the *Section Agent*.

(B) Information flow from the *Section Agent* to the *AGV Control Agent*.

FIGURE 5.6: Vehicle-initiated communication scheme. The *AGV Control Agent* starts by sending AGV information to the *Vehicle Scheduling Agent*. The *Vehicle Scheduling Agent* then request a list of transport jobs from the *Section Agent*. Based on this list and the dispatch rule, the *Vehicle Scheduling Agent* selects an appropriate AGV.

For efficiency reasons, we also include dispatch rules that try to combine fresh pallet dispatch orders with butt pallet dispatch orders. For example, if a fresh anode pallet is required from rodding shop r to segment s cell c, we check whether there is a butt pallet dispatch order to rodding shop r that is nearby the current position of the AGAPTV or on the AGAPTV's route towards the rodding shop that can be picked-up intermediately and dropped-off at the directed rodding shop. To this end, we include a modified First-Come-First-Served (FCFS) dispatch rule that checks whether there is a butt transport request in the drop-off segment of the fresh anode pallet (and then possibly takes a random one). When there is no such a job, we check if a butt pallet transport request exists on the AGAPTVs route to the rodding shop, and if so, this job is picked-up and dropped-of intermediately. In the case of multiple jobs, the first available butt pallet is chosen.

Of course, one could consider alternative vehicle-initiated dispatching concepts. An alternative design would be, for example, to eliminate the *Section Manager* and let the *AGV Control Managers* communicate directly with the *Demand Manager*. However, as we use an approach that involves making multiple decisions on the section level of a smelter (see Section 6.1) with the possibility to deviate demand generation procedures, we prefer using the previously discussed vehicle dispatching approach including the *Section Management*. Furthermore, our approach provides the flexibility to adjust handling procedures in sections easily. In comparison to fully centralized approaches, our approach provides a flexible and fast schedule that can adjust rapidly to changing potroom events.

TABLE 5.2: Overview of vehicle-initiated dispatching rules. Adopted from Egbelu and Tanchoco (1984).

Rule	Description
First-Come-First-Served (FCFS)	Select the job that entered the system as first
Random Job (RJ)	Select a random transport job
Closest to Latest Release Time (CLRT)	Select job closest to its latest release time
Shortest Travel Distance (STD)	Select the nearest transport job
Longest Travel Distance (LTD)	Select the farthest transport job

5.4.2.2 Workcenter-initiated Dispatching

Workcenter-initiated dispatching covers the selection of an AGV based on triggers from the *Demand Management* or *Section Management*. The *Demand Management* initiates transport jobs from the rodding shop to the cells and the *Section Management* initiates transport jobs from the cells to the rodding shop.

As soon as a transport job from the rodding shop to a cell arises, the *Demand Management* informs the *Section Management* about the job characteristics. The dedicated *Section Management* then sends a transportation request to the *Vehicle Scheduler*. Consequently, the *Vehicle Scheduler* obtains AGV characteristics (e.g., current position, idling status, utilization, etc.) for all the AGVs from the *AGV Control Managers*. On its turn, the *Vehicle Scheduler* then selects the most suitable candidate, if any, and informs the selected *AGV Control Manager* about the transport task. The candidate is chosen based on the heuristic rules as shown in Table 5.3. An overview of the hierarchical communication scheme is depicted in Figure 5.7.

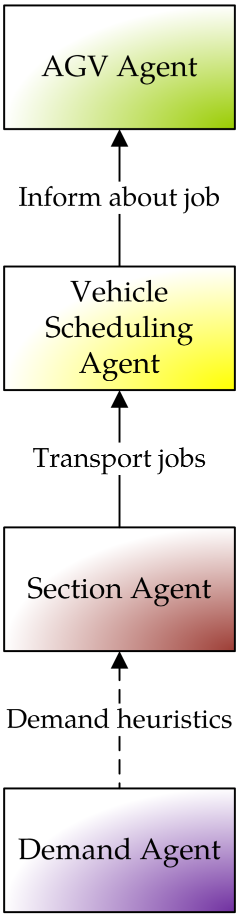


FIGURE 5.7: Workcenter-initiated communication scheme. Dispatch jobs are initiated in the *Section Agent* and pushed to the *Vehicle Scheduling Agent*, which on its turn informs the chosen AGV.

TABLE 5.3: Overview of workcenter-initiated dispatching rules. Adopted from Egbelu and Tanchoco (1984).

Rule	Description
First Available Vehicle (FAV)	First vehicle that becomes available, will pick-up the job
Random Vehicle (RV)	Load is randomly assigned to any available vehicle
Nearest Vehicle (NV)	The vehicle at the shortest distance of the load is assigned to the transport request
Farthest Vehicle (FV)	The vehicle at the greatest distance of the load is assigned to the load
Least Utilized Vehicle (LUV)	The vehicle that has the minimum mean utilization is dispatched to the transport job
Longest Idle Vehicle (LIV)	The vehicle which is idle for the longest time among all vehicles is dispatched to the transport request
Least Cumulative Idle Time (LCIT)	Choose the vehicle that has the lowest total idle time
Fully Charged Vehicle (FCV)	Select the vehicle with the highest battery level

A similar approach is used in the case a transport request is initiated from the *Section Management*, which comprises the transport request from a cell to the rodding shop. Except that then the *Demand Management* is not included because the request originates from the *Section Management*.

5.5 Vehicle Parking

Idleness of vehicles is unavoidable in AGV systems. An AGV becomes idle if it has delivered a transport job at its destination and it is not immediately assigned to a new task. An AGV parking strategy considers parking vehicles at positions such that they can react efficiently to new transportation jobs. The main purpose of these strategies could be to minimize the vehicle response time to new transport requests (i.e., time until the next job is picked-up), minimize the maximum response time of vehicles to travel empty from parking location to the pick-up location of the load, or to evenly distribute idle vehicles in the network (Egbelu, 1993). Below, we first address vehicle parking approaches in Subsection 5.5.1. Afterwards Subsection 5.5.2 advocates the used approach.

5.5.1 Vehicle Parking Approaches

Two main strategies for parking idle vehicles are static and dynamic strategies. In static positioning strategies, the location of a parking area is fixed. We focus on applying static positioning strategies. In general, the potroom layouts are not suitable for parking vehicles within the segments aisles. Parking areas are usually dedicated to fixed locations close to the paths where potroom activities are carried out. The following strategies are commonly used for positioning idle vehicles (Le-Anh and Koster, 2006):

- central-zone positioning: idle vehicles are buffered in a designated parking area. This parking area can be close to pick-up and delivery locations which are characterized by a high volume of transport requests or at, for example, battery-recharge stations. Central refers to serving the entire network from the designated parking zones.
- circulatory-loop positioning: idle vehicles travel on one or more defined loops of the guide-path network until they receive a new transport request.
- drop-off point positioning: idle vehicles remain at the point of the last delivery job until it is reassigned.
- distributed-positioning: employs multiple dwell points as opposed to a single point. One of the dwell points is chosen in case a vehicle becomes idle.

A *central-zone positioning strategy* is a relative easy-to-understand approach that does not require complex computations during run-time because AGVs are always directed towards the same parking location. However, as aluminium producers may have multiple dwell areas and AGAPTVs may drive through the entire potroom area, we expect this strategy is not preferable if one aims to achieve an efficient operational potroom performance.

The *circulatory-loop positioning strategy* is likewise not preferable because of the many expected AGAPTV movement restrictions. Moreover, with respect to maintaining a high potroom safety and possibly avoidance of other movable objects like smelter equipment, we do not expect this strategy would outperform the other ones in terms of achieving a beneficial operational performance. Occurring blockades may affect the circulatory-loop which needs to be adjusted appropriately. Furthermore, it is questionable whether the vehicle response time would be shorter and the additional consumed electricity by the AGAPTVs under this strategy would yield a satisfactory performance.

The *drop-off point positioning strategy* requires some more attention as this would be an interesting approach to consider. The vehicle response time would be short if the next assigned job for the vehicle is close to the AGAPTV idling point. However, the next transport job is not always known upfront (see elaborations in Section 6.1). If the current AGAPTV drop-off point is near an electrolytic-cell, the vehicle response time would be low if the next job is in the same segment or near the surrounding segments. In the case the next job should be picked-up in the rodding shop, the vehicle response time depends on the traffic density, facility layout, and whether there are shift activities planned on the paths. A similar performance can be expected in the case the drop-off point is in the rodding shop.

An advantage of a sole *drop-off point strategy*, so without modifications, is that it would require no complex calculations. However, the transition to the next shift and the occurring blockade restrictions impose that such a strategy without modifications would not be practical. For example, an AGAPTV waiting in an aisle has impact on both the potroom activities carried out in the segment and other AGAPTV movements due to the resulting blockade. Another issue with this strategy is the lack of charging possibilities. When the job arrival intensity is low, the probability of a vehicle being idle increases. If a vehicle is idling for a relatively long period at the drop-off point, the battery is being drained, while a better option may be to charge it by dispatching the vehicle to the charging station.

The *distributed-positioning strategy* can be seen as a combination of the *central-zone* and *drop-off positioning strategy*. Multiple dwell points are used and idling vehicles are directed towards one of these points.

5.5.2 Vehicle Parking Solution Approach

As we aim to develop a generic model that can evaluate various factory layouts and include different operational planning and control rules, we decide to focus on the *distributed-positioning strategy* with a limited number of dwell points. We limit the scope of this thesis to not defining dwell points in the aisles containing the cells and the cross aisles, but in dedicated areas located in the outer ends of the potlines. In these outer parts there is often enough space to park a series of vehicles.

The main reason for this is to not exclude smelter facilities that are characterized by, for example, narrow aisles, specific demand patterns (e.g., arrival intensities) and other blocking restrictions. Also, these parking areas are usually equipped with electricity charging stations. Therefore, as soon as an AGV is idling and thus has no other transport task, a new task is scheduled towards the closest parking location. This task is considered as a low priority task and as soon as another pallet transport task arises, this task can be overruled. Section 6.1 describes the approach used for parking AGAPTVs in more detail. Other more complex parking strategies could be investigated in future research.

5.6 Battery Management

On the tactical level, the battery management has to be addressed. Although battery management is important for vehicle management, literature usually omits this problem. In most manufacturing and distribution areas AGVs travel over relatively short distances and it is often assumed that during idle times batteries can be replaced or swapped (Vis, 2006). One could argue that in shift-based operations, such as considered in our study, there are 'natural' breaks in which the AGV batteries can be recharged or swapped. However, as the distribution of shifts may deviate among scenarios and there is little known about the idling times of AGAPTVs, we can not make any statements regarding whether this assumption would be realistic. Moreover, AGAPTV routes are not always fully known due to blocking restrictions and conflicts, and AGAPTVs likely need to travel long distances. As a result, the AGAPTVs probably have a limited amount of idle time and the assumption seems therefore not valid. For that reason, we decide to include battery management in this study. First, an outline of possible battery management approaches is given in Subsection 5.6.1. Subsection 5.6.2 motivates the used approach in this study.

5.6.1 Battery Management Approaches

In the literature chapter (Chapter 2), we briefly presented three charging strategies:

- automatic charging. An AGV recharges when its available energy reaches a certain level and then the scheduler assigns this AGV for charging;
- opportunity charging. The AGV follows a pre-defined battery charge plan and uses the natural idle time in an AGV's cycle to replenish batteries;
- combination system, which is a combination of the previous two schemes.

In the automatic charging strategy, an AGV drives until its battery is depleted to a certain level and then the AGV is assigned to a charging station (McHaney, 1995). A clear benefit of this strategy is that the condition during the entire life span of the battery can be properly maintained. In the opportunity charging strategy, AGVs are send to charging stations whenever they become idle. An AGV is idling if there is no transport job currently scheduled for this AGV. Opportunity charging is preferable if one wants to maximize the battery level of all AGVs. A third strategy combines the two strategies.

5.6.2 Battery Management Solution Approach

The best moment to start charging for achieving a good long-term battery performance depends on the battery type and loading history. Commonly, the optimal strategy would not be to start loading until the battery level is completely drained to zero but to start loading a bit earlier. Likewise, it is not always optimal to keep charging the battery until it reached a 100% fill rate. The last few percentages would take significantly more time to replenish the battery. As the purchase price and capacity of batteries play a major role in buying AGAPTVs, we introduce a series of battery level parameters which provide a basis for future analysis regarding battery performance. We simplify the actual processes going on in the battery by not covering battery leveling.

The approach comprehends a combined battery charging strategy including elements from both automatic charging and opportunity charging. To this end, we first declare the charging parameters, after which an explanation about the followed approach is given. Although one could argue that, by artificial modifying the threshold values, a smaller set of battery charging parameters could be established, we choose the following battery level parameters to clearly distinguish between the degrees:

- Critical minimum level b_{min} (usually 0%): absolute minimum;
- Preferred level b_{pref}: best start moment for charging the battery;
- Plateau level b_{plat}: battery is usually charged until the plateau level is reached;
- Maximum battery level b_{max} (usually 100%): absolute maximum;
- Automatic charging threshold level b_t: b_{pref} plus estimated battery consumption from current AGAPTV location to nearest charging station including possibly finishing the current job;
- Opportunity charging: battery level window in which opportunity charging may be carried out.

The used approach is further discussed now. The absolute minimum and maximum battery levels of an AGAPTV are defined by respectively b_{min} and b_{max} (see Figure 5.8). It is undesirable that these levels are reached because of a properly maintained battery's condition, but reaching these limits may be unavoidable in some cases. The preferred battery level b_{pref} denotes the best level from whereon charging should take place. This level depends on battery characteristics and, obviously, will scarcely be reached exactly. A consequence of this approach which considers the battery levels of AGVs individually is that it could be the case that suddenly a large population of the fleet needs to recharge their batteries at the same time. However, we leave the design of more sophisticated battery management approaches to a future research.

It is important that already assigned transport tasks can still be executed without the interruption of an AGV having a too low battery level, because we decided to not drop-off pallets at intermediate locations. It is therefore required to check beforehand whether or not a new transport job can be accepted. In this study, a battery management approach is considered that can be used regardless of whether the next transport task is known upfront or not. The approach consists of a combination system where both automatic charging and opportunity charging elements are included. The parts below address these approaches respectively.

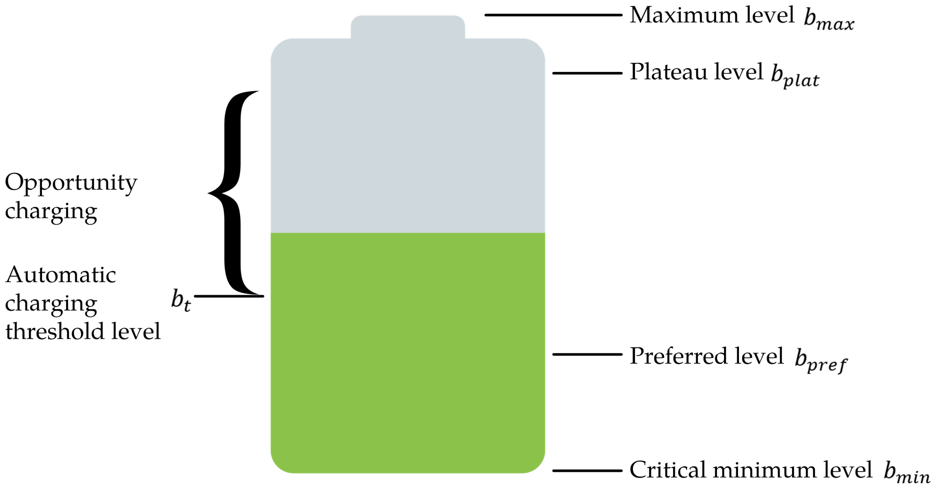


FIGURE 5.8: Battery charging parameters.

5.6.2.1 Automatic Charging Approach

In case an AGAPTV's battery level is lower than or equal to the so-called automatic threshold level b_t, a transport request to the nearest charging station is scheduled. The battery is then recharged until at least the plateau level b_{plat} is reached. Two variants regarding such a plateau level are considered:

1. Recharge a minimum amount of b_{δ_t}-time units from the moment charging is taking place. Preferably this amount is higher than the time is takes to replenish a battery from b_{min} to b_{pref}.
2. Recharge until at least the battery reaches the level b_{plat}. This value can for instance be set to the plateau level.

The automatic threshold level b_t depends on the vehicle's state and position. Basically, b_t presents an estimation of the battery level from whereon it is desirable to schedule a driving task towards the nearest charging station when the expected battery level at the moment of arrival is b_{pref}:

$$\begin{aligned} b_t &= b_{pref} + EP_{k,l,c}, \\ EP_{k,l,c} &= \overline{p}_{loaded} \cdot ET_{k,l} + \overline{p}_{unloaded} \cdot \overline{ET}_{l,c}, \\ \overline{ET}_{l,c} &= \frac{1}{C} \sum_{1}^{C} ET_{l,c} \end{aligned} \tag{5.2}$$

where, $EP_{k,c,l}$ expresses the expected power consumption from current AGAPTV position k to charging station c via drop-off location l. The power consumption $\overline{p}$ represents the average battery consumption of the AGAPTV for handling a certain load. The expected travel time from the drop-off location to the charging station is approximated by taking the average travel time to all charging stations. The average is considered because, in general, the charging stations are located evenly across the layout.

One may argue that using an approach with a fixed level indicating that charging is needed is desirable in some cases because of its simplicity. However, when the model must be applicable to a wide range of plant layouts including differentiation of charging station locations, a fixed automatic charging level may limit the efficiency. For example, consider having a large potroom with only one charging station. The automatic charging level then has to be set relatively high because long trips should be covered as well, leading to relative early charging moments.

5.6.2.2 Opportunity Charging Approach

In addition to the automatic-charging approach, opportunity charging is used. Opportunity charging considers the case that the automatic charging threshold is not being reached and that there is sufficient slack in-between doing the next job such that the battery can be recharged somewhat intermediately. A charging moment is scheduled once the following formula is satisfied:

$$S_{j+1} - Et_{k,c,l} \geq \theta\alpha \tag{5.3}$$

where,

$$\begin{aligned} S_{j+1} &= Ed_{j+1} - t_{current}, \\ Et_{k,c,l} &= \min(Et_{k,c} + Et_{c,l}), \forall c \end{aligned} \tag{5.4}$$

S_{j+1} denotes the slack time until the next job requires the pallet. S_{j+1} is expressed as the earliest delivery time Ed_{j+1} minus the current time. $Et_{k,c}$ is the expected travel time from the current AGAPTV position k to charging station c and $Et_{c,l}$ is the expected travel time from charging station c to the P/D location l. The formula considers expected travel times, because these times are determined based on the system state at discrete moments in time. Remark that in case of a fresh anode pallet, the anode pallet release time t_a should be subtracted for determining S_{j+1}:

$$S_{j+1} = Ed_{j+1} - t_{current} - t_a \tag{5.5}$$

The left hand-side of Formula 5.3 should exceed a certain threshold $\theta\alpha$. This threshold value represents the minimum charging time of the AGAPTV expressed in time units and depends on a desired minimum increase of $\alpha\%$ in the battery level. The threshold-formula is included because it is not convenient to charge for only a negligible increase in the battery level. Furthermore, the actual travel time of the tour could deviate from the original determined expected one and might cause an issue in delivering the pallet on-time. By including both an automatic charging approach and an opportunity charging approach with the ability to tune parameters, we expect to effectively incorporate a valid battery management methodology.

5.7 Vehicle Routing

The vehicle routing is addressed on the operational level and is aimed at finding paths for vehicles that are dispatched for certain tasks. Scheduling and routing vehicles in AGVs systems are closely related and should be addressed concurrently (Le-Anh and Koster, 2006). The vehicle routing problem needs to simultaneously address resolving and preventing deadlocks as well. On the tactical level, we already proposed a vehicle scheduling approach to decide upon which vehicle (or workstation) to select for handling transport jobs (see Section 5.4). Design choices regarding the approach for finding and adjusting routes are discussed now. Subsection 5.7.1 outlines the solution approach and Subsection 5.7.2 provides details regarding the construction of the routes.

5.7.1 Vehicle Routing Approach

The vehicle routing of the AGV system addresses how routes from and to P/D-locations are constructed and modified due to occurring and lifted blockades. It also describes which triggers may influence the routes and thus possibly require the calculation of new routes. The goal of vehicle routing is to find the shortest paths between an origin and a destination point. Plenty of solution techniques are usable from an algorithmic point-of-view as we discuss in Subsection 6.2.9, but for the design of the AGV system, we should address a few design considerations first. Vehicle routing is interconnected with the *Conflict Resolution* agent and the *Vehicle Scheduler*, but primarily focusses on the construction of shortest paths. Triggers that require interaction with the vehicle routing are:

1. Pallets positioned in the segment aisles: release and occurrence of blockades.
2. Crane activities: release and occurrence of blockades.
3. Metal tapping activities: release and occurrence of blockades.
4. Vehicle-initiated dispatching rules: shortest path calculations.
5. Workcenter-initiated dispatching rules: shortest path calculations.
6. Battery charging tasks: shortest path calculations.
7. Parking task: shortest path calculations.
8. Conflict resolution tasks: safely conducting collision avoidance maneuvers after which the route can be continued/re-calculated.

Important in the route calculation is that the computational time should not be too time-consuming because the environment can change and affect the solution quality quickly. Consequently, the previously found solution may not be feasible or optimal anymore and requires a re-computation. Blockades and collision avoidance maneuvers are examples of (environmental) events that could influence the routes. Besides that computational time should be considered in the vehicle routing approach, the complexity and solution quality are of importance as well. Another design consideration is the capability to foresee the dynamics of the environment and act adequately to avoid collisions by stopping, slowing-down or taking an alternative route (Qiu et al., 2002).

We now elaborate upon solution approaches applied to vehicle routing. Chapter 3 already addressed several dynamic planning strategies with their characteristics which we can use in our analysis. A solution approach to coping with those design considerations is a time-based routing algorithm that finds unique time-windows in which AGAPTVs can traverse a path. However, as our evaluation model must be able to evaluate the impact of rapidly changing circumstances while still achieving a good solution quality, such an algorithm may be insufficient or not practical. For example, taking into account the ability to effectively and efficiently cope with bi-directional paths, suddenly occurring path blockades, collision avoidance maneuvers, demand fluctuations, and other scheduling uncertainties, would make such a model rapidly complex or computationally expensive. We expect that for developing an evaluation model that is able to assess a series of scenarios with each having unique characteristics, putting a lot of effort in designing time-based routing algorithms is unfavorable above other approaches.

An alternative approach is similar to the one as discussed by Gerrits (2016) but with some modifications. That approach uses forward sensors on AGVs to detect near-collision issues and a set of priority rules for making stop, go, and slowdown decisions. Communication is done among the AGVs and routing and collision problems are solved locally. To this end, a list of predefined rules declares what priority is given to what vehicle. Considering this approach, head-to-tail collisions are not likely to occur because AGAPTVs drive at the same speed. In our case, the bidirectional guide-paths would increase the complexity for scheduling the routes and effectively avoiding collisions. This complexity is even more increased when considering pallet placement maneuvers which require forwards and backwards driving in the same aisle segment. To adjust this solution approach for the purpose of this thesis, the option to change driving directions is added to the decision set.

We expect that the latter solution would be more beneficial for the purpose of Hencon with respect to the clarity of the model, scalability, ability to adjust the system to future extensions, and computational effort. By considering such a vehicle routing approach that is relatively simple, easy to adjust, and applicable to a major population of Hencon's clients, the genericness of the system is to a significant degree guaranteed. A drawback is that vehicle routing solutions may not be as efficient in terms of achieving a good system performance in comparison to a time-based routing algorithm. However, as various system configurations could be examined with the evaluation model, we expect that we can still provide good results that are not considerably worse. Another issue is that this technique is not effective for systems with many curved guide-paths (Le-Anh and Koster, 2006). However, by using this forward sensing technique in combination with other collision avoidance techniques, as we discuss in Section 5.8, we could still provide an effective vehicle routing approach. Furthermore, we expect that regarding the implementation the priority rule-based approach would be more favorable from a practical perspective. For these reasons, we decide to design a modified variant of Gerrits (2016). Design decisions concerning the vehicle route construction design of this approach require a bit more explanation that is addressed below.

5.7.2 Vehicle Route Construction Design

The construction of shortest paths can be done in several ways as we discuss in Subsection 6.2.9. In addition to these shortest path algorithms, the vehicle routing should act adequately when conflicts arise and collisions should be avoided. To elaborate on the influence of route construction design on these issues, suppose an initially constructed route is not feasible anymore because changing shifts resulted in new blockades on the route. If an AGAPTV is already on its route and detects that it cannot drive further because of blocking constraints, the route should be re-computed.

Blockades are temporary of nature and different route construction approaches can be used to cope with this. One way is to determine routes statically and only re-schedule the route once an AGAPTV detects a blockade. We refer to this approach in which routes are only re-computed if a blockade is detected in the next path as a *reactive vehicle routing*. Another way to determine routes is to dynamically re-calculate them based on the occurrence and release of blockades trigger. We denote this type of scheduling as *pro-active vehicle routing*.

Both approaches have their pros and cons. Reactive vehicle routing could prevent unnecessary bypasses because blockades might be temporary. Pro-active approaches on the other hand, may find more efficient routes by adjusting the routes based on triggers from the environment instead of blockades detected by the AGVs. Likewise, a trade-off can be made regarding the computational effort. Reactive vehicle routing only re-schedules routes once an AGV detects a blockade, while pro-active vehicle routing re-schedules routes if a blockade is released or occurred. Furthermore, there is a practical issue regarding the implementation of the approaches. Not all of Hencon clients have organized their infrastructure such that a pro-active vehicle routing approach can be implemented easily. However, as we expect that pro-active vehicle routing will outperform reactive vehicle routing in some cases, it is interesting to include both approaches. To this end, we consider both vehicle routing approaches as part of the evaluation model. The next part of the AGV system design, Section 5.8, further elaborates on the integration of the conflict resolution and the vehicle routing approach.

5.8 Conflict Resolution

The final part of the operational design decisions is the conflict resolution. In particular in conventional guide-paths were space is often limited available, deadlock resolution and prevention issues are important (Le-Anh and Koster, 2006). Jing and Ying (1994) list the following problems that may arise when routing AGVs:

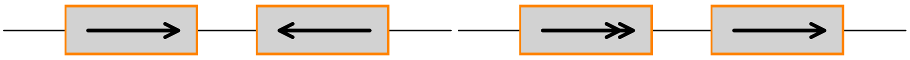
- collision: occurs when more than one AGV attempts to occupy the same part of a path at the same time (see Figure 5.9c);
- congestion: arises at places where there is insufficient aisle capacity such that for a certain period of time the number of arrivals is greater than the outgoing flow (see Figure 5.9d);
- deadlock: occurs when multiple AGVs mutually wait for release in such a way that the situation cannot be resolved without some forms of intervention. Without this, the AGVs will be waiting forever to proceed (see Figure 5.9h);
- livelock: may arise at the intersection of aisles where a stream of traffic is always granted priority above other streams which wait indefinitely (see Figure 5.9e).

As addressed before, conflicts may arise in several forms. Proper conflict resolution aims to achieve a collision-free environment and minimize the waiting time due to conflicts. Hence, the overall system performance should not be negatively affected substantially. In general, the number of conflicts will raise when the number of AGVs in the system increases, the size of the guide-path network decreases, or the traffic intensity in a region increases. So, an effective prevention and/or resolving approach is desirable.

In the previous subsection, we already introduced the forward sensing technique to avoid collisions in the vehicle routing but the concepts highlighted so far are not yet describing its full functionality. An important design aspect of this technique is the accompanying set of priority rules. The conflict resolution design we propose in Subsection 5.8.1, designates those rules and applies them with a conflict resolution approach covered in Subsection 5.8.2. The following part of this subsection gives further details regarding the conflict resolution methods considering the other problems as described above as well.

5.8.1 Conflict Resolution Approach

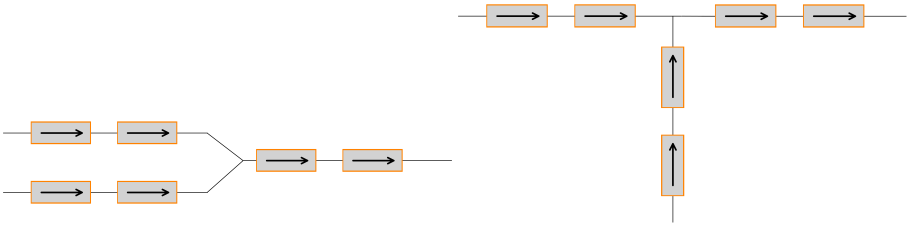
To cope with the previously addressed conflict issues, we employ a zone control method. In a zone control approach, the guide-path network is partitioned into a number of zones with a restrictive vehicle movement rule (Moorthy et al., 2003). Zone control is often seen as an efficient method to avoid deadlocks (Le-Anh and Koster, 2006). Each zone, which is specified with a certain width and length, should be large enough to accommodate the entire body of a vehicle possibly extended with the distance required to stop an AGV. Typically, only one AGV is allowed to occupy a zone and any other vehicles intended to enter the zone have to wait for movement clearance (Moorthy et al., 2003). A drawback is that deadlocks may arise due to the zone-partitioning rule. So, a zone basically acts as a buffer in the system which may be occupied by a limited number of vehicles.



(A) Head-to-head collision.

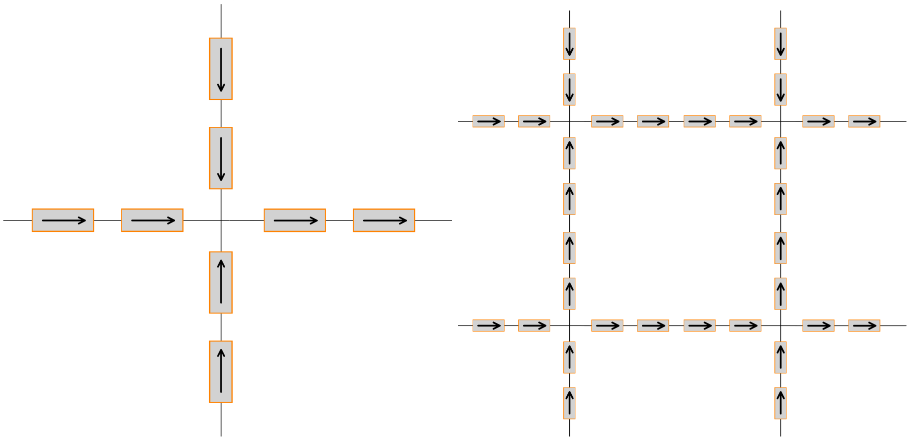
(B) Head-to-tail collision.

(C) Collisions.



(D) Congestion.

(E) Livelock.



(F) Non-local deadlock.

(G) Local deadlock.

(H) Deadlocks.

FIGURE 5.9: Possible conflicts in an AGV system. Adapted from Gerrits (2016).

Two types of zone control methods can be distinguished: static zoning and dynamic zoning. A *static zone control* uses fixed zone positions and sizes while a dynamic zone control may adjust the positions and sizes (Le-Anh and Koster, 2006). In a *dynamic strategy*, zones can be changed depending on the system state. Although the dynamic zone control would be interesting to include, we decide to not use this variant. Because we simplify potroom crane movements and do no know all transport demand and blocking restrictions upfront, we could not expose the full potential of a dynamic zone control while it may take a considerable amount of time to even design a basic variant. Furthermore, we expect the static variant can be easier controlled by Hencon's clients than the dynamic one. We thus leave the dynamic zone control to further research. The subsequent part of this subsection describes the considered zone control method.

5.8.2 Zone Control Construction

The used zone control approach for avoiding vehicle collisions consists of the declaration of dedicated zones in the potroom and a set of elementary traffic rules. We define the following zones:

- northern back aisle of each segment (indicated green in Figure 5.10);
- northern center aisle of each segment (indicated blue);
- southern center aisle of each segment (indicated red);
- southern back aisle of each segment (indicated white);
- cross aisle in-between segments (indicated yellow);
- cross aisle in-between potrooms (indicated black).

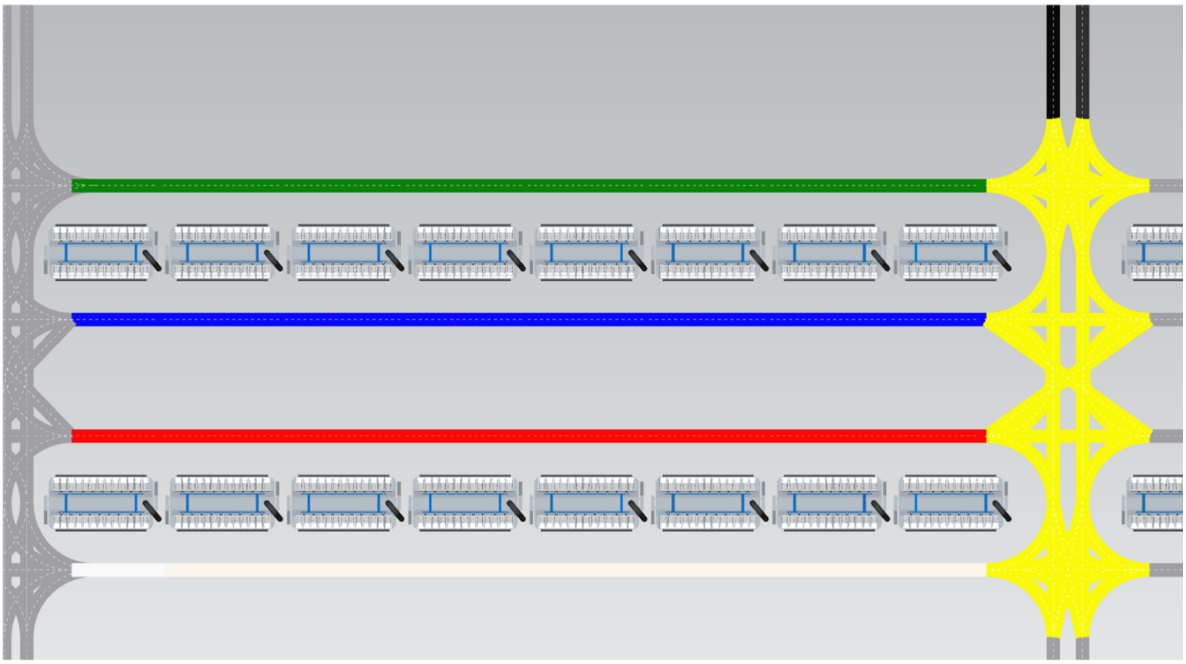


FIGURE 5.10: Zone partitioning. Zones in each segment are: northern back aisle (green), northern center aisle (blue), southern center aisle (red), southern back aisle (white). Additionally, a zone is dedicated to the paths in-between segments (yellow) and in-between potrooms (black).

Independent of the type of transport, we restrict the number of AGAPTVs to be at most one per zone. As soon as a vehicle wants to enter the next zone, it is checked at the checkpoint, which are the intersection points of the zones, whether that zone is already occupied. When this is the case, priority is given first to vehicles according to the designated priority rule. Based on defined zones and intersection checkpoints at the zones, we decide to consider stochastic priority rules that give priority to a vehicle at random. Each time both vehicles reach the intersecting checkpoint, priority is given based on an uniform probability distribution function with a variable as shown in Table 5.4. By default the probability distribution functions grant the priority to a vehicle on 50% of the time. However, in the case of a blocked segment aisle, the vehicle in that aisle always gets priority, which means that the conflicting cross aisle vehicle should conduct the avoidance maneuver.

TABLE 5.4: Zone partitioning priority rules probabilities.

		Interference with			
		Segment aisle	Blocked segment aisle*	Cross aisle	Potroom aisle
Check-point	Segment aisle	-	-	z_{SC}	
	Cross aisle	z_{CS}	z_{CBS}	-	z_{CP}
	Potroom aisle	-	-	z_{PC}	-

*: Blocked due to either metal tapping or anode changing (crane).

Appendix F illustrates how a collision avoidance maneuver is carried out when an AGAPTV in the cross aisle detects a possible collision at the checkpoint of a segment aisle and the AGAPTV in the segment aisle grants priority. In such a maneuver, the vehicle positioned in the cross aisle maneuvers away from the intersection such that the other vehicle can continue its route. Similar procedures are used in other conflicting cases.

Notice that this approach supports in eliminating deadlocks. In particular system states in which livelocks, non-local deadlocks and local deadlocks happen will benefit from the stochastic element that allows vehicles to (temporary) escape from blockades. Despite that deadlocks cannot be avoided entirely with this strategy, e.g., because the system could end up in a state in which the AGAPTVs are continuously conducting avoidance maneuvers, we argue that by considering a set of stochastic variables, the waiting times will be acceptable in many cases and the number of avoidance maneuvers limited. In future research, one could investigate the impact of more sophisticated zone-control methods like adjustable priority rules or dynamic zones.

5.9 Conclusion

The AGV system design discussed in this chapter, outlines how strategic, tactic, and operational decisions are translated to functionalities of the AGV system framework. To summarize the fundings with respect to the decision framework of Le-Anh and Koster (2006) we conclude:

- Requirements and data: the AGV system incorporates facility characteristics and constraints such as blockades. Since there is no uniformly used approach for generating anode pallet demand (i.e., every smelter is unique), the system must be able to include a variety of demand patterns.
- Guide-path design: a conventional flow with multiple lanes that are bidirectional.
- Estimating the number of vehicles: Formula 5.1.
- Vehicle scheduling: vehicle initiated dispatching (five rules) and work center-initiated dispatching (seven rules).
- Vehicle positioning: distributed-positioning rule where the designation of dwellpoints and allocation rules is case specific. Parking location can only be designated in outer parts of the potline where there is sufficient space. Idling vehicles are send to these places by a low priority task.
- Battery management: automatic and opportunity charging. The automatic variant includes charging the battery at the moment an automatic charging threshold is reached and charges either until a fixed level b_{plat} is reached or until a certain time b_{δ_t} is passed, while in the opportunity charging method the battery is recharged once there is sufficient time in-between jobs. An opportunity charge is only scheduled once the opportunity arises that at least $\theta\alpha$ time units can be used to increase the battery at least by $\alpha\%$.
- Vehicle routing: reactive and proactive.
- Deadlock resolution: conflicts are detected by a forward sensing technique in addition to a zone control method. The guide-path network is divided into fixed zones which may be occupied by at most one vehicle at the same time. Priority rules are used for granting an AGAPTV priority above the other. In this zone partitioning rule, a stochastic variable expresses which vehicle is granted priority.

Chapter 6

Model Design: Scenario Evaluation Model

This chapter provides the evaluation model of the AGV implementation with corresponding MAS control strategy. Recall that the MAS functions as a planning and control system for the AGV system (see Figure 6.1). These two models are integrated into an evaluation model of which the conceptual model and the model content are presented in this chapter. Section 6.1 presents the conceptual model of integrated MAS and AGV system. Section 6.2 describes the model content. Section 6.3 concludes this chapter.

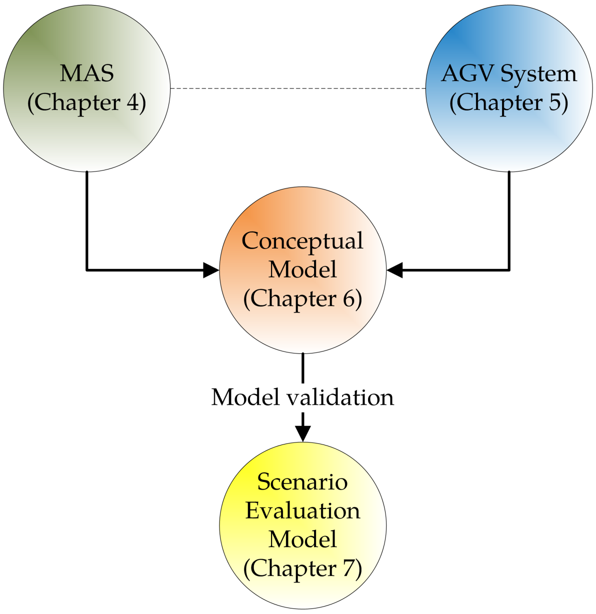


FIGURE 6.1: Methodology outline from building the models to model validation.

6.1 Conceptual Model

To design a sound and valid simulation model, a conceptual model is presented first. The conceptual model describes an abstraction of the 'real world' and forms the blueprint of an implementable model. A formal definition of a conceptual model is given by Robinson (2008a): a non-software specific description of the computer simulation model, describing the objectives, inputs, outputs, content, assumption, and simplifications of the model.

We follow a structured approach to design a valid simulation model. We decide to select the framework for conceptual modeling as reported in Robinson (2008b). Basically, this framework consists of the activities:

- Understanding the problem situation (Subsection 6.1.1)
- Determining the modelling and general project objectives (Subsection 6.1.2)
- Identifying the model outputs (responses) (Subsection 6.1.3)

- Identifying the model inputs (experimental factors) (Subsection 6.1.4
- Determining the model content (scope and level of detail), identifying any assumptions and simplifications (Section 6.2).

Additionally, to enhance the verifiability and validity of our model, we regularly interact with the managers and discuss the assumptions and simplifications with the management. Below we subsequently discuss the aforementioned framework activities.

6.1.1 Problem Situation

It is important to have a proper understanding of the description of the problem situation. The problem situation is what forms the input for the modelling and general project objectives. In the previous chapters, we already exhaustively discussed the problem situation. The problem situation with respect to the simulation model and Hencon as stakeholder can be summarized as follows:

Problem Situation: *Hencon aims to provide an appropriate evaluation of the performance of anode transporting AGVs in primary aluminium production facilities. Hencon wishes to investigate current situations and experiment with alternative operational planning and control strategies that could be beneficial for their customers. Ultimately, Hencon can then not only provide recommendations about a preferred number of AGVs and planning and control rules to their customers, but also provide insights into the achieved performance.*

To study the implications of alternative operational planning and control strategies for various scenarios, we use simulation. Simulation can be described as experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of a better understanding and/or improving of that system (Robinson, 2014). Simulation allows us to model real-world systems that are too complex to accurately describe by a mathematical model that can be evaluated analytically (Law, 2015). Simulation can be used to systematically evaluate modifications to model settings and study the long-term behavior. Simulation thus provides an adequate alternative opposed to experimenting in reality, which is more realistic but expensive and time-consuming in a capital intensive industry like the aluminium industry.

6.1.2 Modelling and General Project Objectives

This modelling and general project objectives part fulfills two purposes. First the modelling objectives should describe the purpose of the model and modelling project (Robinson, 2008a). Second the general project objectives should include the time-scales for the project and the nature of the model and its use. Robinson (2008a) discussed requirements of a conceptual model (validity, creditability, utility, and feasibility) and some general project objective considerations (flexibility, run-speed, visual display, ease-of-use, and model/component reuse), which we will connect to our objectives. The modelling and general project objectives are:

- The model should provide accurate insight into the logistic performance of AGAPTVs considering a given factory layout and interaction with the metal transport (*validity*).
- Demonstrate the impact of different operational planning & control strategies and be applicable to typical client situations (*validity*).
- Acts as a decision support tool for the management of Hencon to select appropriate designs (*validity, utility*). The intended users should be able to gain insights within reasonable time-limits (*run-speed, utility*) and without too much complexity involved (*ease-of-use, utility*).
- Hencon and its clients should have sufficient confidence in the model (*creditability*). To this end, the model should be visually attractive (*visual display*) and flexible such that it can be modified/extended by future designers/developers (*flexibility, model reuse*).
- The model must be *feasible* to build, that is, within reasonable boundaries of data input and time limitations.

In particular, we use discrete-event simulation to build the simulation model and conduct experiments. In such a simulation, the system can change at only a countable number of points in time (Law, 2015). In other words, the system is modelled as a series of events that may change the state of the system.

6.1.3 Model Outputs

Table 6.1 expresses the Key Performance Indicators (KPIs) considered in the evaluation model. This list of KPIs is constructed in collaboration with managers from Hencon.

TABLE 6.1: Model output

# KPI	Measurable unit (description)
Anode pallet cycle time	Average time between initialization of fresh pallet at the rodding shop until dropping off the butt pallet at the rodding shop (emergency shipments are excluded)
Anode cooling duration	Average waiting time between butt (anode pallet) earliest release time $BERT_{p,s,a}$ and butt pick-up time $BPT_{p,s,c}$ per butt pallet (emergency shipments are excluded)
Zone waiting time	Average, minimum, and maximum waiting time in queue expressed per zone
Conflicts per vehicle	Average number of collision avoidance maneuvers with respect to the zone-partitioning control rule, expressed as average number of times per vehicle per anode shift day
Conflicts per zone	Average number of conflicts per zone
Route adjustments	Average number of re-scheduling per trip
Vehicle density	Average amount of time spent per zone
Vehicle fresh response time	Average time between fresh pallet earliest release time ($FERT_{p,s,a}$) and fresh pallet pick-up time ($FPT_{p,s,a}$)
Vehicle butt response time	Average time between butt pallet earliest release time ($BERT_{p,s,a}$) and butt pallet pick-up time ($BPT_{p,s,a}$)
Number of too late fresh deliveries	Average, minimum, and maximum number of fresh emergency pallets (when $FLRT_{p,s,a}$ is exceeded)
Number of too late butt deliveries	Average, minimum, and maximum number of butt emergency pallets (when $BLRT_{p,s,a}$ is exceeded)
Empty rides	Average number of empty rides (absolute and relative) per vehicle per shift-day
Late deliveries	Number of too late deliveries divided by the total deliveries excluding emergency shipments
Early deliveries	Number of too early deliveries divided by the total deliveries excluding emergency shipments
Crane delivery time	Average, minimum, and maximum placement time between dropping-off the pallet and the time the crane actually needs the pallet
Crane working time	Average time the crane is swapping anodes, expressed as average over all sections and anode changing shifts
Crane waiting time	Average time the crane is waiting for its next job (time there is no job between $WEST_{p,s,a}$ and last swapped anode, excluding emergency shipments), expressed as average over all sections and anode changing shifts
Number of emergency shipments	Average, minimum, and maximum number of released fresh anodes not picked-up before $FLRT_{p,s,a}$
AGAPTV travel time	Average travel time per AGAPTV (absolute and relative)
AGAPTV waiting time	Average waiting time per AGAPTV (time a vehicle is not moving)
AGAPTV charging time	Average charging time per AGAPTV
Opportunity charging	Average, minimum, maximum number of opportunity charges per vehicle per shiftday
Battery level once starting charging	Average battery level of a vehicle starting charging
AGAPTV idling time	Average waiting time until a new transport job is assigned
AGAPTV utilization	Travel time plus service time divided by idling, waiting, charging, service, and travel time

6.1.4 Model Inputs

A distinction between model input parameters and experimental input factors can be made. Input parameters are uncontrollable factors that are considered to be set prior to conducting the experiments and the value of such a parameter depends on the potroom characteristics. Usually, one adjusts these parameters to specific instances and will only vary the values of them for experimenting. Table 6.2 depicts the input parameters. Experimental input factors, on the other hand, are controllable and can be modified by experimenting. Table 6.3 shows the experimental factors. Although one can consider the defined parameters as experimental factors as well (hence, the model is generic in that sense), this thesis limits the number of possible experimental configurations by considering the set of input parameters as being uncontrollable.

TABLE 6.2: Model input: parameters

Input (remark)
Physical layout properties (Subsection 6.2.2)
Blocked areas (Subsection 6.2.2)
Electricity charging stations locations (Subsection 6.2.2)
Zone control priority schema (see Subsection 5.8.2)
Conflict resolution probability distribution functions (see Subsection 5.8.2)
Number of anodes specified per cell
Setting cycle specified per cell
Shift-based working routine: time-window restrictions in which all scheduled activities should be carried out for a given section (default: anode changing 8 hours, metal tapping 8 hours, and pot tending 8 hours)
Anode pallet release time (minutes before the actual anode changing shift starts; default 4 hours)
AGAPTV parameters (see Appendix C)
Battery charging: maximum level b_{max}, preferred level b_{pref}, critical minimum level b_{min} (default $b_{max} = 100\%$, $b_{pref} = 20\%$, $b_{min} = 0\%$; see Subsection 5.6)
Pick-up and drop-off times of (empty) anode pallets
Service time distribution of anode replenishment in cells

TABLE 6.3: Model input: experimental factors

Input (remark) [options]
Number of AGAPTVs (if possible, default Formula 5.1) [1-∞]
Anode pallet capacity [1-∞]
Anode demand heuristics (see Appendix L) [1-4]
Anode pallet demand heuristics (see Appendix N) [1-3]
Pallet location assignment (see Appendix O) [1-5]
Crane working operation sequence (see Appendix P) [1-3]
Automatic charging: fixed plateau level b_{plat} [0-100%] (see Subsection 5.6)
Automatic charging: minimum charging time b_{δ_t} ⟨0-∞] (see Subsection 5.6)
Opportunity charging: minimum increase $\alpha\%$ in battery level (see Subsection 5.6)
Vehicle-initiated dispatch rules (see Subsection 5.4.2.1) [1-5]
Workcenter-initiated dispatch rules (see Subsection 5.4.2.2) [1-8]
Vehicle route construction: reactive (see Subsection 5.7.2)
Vehicle route construction: proactive (see Subsection 5.7.2)

6.1.5 Model Scope and Level of Detail

The scope outlines what to model and the level of detail outlines how to model it (Robinson, 2008b). What to model, assumptions and simplifications are addressed in this subsection, while Subsection 6.2 describes the model content and focusses on how to model it.

The scenario evaluation model covers activities involved in primary aluminium production facilities with a focus on the AGAPTVs. In particular, we focus on smelters using an end-to-end layout. Anode pallets should be transported from rodding shops to nearby cells and visa versa. This study focusses on the operational planning & control of the AGAPTVs and does not embody the entire aluminium production and manufacturing process. We assume the anode pallet demand is generated by the MES according to either certain demand schemes that estimate the behavior of such a system (see Section 6.2.3) or provided manually to mimic the exact customer demand. Furthermore, processes within an electrolytic-cell are simplified in the model. In reality, an electric current is passed through cells and the configuration of this plays a major role in how fast the anodes are consumed. We assume anodes are consumed according to the demand patterns as discussed in Section 6.2.3. We justify this simplification by enabling the option to provide the demand pattern manually.

Aluminium production is not completely embodied in the scope. The processes entailed in producing/manufacturing anodes and anode pallets are not included. We assume the storage areas containing fresh anode pallets and butt anode pallets cannot run out of supplies and have an unlimited storage capacity. Likewise, we assume a homogeneous type of workforce for replacing anodes in cells. A workforce handles activities embodied in the scope of one section only during a shift. Additionally, other type of vehicles such as metal transporters are not included in the scope. Although we face deficiencies regarding model validation because of the exclusion of metal transporting vehicle, we partly include the metal tapping processes inside segments by blocking them once metal tapping takes place. We thereby assume AGAPTVs can maneuver freely in-between other vehicles.

We consider the anode setting, metal tapping, and pot tending shift to follow each other repetitively in a section. In the anode setting shift, the crane behavior is simplified by using heuristics. When the anode swapping process is taking place, certain paths as defined in Subsection 5.1.4 will be blocked. The service-times of replacing anodes follow a certain probability distribution which is aligned with customer specifications. Although the crane behavior is not modelled explicitly, we argue this approach is valid for representing reality because blocking restrictions are considered and the heuristics can be tailored to simulate the behavior of customers to a high degree.

AGAPTVs are simplified as being a homogeneous fleet including the same type of functionalities and similar characteristics. Pick-up and drop-off times are considered to follow a fixed amount of time. Furthermore, we do not consider failure behavior and vehicle maintenance. Also, battery leveling is not included. We expect these features have a limited impact on the performance and delay a rapid model development.

The discussed model scope so far including assumptions and simplifications is supplemented with the content described later on. Appendix F provides an overview of the model scope.

6.2 Model Content

The model content describes how the inputs are accepted and appropriately modelled to the required outputs. Explanation and flowcharts regarding certain events require attention. This section subsequently covers these elements: model initialization and model reset, guide-path construction, demand management, section management, AGV parking management, vehicle scheduling, battery management, vehicle routing, and conflict resolution.

6.2.1 Model Initialization and Reset

Model initialization comprises the preparation of the model such that it can run the experiments appropriately. Because the system operates 24 hours a day and there is no natural event to specify the end of a simulation run, we have a nonterminating simulation. We are interested in the behavior of the system on the long run when it is operating "normally". This affects how the simulation model should be initialized and reset.

The way the model initialization and resetting is organized also depends on the configuration of parameters and experimental factors chosen by the user. For example, the generation of fresh anode pallets can be done randomly or according to a specified pattern (see Subsection 6.2.3). Another example is the specification of the activity duration in shifts. As a consequence, the system may behave differently in each setting and yield different characteristics with respect to the output performance (i.e., steady-state parameters, steady-state cycle parameters or transient performance). We apply the considered length of the three shift activities together as one run (usually one day). Thereby we simplify the model by considering that this summed duration is similar in the entire potroom.

Before the experiments can be started, the model initialization takes care of preparing the model for the upcoming simulation run. The model initialization is decomposed into six phases:

1. **Model input**. Provide the input parameters, experimental factors (see Subsection 6.1.4), and experimental settings (warmup length, number of runs, and number of replications). The simulation model is non-terminating because there is no natural event that specifies the end of a run. We define a run as one shiftday, which is the duration of the three activity types (anode changing, metal tapping, and pot tending) together.
2. **Construction of the guide-path**. Based on the input parameters, the guide-path is built (see Subsection 6.2.2).
3. **Adjustments to the guide-path**. The user can manually or by small scripts modify paths. This is useful because the previous step creates a base layout that should be tailored to specific instances.
4. **Finalizing the guide-path**. After the user has made some adjustments (or not) to the guide-path, the paths are finalized (e.g., properly aligning and connecting the paths, checking the validity and feasibility, and possibly warning the user).
5. **Initialization of first run**.
6. **Continuation of simulation runs**. Once a run has end, it is checked whether the required number of runs is reached yet. If this is the case, possibly a new replication and experiment are initiated (see Appendix H, Figure H.1). Otherwise, the next run is initiated (see Appendix H, Figure H.2).

6.2.2 Guide-path Construction

The guide-path is constructed by using a set of input parameters. Let us first declare these parameters. After that, we outline how the guide-path is actually constructed.

The construction relies on a plant layout where we define a base-point (x=0,y=0) as the south-western end of the most south-western cell (Cartesian coordinate system). This cell is part of the first potroom and the subsequent potrooms are located to the north of it. Next segments are directed towards the east of it. The data input required for constructing the guide-path is given in Appendix I.

Given these input parameters, the model constructs the guide-path in the phases as further explained in Appendix I.

6.2.3 Demand Management

The demand management controls ingoing and outgoing anodes and anode pallets. It keeps track of anode pallets arriving in the rodding shop and pallets ultimately again arriving at the rodding shop. To this end, it communicates relevant data to the other agents in the system. As addressed before, information regarding the arrival and departure of anode pallets in practice is done through the Manufacturing Execution System (MES).

We decide to include a comprehensive approach by which the entire process from the moment an anode is needed until the transport job is released and dropped-off, is included. For that reason, we first introduce some definitions and characteristics in Subsection 6.2.3.1. Subsection 6.2.3.2 outlines the demand flow methodology embodied in the simulation model. Finally, Subsection 6.2.5 discusses some heuristics for initializing the demand schema's.

6.2.3.1 Demand Characteristics and Definitions

This subsection clarifies some terminology and further defines the scope of the evaluation model. The focus is first on addressing how shift & sections are defined. After which load characteristics are discussed.

We define a shift as a time-window in which all activities of a certain activity type (i.e., anode changing, metal tapping or pot tending) are scheduled. In a section, only one activity is performed during a shift. The activities anode changing, metal tapping, and pot tending follow each other in succession. The length of a shift is usually eight hours for each activity type, but this is modifiable in the model. Both the shift duration as well as the duration per activity type are adjustable. For example, one could schedule the anode changing activity with a duration of eight hours, metal tapping of six hours, and pot tending of ten hours. Once the shift length is set, we consider this length as fixed during the entire systems' life.

Recall that in a shift & section way of working, cells are clustered in sections and the working schedule is fitted to the activities carried out in these sections. We define a section as a cluster of adjoining electrolytic-cells that may share anode pallet demand and in which common activities are carried out. Two cells directly placed opposite to each other on the main aisle are also considered in the same section. In theory, a section can comprise all cells in the potroom, but we limit ourselves to the extreme lower limit of one section comprising two opposite neighbor cells in the center aisle of a segment and the extreme upper limit of one section covering an entire potroom. The minimum size of a section is, therefore, two and the maximum size comprises an entire potroom.

In a transportation control system, the desire to have the load on-time at the destination is often modeled by time-window restrictions. Each transportation request is then characterized by, for example, an earliest- and latest delivery time. We characterize the transport jobs by time-windows as well. To this end, we define the following job characteristics:

- $WEST_{p,s,a}$, *Workforce Earliest Start Time*: start time when the crane operators may start their anode changing shift in potroom p section s anode shift a;
- $WLST_{p,s,a}$, *Workforce Latest Start Time*: latest time when the crane operators can start swapping anodes on a pallet;
- $WST_{p,s,a}$, *Workforce Start Time*: actual start time when the crane operators start their anode swapping activities;
- $FERT_{p,s,a}$, *Fresh (anode pallet) Earliest Release Time*: release time at the rodding shop from whereon the fresh pallet can be picked-up. Set by the user (default: 4 hours, alternatively one can use the formula as discussed in Appendix J);
- $FLRT_{p,s,a}$, *Fresh (anode pallet) Latest Release Time*: latest time when the fresh anode pallet can be picked-up at the rodding shop. Set by the user (default: $WLST$);
- $FPT_{p,s,a}$, *Fresh (anode pallet) Pick-up Time*: fresh pallet pick-up time at the rodding shop;
- $FDT_{p,s,a}$, *Fresh (anode pallet) Drop-off Time*: fresh pallet drop-off time at the cell segment;
- $BERT_{p,s,a}$, *Butt (anode pallet) Earliest Release Time*: release time at the P/D-point at which the butt anode pallet can be picked-up;
- $BLRT_{p,s,a}$, *Butt (anode pallet) Latest Release Time*: latest release time when the butt anode pallet can be picked-up. Set by the user (default: 4 hours after being dropped-off);
- $BPT_{p,s,a}$, *Butt (anode pallet) Pick-up Time*: butt pallet pick-up time at the cell segment;
- $BDT_{p,s,a}$, *Butt (anode pallet) Drop-off Time*: butt pallet drop-off time at the rodding shop.

A transport picked-up later than the latest release times ($FLRT$ and $BLRT$) would not yield a desirable result. A fresh anode pallet picked-up after this time would namely be too late at the destination and result in excessive waiting times for the workforce that handles the crane operations. Likewise, we have to limit the latest release time of the butt anode pallets because they may otherwise burden efficient vehicle movements. However, it is unavoidable that in some cases these latest release times will be exceeded. Therefore, we include so-called "emergency" shipments for handling those late anode pallets. An emergency shipment includes the entire process from picking up the pallet until dropping of the pallet without any interference with the AGV system. We assume these emergency activities are carried out immediately. These assumptions can be advocated in practice by acting adequately when these outliers are expected to happen. For instance, a human-driven forklift can be used to maneuver almost freely through the system as a substitute for an emergency team. However, remark that we keep track of these emergency shipments and ideally one would eliminate them completely. We expect this can be done, for example, by examining the system performance and then fine-tune parameters or by considering different experimental configurations. We leave this up for further research.

6.2.3.2 Demand Flow Methodology

The pallet's capacity (in most cases) exceeds the demand from one individual cell, therefore, individual anode demand from cells is combined into pallets and those pallets are transported to dedicated places in the section. Anode changing operations are covered on a high-level only. That is, we do not model operators and crane movements explicitly, but we model the anode changing process as a time-consuming activity only with the inclusion of AGV path blocking restrictions. Ideally, one would have the anode pallets as close as possible to the corresponding cells because the required crane movements are then limited. This is, however, not always possible, because of, for example:

- pallet placement restrictions;
- anodes located on the back aisles need to be moved by crane via the center aisle;
- pallet orientation should be taken into account;
- conflicting pallet placement interests (e.g., where to position one pallet if two neighboring cells require one anode each and another cell a couple of meters further requires one anode?);
- possible workforce flow through different sections.

Based on this analysis and our already made design choices, we could deduce at least three design elements that should be examined in more detail: (1) the transition from anode demand to anode pallet demand, (2) the interaction with the crane, (3) and the pick-up and delivery sequence of pallets. Below, we address the methodology followed to cover these design considerations.

To model the anode pallet demand properly, we propose the material flow determination approach as shown in Figure 6.2 of which Appendix K presents the corresponding entity relationship diagram. The *Demand Management* first establishes an anode demand scheme. This scheme represents fresh anodes that need to be changed in a shift. Currently, the demand for anodes follows a cyclic and predictable pattern. That is, anodes need to be changed when the setting cycle elapsed. We assume this setting cycle or at least its distribution type is known upfront. In the case of equal setting cycles for all anodes, the anode setting cycle scheme repeats itself each setting cycle period. The scheme should be obtained from customers and is expected to be unique per customer. Alternatively, Appendix L provides a set of five heuristics that can be used to mimic the anode demand normally arising from the MES.

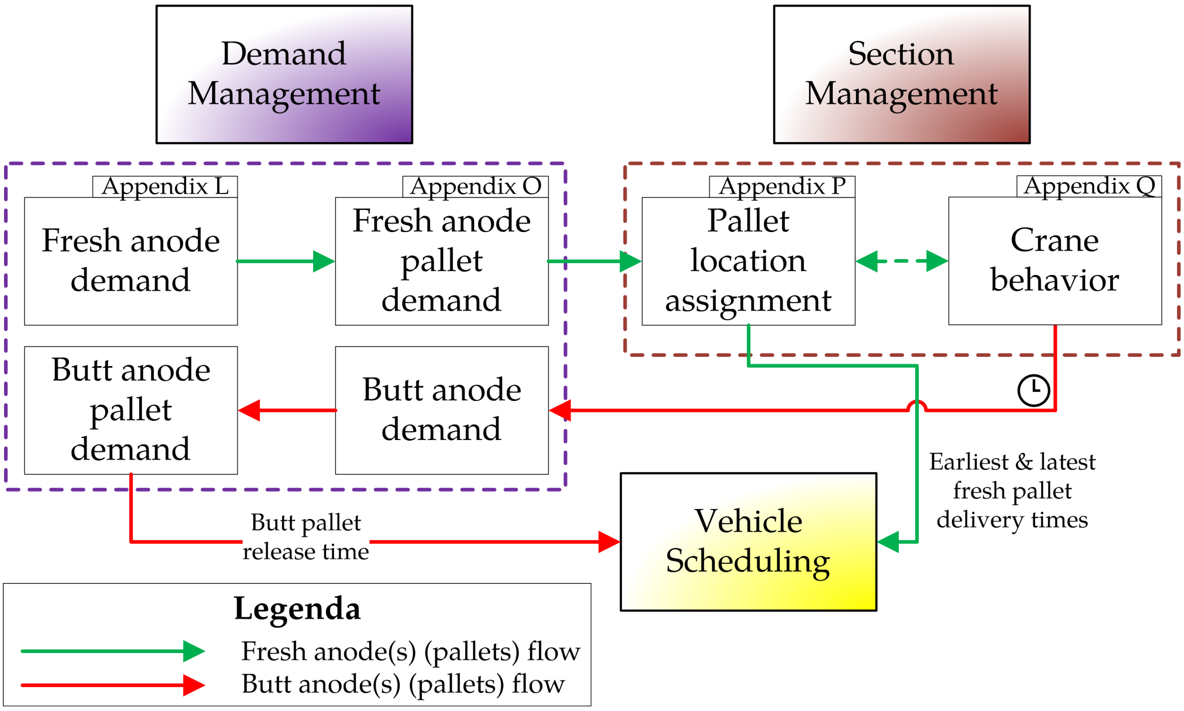


FIGURE 6.2: Material flow determination approach representing information flows between the Demand Management, Section Management, and Vehicle Scheduling.

Once the anode demand is known, the *Demand Management* generates the anode pallet demand. The resulting anode pallet demand schema contains a schedule of pallets that need to be delivered to a section for anode changing shifts. Appendix N presents three heuristics as alternatives to a manually provided schedule.

The *Section Management* then obtains information regarding the pick-up and drop-off locations of pallets. We consider a static pallet position of which the location cannot be changed anymore once they are allocated to a position. However, the pallet may be a different one than initially scheduled. For example, when the first planned AGV A has a delay and another AGV B that is earlier at the section has to wait before AGV A arrives, then AGV B can already drop-off a pallet at the place originally assigned to the delayed pallet A because otherwise the initial planned pallet position of AGV B may block the passage for the pallet from AGV A. The main goal of determining the pallet drop-off locations is to deliver them as close as possible to the corresponding cells to avoid unnecessary crane movements. Parallel to modeling the crane behavior, the allocation of pallets thus requires attention. The proposed pallet allocation heuristics are presented in Appendix O.

In addition to determining proper P/D-locations, the sequence in which the jobs are handled is of importance. To this end, the *Section Management* uses the anode pallet demand schema and P/D-locations, and determines the sequence in which the anodes are interchanged. The sequence relies on how the crane operators plan their anode changing activities. We consider having one workforce team per shift per section. Usually, the teams follow a certain pattern like starting changing anodes in the western end and gradually work through the eastern end. To adequately model the behavior of cranes, we propose some heuristics to simulate the crane operation "flow" through the potrooms in Appendix P. These heuristics are limited to handling the anode demand per pallet.

Although the way the crane operates affects how and where the pallets will be positioned and visa versa, the approach we propose considers the crane operations mainly as leading followed by the pallet position allocation. Our approach focuses on the supportive role of pallet transport which will marginally affect the way crane operators continue their activities. Furthermore, our approach allows the model to be flexible for evaluating different work systems and it is a straightforward approach that is easy to understand. An approach that, for example, simultaneously address crane operations and pallet allocations might be superior to our approach, however, we suggest to investigate this potential in future research. So, first, the pallets are assigned statically, after which the workforce flow through the section is modelled.

One remark regarding the maximum number of possible pallet placements per segment on each side of the center aisle. This number equals the number of electrolytic-cells minus the two outer cells (on each side) because on these outer ends their pallet drop-off and pick-up is not permitted. When the possible assignment positions are not sufficient to cover the anode demand in a section, we consider that the leftover pallets (following from the heuristics) are delivered to the section by "emergency" shipments. In further research, one could, for example, include a dynamic pallet assignment approach in which multiple pallets are assigned to one position with different reserved time slots. The considered crane behavior heuristics affect how the butt pallets transport requests are generated. If all anodes in the pallet are interchanged, we decide to release the subsequent pallet transport request.

Lastly, we include three variants of rodding shop pick-up and drop-off rules. As evaluation rules we examine (1) the selection of a random rodding shop, (2) the selection of the nearest rodding shop, and (3) the selection of the farthest rodding shop. The rodding shops are selected once the transport request is generated and do not change intermediately.

To summarize, the demand generation heuristics as discussed above consists of:

- Generating fresh anode pallet demand (4 heuristics, Appendix L).
- Transition to fresh anode pallet demand (3 heuristics, Appendix N).
- Assignment of pallet locations (5 heuristics, Appendix O).
- Modelling crane behavior (3 heuristics, Appendix P).
- Selection of rodding shop as pick-up locations (3 heuristics).
- Selection of rodding shop as drop-off locations (3 heuristics).

6.2.4 Section Management

The *Section Management* obtains information regarding which shift is currently planned in that section and it manages all activities carried out in that section. Below, we subsequently discuss the shift activities and the resulting blockade effects, the anode changing service time, and additional assumptions regarding the shifts & section working approach.

6.2.4.1 Shift Activities and Blockade Effects

Recall that the anode changing, metal tapping, and pot tending shift sequentially alternate each other in that order. Each of these activity types have their corresponding blockade restrictions that affect the passage of vehicles in the corresponding section:

- **Anode changing shift**: besides that pallets block the passage and affect the routing of vehicles, crane operations result in additional blockades. We include the blockade that once the workforce team is changing an anode, the entire center aisle path from the anode pallet until the changing anode is blocked as shown in the blue region of the example in Figure 6.3. Furthermore, the back aisles are blocked once the operators are active on that side. Crane operations may block multiple segments at once, because of the section definition and pallet allocation distribution. Vehicles may resume their path if they already entered the path while the blockade has occurred.
- **Metal tapping shift**: the entire section is blocked for AGAPTVs. Vehicles may resume their path if they already entered the corresponding section where the blockade has occurred.
- **Pot tending shift**: nothing is blocked, instead, we assume pot tending operations do not interfere with the AGAPTV system. However, as discussed in the sensitivity analysis (see Chapter 7), we examine the impact of pot tending activities by considering randomly occurring blockades.

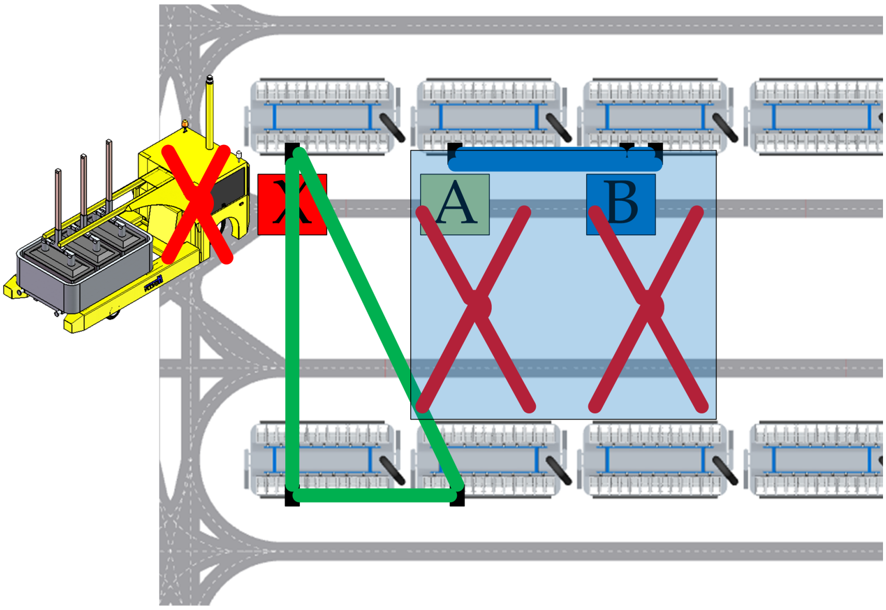


FIGURE 6.3: Example of a blockade that occurs when anode changing is in progress. The AGAPTV cannot travel further to drop his pallet at location A because the crane is operating and blocking the passage.

6.2.4.2 Anode Changing Service Times

The processing time required to interchange an anode depends, among others, on the clients workforce and how far the crane moves. As we do not include these aspects, we argue that it is reasonable to assume the processing time required to replace an old anode by a new one is randomly varying between a minimum and maximum interval (e.g., uniformly distributed). These limits should be determined in collaboration with clients.

6.2.4.3 Additional Assumptions Regarding the Shift & Section Working Approach

Additional assumptions regarding the shift & section way of working are:

1. In a section the restriction of having at most one AGAPTV may not be violated, except possibly when the collision avoidance maneuverer is performed.
2. One workforce team is available per section. A workforce employs one crane that can work on one cell at the same time. A segment may contain multiple workforce teams because of the section definition. In practice, it is, however, not desirable to have multiple cranes per segment. In the model one should take this into consideration when providing the section distribution schema.

3. The anode changing operations may begin if the anode changing shift starts. We assume the workforce trip to the cell does not interfere with our system. Once the pallets arrive and the anode changing shift is already started, the crane operator can start with changing anodes on the designated cells. In case the workforce has to wait before a new pallet arrives and they can continue their work, we assume they will not interfere with the AGAPTVs and thus do not cause additional blocking constraints. This assumption is valid because we expect that most of the time the team can maneuver the crane in advance to a different position that not interfere with the vehicles.
4. The workforce team leaves the section once the shift ends or in case all anodes are replaced. A leaving workforce does not further interfere with the logistics in our system. We consider all anode changing operations end once the anode shift plus possibly the *maximum butt anode pallet latest release time* (see Subsection 6.2.3.1) has elapsed. Crane operations still active after this time may proceed but anodes left to be changed are carried out by "emergency teams". Such a team takes over the changing operations and we assume that all left anodes are immediately changed and ready to be transported by the AGAPTVs.
5. In case an AGV with a fresh anode pallet arrives too late at a section because the anode changing shift (*plus maximum butt anode pallet release time*) has already ended, the AGV will continue its route to the drop-off point in the section and then drops-off the load. The anodes are then assumed to be swapped by an additional workforce team that starts immediately under the same blocking restrictions as regular changing operations.
6. Intermediate crane movements from cell to cell are not considered. We assume the crane can move freely in between the cells without interfering with AGAPTVs or pallets. So, in case the crane should be moved from the most western position in a section to the most eastern position in the section filled with pallets, this is done without interference with our system. The time it requires to transfer the crane from cell to cell is assumed to be incorporated in the anode changing service time. In case an AGV gets blocked due to moving crane behavior, we simplify the model such that the AGV can freely resume its route out of the blockade.
7. In case a dropped fresh pallet is fully occupied by fresh anodes, there is no place to store the first anode butt directly into the pallet. Hence, first one fresh anode needs to be placed temporary outside the pallet, after which the anode swapping can start. Despite that this is not desirable because the anode could block pathways and bath residuals attached to the butt can contaminate the floor, we simplify the model by not including this additional empty place in (one of) the pallet(s). We justify this simplification by assuming that the workforce team appropriately handles the swapping procedures (e.g., clean up the contamination after replacing anodes). Remark that for the long-term this may not be desirable. Chapter 9 highlights how one can cope with this safety measure in future planning & control heuristics.
8. The workforce team has no limitations on its availability (e.g., no lunch breaks, failures, maintenance, etc.).

6.2.5 Demand Schema Generation

The demand schema consists of four characteristics that together with the potroom layout provide the input for the anode pallet demand. The demand schema presents on which shift which anode needs to be changed. Furthermore, the schema presents which cells are grouped into sections and thus may share their pallet demand. The schema also specifies the setting cycles for each cell. Lastly, the schema specifies which sections should be done in which shift. Recall that the three activity types - anode changing, metal tapping, and pot tending - sequentially alternate each other. Remember also that sections in which the same activity is started have the same alternating sequence and shift start moments (see Chapter 2 and assumptions made previously). To model this appropriately, we declare a so-called shift index. The shift index, indicated per section, declares in which shift stream the activity types follow each other.

Input for the demand schema is usually obtained from clients. However, the data gathering process is often a time-consuming task and not all customers are capable or willing to provide this. As alternative, we provide some heuristics in Appendix Q for generating this input. Potroom construction parameters (e.g., number of potrooms, number of segments, number of cells, etc.) and possibly (manual) modifications to the plant layout induce the size of the dimensions for this input.

6.2.6 AGV Parking Management

The *Parking Management* acts when the vehicle becomes idle and no transport job is assigned to it yet. Recall that a *distributed-positioning strategy* is used with multiple dwell points (Subsection 5.5.1). We decided to designate all rodding shops as dwell points for vehicle parking. So, besides that the rodding shops function as P/D-point for anode pallets they also handle the parking of AGAPTVs and facilitate electricity stations.

The *Parking Management* comprises two events, the event of an idling AGV that has no job assigned to it yet and the event that the AGV reaches the parking location. When the first event occurs, the *Vehicle Scheduler* first applies the dispatch rules. When there is no job assigned to the vehicle, a so-called low priority parking task is scheduled. The vehicle then drives towards the nearest parking location while interruption is allowed. That is, the *Vehicle Scheduler* can assign an anode transport job in the meantime that overrules the low priority task. Appendix S visualizes this in the flowchart.

If the AGAPTV reached the parking location without having an interruption of an assigned pallet transport job, we use this opportunity for charging the vehicle's battery. Appendix S shows this in a flowchart.

6.2.7 Vehicle Scheduling

The *Vehicle Scheduler* is triggered based on workcenter- and vehicle-initiated events (see Subsection 5.4.2). Both dispatching strategies are considered in the evaluation model but they can be tuned individually. The subsections below subsequently discuss how vehicle-initiated strategies and workcenter-initiated strategies are organized in the model. Furthermore, the *Vehicle Scheduler* requires an approach for adequately determining the access route to a segment corresponding to the pallet orientation (see Chapter 2). That is, already dropped-off pallets and active cranes impose limitations to both the scheduling and routing of vehicles. We finalize this subsection with discussing the mechanism for coping with this problem.

6.2.7.1 Vehicle-initiated Scheduling

The vehicle-initiated dispatching approach is triggered by two means: (1) AGAPTV becomes idle after a pallet is dropped-off and (2) AGAPTV becomes idle at the charging station when the battery plateau is reached under the automatic charging task.

Figure S.1 of Appendix S depicts the logic flowchart of the first trigger which we concisely explain now. After a pallet is dropped-off, it is checked whether there is a critical charging task scheduled for this vehicle. If that is the case, the route to the nearest charging location is constructed and assigned to the concerned vehicle. When there is not such a critical charging task planned, the transport list is considered and if there is at least one transport job, the dispatch rule is applied to the list. Consequently, the selected job is designated to the vehicle and the system is updated. When there are no jobs left to be selected, either a low priority trip to the parking location or charging location or a high priority trip to the charging station is scheduled. Low priority trips may be interrupted once the workcenter dispatch rule selects the vehicle but high priority trips cannot be interrupted.

The second trigger will only be activated if the battery plateau level b_{plat} is being reached under the automatic charging task (see Subsection 5.6.2). Figure S.2 of Appendix S shows the corresponding logic flowchart. If the trigger is activated, the AGAPTV list is updated first. After that, there is checked whether there is a transport job available. If there is at least one job waiting, the dispatch allocation rule is applied and the selected job is assigned to the vehicle.

6.2.7.2 Workcenter-initiated Scheduling

There is one trigger that activates the workcenter-initiated dispatching strategy: a new pallet transport request is initiated. This holds for both the fresh anode pallets and butt anode pallets. Appendix T gives the logic flowchart regarding the corresponding scheduling process. First, the transport list is updated by including the new transport job. In case there is at least one AGAPTV available, the dispatch rule is applied and the selected vehicle is assigned to the job. When no vehicle is available, the job has to wait until there is one free by which the dispatch rule favors this job.

Notice that, depending on the selected experimental configurations, fresh anode pallet transport jobs can be initiated in batches. That is, multiple transport jobs become available at the same time. To avoid possible biases as a result of design choices in the implementation, the selection of a new job is done randomly out of the jobs still to do. The process is continued by applying the workcenter-initiated dispatching rule for this arbitrarily chosen job.

6.2.7.3 Pallet Implications on the Access Route

As addressed before, pallets require a specific orientation to allow cranes working with the anodes properly. The northern center aisle requires northern pallets and the southern center aisle requires southern pallets. Recall that the AGAPTV cannot pick-up and drop-off pallets from both the front and back side of the vehicle due to its physical properties. A consequence of this is that, in some cases, the AGAPTV needs to perform a backwards maneuver for picking-up and dropping-off pallets (see Figure 5.2 and Figure 5.3).

The vehicle scheduling and routing incorporate this restriction as follows. The first pallet of a segment can be dropped-off without performing the backward driving maneuver. Hence, the AGAPTV can then simply continue its route. However, this may not be desirable in some cases. For example, when the path of the segment is long and the drop-off point was somewhere at the early cells of that segment. Similar issues arise for subsequent pallets and the pick-up of them. As the segment access route is in particular of importance for the subsequent pallets, we consider the following approach:

- *First fresh anode pallet of the segment*: schedule route to the cell. At the segment entrance drive forwards and leave the cell segment forwards.
- *Subsequent fresh anode pallets of the segment*: schedule route to the entrance side (either east or west) that follows from the anode pallet demand schema. Choose the shortest path in case it prescribes no specific access side. At the segment entrance decide whether to perform the task backwards of forwards.
- *First anode butt pallet of the segment*: similar as non-first fresh anode pallets.
- *Last anode butt pallet of the segment*: schedule route to the cell. At the segment entrance drive backwards and leave the cell segment backwards. At the segment aisle, rotate the vehicle such that it continue its route forwards driving.

Pallet rotation is assumed to be set appropriately at the rodding shops and rodding shops can handle both orientations. Remark that the pallet orientation is only importance for the scheduling of fresh anode pallets leaving the rodding shop.

6.2.8 Battery Management

The main functionality of the *Battery Management* is already discussed in Subsection 5.6. Also, the scheduling of low-priority battery tasks is previously explained or will be discussed in the subsequent subsections. However, some other details regarding the battery management require more attention.

Recall that the model comprehends an automatic and opportunity charging approach. The automatic charging threshold value b_t is determined after a pallet is dropped-off by means of Formula 5.2. When this current battery level satisfies the equation, a high-priority task is scheduled that may not be interrupted by other pallet transports. Other arising conflicts are not treated differently because of this priority level.

The opportunity charging method is triggered once a new pallet transport is designated to an AGAPTV. When Formula 5.3 is then satisfied, an opportunity charging task is scheduled to charging station c.

In rare occasions, the absolute minimum b_{min} can be reached. For example, when the vehicle is stuck in-between sections and cannot continue its route because other vehicles are always prioritized. In these seldom cases, the model assumes an emergency team takes over the control of the AGAPTV. The emergency team takes care of the possible delivery of the corresponding pallet and transporting the AGAPTV to the nearest charging station. Remark that the model keeps track of the number of times this event occurs.

6.2.9 Vehicle Routing

The goal of the *Vehicle Routing* agent is to determine the shortest paths between P/D locations and the shortest routes between the location of the AGAPTV and the P/D locations. We focus on a solution for finding the shortest paths with respect to distance minimization.

We commence with a comparison of shortest paths algorithms used in the simulation models. After that, we address how to model the vehicle routing functionality in the evaluation model. As pointed out in Subsection 5.7.2, we consider two vehicle route construction approaches for adjusting routes based on the occurrence or release of blockades in the evaluation model: *reactive* and *pro-active*. Finally, we discuss how these strategies are embodied in the model.

6.2.9.1 Comparison of Shortest Path Algorithms for the Usage in Simulation Models

Considering the large number of P/D locations in large-scale potrooms, our solution search space for finding optimal solutions would be enormous. Adding to that the possibility that individual paths can be blocked, the solution space increases even more.

Different approaches have been proposed for finding the shortest paths between nodes in these situations. The shortest paths can be calculated in an offine or online manner (see Subsection 3.2.2). Computing all shortest paths beforehand and storing in respective matrices (e.g., Floyd-Warshall's algorithm) is an offline approach which requires short computational time in model execution, but pre-calculations and additional storage space consumption (Gutenschwager et al., 2012). This may become a restrictive factor even for moderately large guide-paths. On the other hand, online vehicle scheduling approaches (e.g, Dijkstra's algorithm or A*) calculate shortest paths during the simulation run.

Both online and offline strategies should require similar computational times in case each shortest path is needed once for any simulation run with the respective P/D locations (Gutenschwager et al., 2012). However, some shortest paths might be needed multiple times whereas others are barely needed or not used at all. Furthermore, the number of replications of simulation runs within an experiment plays a major role in deciding upon the shortest path solving strategy. Remark that the paths may only differ a few nodes at the start or the end of the complete graph (e.g., a few rodding shops) which favors using an offline approach for a selected part of the graph. However, as we consider workcenter-initiated dispatching strategies with a trigger that requires computing the result on criteria depending on the vehicle's current position, it is not desirable to pre-compute solutions for all possible vehicle positions. A vehicle can namely be somewhere in-between nodes.

Considering the pros and cons, we decide to dismiss complete enumeration of the shortest paths under all blocking circumstances in an offline strategy. Instead, we need a method that does not rely on excessive pre-computations while many options are not considered at all. Alternatively, one could use a hybrid approach, for example, in which some regular driven routes are pre-computed. However, to use such an approach in a generic model may not that straightforward. The amount of time required to pre-process the optimal routes is also expected to be considerably higher than computing the routes once they are actually needed in the simulation model. Therefore, our approach contains an online vehicle routing strategy in which all computation has to be done during the simulation run. Below we address how the approach is comprised in the evaluation model design.

6.2.9.2 Modelling the Shortest Path Functionalities

The main functionality of the *Vehicle Routing* is to adequately determine the route AGAPTVs should travel. As we discuss in Chapter 7, the discrete-event simulation software *Tecnomatix Plant Simulation* is used for modeling and generating the entire plant layout including all paths, connections between paths, cells, and other stations by means of respective methods. For modeling the nodes, a so-called method is being used in this software. This method checks whether the node is the current destination of the vehicle. If so, the current transport order will be fulfilled and the proceeding dispatching rules are applied. For calculating the routes, the built-in algorithms for determining the path of a vehicle from its current location to a given destination is used, which appears to be a derivative of Dijkstra's algorithm.

Besides calculating the shortest paths, the *Vehicle Routing* is concerned with the re-scheduling of routes and detecting collisions, crane blockades, and vehicle conflicts. Appendix U gives a logic flowchart regarding the arrival of an AGAPTV at a segment entrance. Let us concisely explain the process overview as depicted in Figure U.1. The process starts with an AGAPTV arriving at the segment entrance. When another AGAPTV is currently in the cell segment, the collision avoidance process is started (see Subsection 6.2.10). Otherwise, it is checked whether the reached segment is the destination, and if so, the path to the first fresh anode pallet of that segment is free which allows the AGAPTV to travel to the P/D-point. Regarding other pallets, the process shown in Figure U.2 is carried out. This process involves executing the pick-up or drop-off task on the suitable side of the segment. When the reached segment is not the destination segment, the passage is only free if the metal tapping activity is not going on and the crane is not blocking the access to the P/D-point. For further details of the vehicle routing process, we refer to the logic flowchart of Appendix U.

6.2.9.3 Adjustments of Routes because of Blockades

As reported in Subsection 5.7.1, the model contains two vehicle routing approaches for dealing with route blockades: *reactive* and *pro-active*. Below we briefly explain how these strategies are realized in the model.

Figure U.3 of Appendix U presents the logic flowchart of the pro-active vehicle routing strategy. The type of blockades that affect the route are listed in Subsection 5.7.1. When a blockade occurs, it is for each vehicle checked whether it affects the route. The sequence in which the vehicle routes are checked for this condition is random. If the route is affected, a new optimal route is constructed. When a blockade expires, it is checked for each vehicle whether a better solution can be achieved if the route is re-scheduled under the new conditions. The model allows vehicles to temporary escape from the current section in case the blockade occurs in this section. When no feasible solution is found by the vehicle routing algorithm, it checks whether it can reach one of the nearest cross aisles. Otherwise, the vehicle will stop driving and wait for next commands.

Figure U.4 of Appendix U gives the logic flowchart concerning the reactive vehicle routing strategy. This approach only adjusts the route of an AGAPTV if the vehicle cannot traverse the next path. Likewise, as under the pro-active strategy, the vehicle drives towards the nearest cross aisle in case no feasible solution can be found.

6.2.10 Conflict Resolution

The *Conflict Management* employs a zone-control method in which the guide-path is partitioned into zones with a restrictive vehicle movement rule. Table 5.4 shows the required model input. Appendix V gives the process flowchart presenting how the model incorporates the zone-partitioning rule. Below we concisely explain this chart.

Once an AGAPTV reaches the entrance of the cell segment path, cross aisle or segment aisle, the first step is to check whether there is another vehicle present in the to-be-visited zone. The flowchart considers the case that such a vehicle is detected. When the vehicle in the segment aisle cannot leave the segment without interfering with the vehicle near the entrance, the segment aisle vehicle is granted always priority (see Subsection 5.8). In any other case, priority is given to the vehicle according to a probability distribution function. The prioritized vehicle may continue its route while the non-prioritized vehicle performs an avoidance maneuver as exemplified in Figure V.1.

6.3 Conclusion

In this chapter, we provided the blueprint for the development of the scenario evaluation model. First, we discussed the conceptual model that contains the problem context, modelling objectives, the model inputs and outputs, the scope and level of detail of the model. Hencon aims to examine current situations of customers and experiment with alternative operational planning and control strategies to strengthen its competitive advantage.

Next, the model content including its assumptions and simplifications is outlined. Important is the involvement of a modelling part that attempts to mimic the behavior from a MES, which allows Hencon to assess the performance of a customer without knowing all its details. Important assumptions are that we assume that the rodding shops have infinite capacity, the fleet is homogeneous, and over- and underflows in the system are captured by emergency shipments.

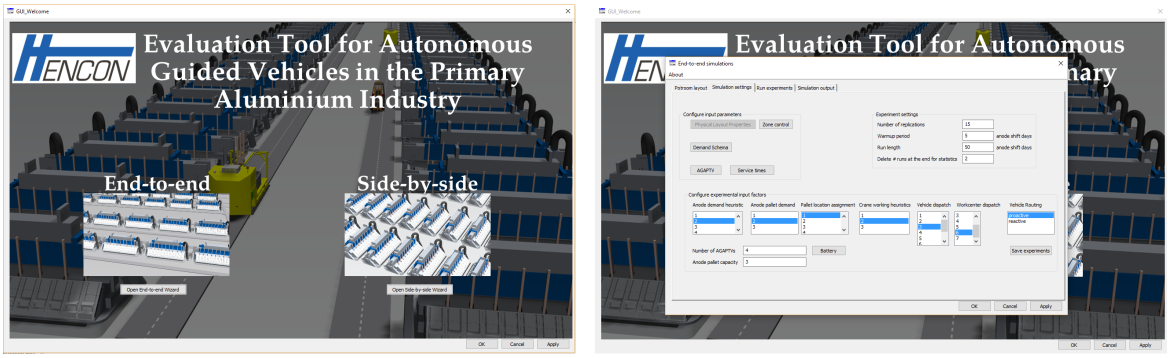
Chapter 7

Model Verification and Validation

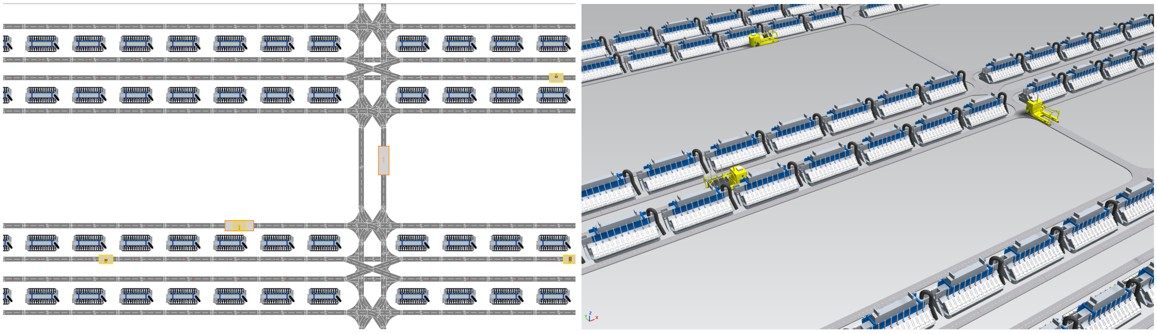
This chapter describes how the conceptual model is verified and validated. Section 7.1 provides an introduction. Section 7.2 contains the model verification and Section 7.3 the model validation. Section 7.4 concludes this chapter.

7.1 Introduction

A proper model verification and validation is essential for establishing a robust and stable model and ultimately creditability to the model's users. By analyzing the results and phenomena that are obtained from the simulations, we gather insights into the performance. The conceptual model of the previous chapter has been implemented in the discrete event simulation software *Tecnomatix Plant Simulation* 13.0.3. Figure 7.1 shows four screenshots of the developed model. The electrolytic-cells are positioned in an end-to-end position and are delivered via the rodding shops as can be seen in the northern and southern aisle of Figure 7.1b.



(A) Graphical user interface start screen.
(B) Graphical user interface end-to-end simulations.



(C) 2D screenshot of a factory layout.
(D) 3D screenshot of a factory layout.

FIGURE 7.1: Screenshots of implemented simulation model.

By analyzing the results and phenomena that are obtained from these simulations, we gather insights into the performance under several scenarios and could then identify possible improvements of the traffic control strategy. For our analysis we consider the layout as depicted in Figure 7.1b, which closely mimics a real-world plant layout. The smelter consists of four potrooms of which the first two have five segments and the last two potrooms seven segments. For further details regarding the construction of this plant layout including the corresponding model parameters, we refer to Appendix W.

7.2 Model Verification

Verification assures that the conceptual model is appropriately translated to an implemented simulation model (Law, 2015). We first build the model in a simplistic manner by starting with small modules, after which we gradually expanded to include more sophisticated methods. Furthermore, the following model verification techniques have been used:

- **Debugging modules or subprograms**. We verified our model by making sure that first all components and sub-components of the model were tested before they were added to the entire system. The functionality of agents is coded first in separated parts of the system, after which they are integrated with the other modules. The outputs of subsets is also checked with several artificial inputs by checking (temporary) generated data outputs;
- **Using a commercial simulation package that is common in this industry**. *Tecnomatix Plant Simulation 13* (13.0.3) is used which is an discrete event simulation tool that is often used to model logistics systems. The verification process benefits from already existing functions in the software package;
- **Run under simplifying assumptions**. Reduction of the model to its minimal workable behavior helps in understanding smaller parts of the system after which more complex models could be examined. We verified and validated the model by considering simplified instances of the model. Gradually, we extended the complexity of the model by including more extreme variants and establishing the connections between other parts of the system. For example, the *Demand Management* and *Vehicle Scheduling* modules are first developed by including only one section and one AGV. After we verified the correctness of those two subsystems, we extended the code by including multiple sections and vehicles. After being sure that the models runs correctly under the simplified circumstances, we made sure the more complex models work properly as well;
- **Running the model under a variety of settings**. We ran the model under various settings when building the model. For example, the construction of the guide-path is a process that depends on various input parameterizations. We modified the input parameters regularly to assess whether the guide-path was correctly constructed. Furthermore, many components were generically built such that they could be extended in a later development phase easily. For example, we used tables to store the information required for dispatching transport jobs. These tables were sorted according to one of the many heuristics. Additionally, we provided some consistency checks in the model to warn the user in case we expect that the model input might not be appropriate. This may occur, for example, in the guide-path construction phase of the model when the user provides a negative distance or forgot to declare an input value;
- **Structured walk-through** by explaining the model to other persons. Several demonstrations were given to employees of Hencon. The demonstrations were supported by **animations** and **flowcharts** of processes of the system. Animations provide information about the internal behavior of the model in a graphical form. For example, in the guide-path construction phase, the guide-path development steps were illustrated step-by-step with the support of animations. Flowcharts describe how (logical) actions in the system take place when an event occurs. Additionally, we created a manual for the users. The manual explains how the model works including examples and illustrations.
- **Trace outputs** are used for isolating incorrect behavior in the model. We used traces many times to verify whether triggers were activated at the right moment and resulting in the correct end events. The simulation software helped us in observing the behavior of parts of the code in a step-by-step approach. Tracing outputs were in particular useful for verifying whether the collision avoidance maneuvers were correctly carried out. Those procedures consist of several consecutive steps (of code and animations) spread over minor time frames.

7.3 Model Validation

Validation is the process of determining whether a simulation model accurately represent the system, for the particular objectives of the study (Law, 2015). A key element in validating the model is to compare our simulation model to a real-world representation. Although customers are currently using AGAPTVs in a similar production environment as embodied in the scope of this thesis, it is difficult to validate the model based on one of these customers. There is namely not enough data about these cases available. Despite the limited availability of data concerning its performance, we validated the simulation model by discussing the system behavior with employees of Hencon and comparing it with preliminary theoretical analysis made earlier and conducting a theoretical analysis.

In addition to these validation techniques, we use other methods as discussed in the subsections below. Subsection 7.3.1 employs conceptual model validation. Subsection 7.3.2 validates the model by using white-box techniques and Subsection 7.3.3 describes a black-box validation.

Recall that the aluminium production runs 7 days per week, 24 hours per day. The aluminium production process is continuous and has no 'natural' event that specifies the end of a simulation run. There is no guarantee that the system will start and end each period empty. Hence, the type of simulation concerns a non-terminating simulation. Based on preliminary tests, we apply the consider 100 anode shift days as a replication for our simulation experiments.

7.3.1 Conceptual Model Validation

The conceptual model of the previous chapter is a representation of the system in which assumptions and simplifications are made and the boundary of this study is formulated. According to Robinson (1997) there is no formal way of validating the conceptual model. We validated the conceptual model by having discussions with employees of Hencon about the list of assumptions and simplifications as presented in this thesis (Appendix G. We validated both structural assumptions (how the system operates) and data assumptions (reliability of data and its statistical analysis) and agreed upon them with Hencon.

7.3.2 White-box Validation

We employ a white-box validation to assess the behavior of subsets of the simulation model. White-box validation addresses the validity of constituent parts of the the model (Robinson, 1997). The content of subsets of the system is validated by data checks such as storing and inspecting intermediate simulation results and interpreted by discussing the results. That is, for example, timings, control of flows (e.g., routing), and control logic are continuously checked throughout model coding. Below, we discuss a white-box validation of the *Demand Management*, *Section Management*, and *Battery Management*. The internal structure of the other agents is less data-driven and validated by checking the code, visual observations, inspecting output reports from simulation runs, and black-box validation.

7.3.2.1 Demand Management Validation

The *Demand Management* is validated by using as input:

- the plant layout as shown in Figure 7.1b. The corresponding building parameters are given in Appendix W;
- shift durations of 8 hours;
- a fixed number of anodes for all cells of 16 (anode distribution heuristic [1]);
- each potroom is split into three sections which roughly contain the same number of segments (section distribution heuristic [3] with parameter 3);
- setting cycle per potroom is equal to 28 (setting cycle distribution heuristic [1] with parameters 28 and 28);
- split the potrooms into three subparts that roughly contain the same number of sections (shift indexing heuristic [3]).

We validated the *Demand Management* by discussing the simulation results with employees of Hencon. We validated the results (see Table 7.1) and behavior of the system by considering:

- The combination of anode-shift day and anode-shift index number should be unique and in ascending order;

- The average fresh pallet transports initiated per anode shift should roughly be equal to: 16 anodes * 432 cells = 6.912 anodes in the potroom, of which $\frac{6.912}{28} \approx 247$ need to be replenished every day, consolidating this in pallet demand yield roughly $\frac{247}{3} \approx 82$ pallets per day which is ≈ 27 pallets per anode shift;
- The repetitive behavior of the demand once the setting cycle has elapsed;
- Visual validation of the *Section Demand* management by comparing the simulation demand for several sections with a spreadsheet document from one of the customers of which its smelter layout closely mimics the concerned smelter layout.

TABLE 7.1: Excerpt of output data from the *Demand Manager*.

Anode-shift Day	**Anode-shift index**	**Shift start time**	**Total number of fresh pallets initiated**
1	1	0:00:00	22
1	2	8:00:00	29
1	3	16:00:00	30
2	1	1:00:00:00	26
2	2	1:08:00:00	39
2	3	1:16:00:00	21
3	1	2:00:00:00	31
3	2	2:08:00:00	25
⋮	⋮	⋮	⋮
29	1	29:00:00:00	22
29	2	29:08:00:00	29
29	3	29:16:00:00	30
30	1	30:00:00:00	26

We validated the results as shown in Table 7.1 as follows:

- The index number corresponds to sections that have an identical changing sequence of activities. So, all sections designated by shift index i may start with changing anodes when the shift start time is reached. We observed three unique streams of anode shifts per shift day, which is in line with the reality. The table also shows that shift start times are multiples of 8 hours and in ascending order;
- The average number of fresh pallet transports initiated during the period of a setting cycle of 28 days is 26.82 which is approximately 27 and thus valid with practice;
- We observe a fresh pallet demand pattern that repeats itself every setting cycle. After 28 days the demand pattern repeats itself, which is as expected from practice;
- We compared our results with the information sheet and observed roughly the same demand pattern.

7.3.2.2 Section Management

We validated the *Section Management* by considering:

- The arrival of pallets should be equal to the departure of pallets;
- AGAPTVs cannot traverse a lane in which the crane is active, except if the vehicle is already in that aisle;
- AGAPTVs may not enter sections where the metal tapping activity is active, except when the vehicle is already in that section.

Figure 7.2 shows the pallets required in a setting cycle and the number of pallets that are delivered too late. We considered the same situation as discussed in Subsection 7.3.2.1 and include two AGAPTVs in the system. We considered the dispatch rules that randomly select the next job or vehicle. Also, for this subset validation, the rodding shop pick-up and drop-off locations are selected at random. Furthermore, we excluded the functionality of the *Battery Management* because for this

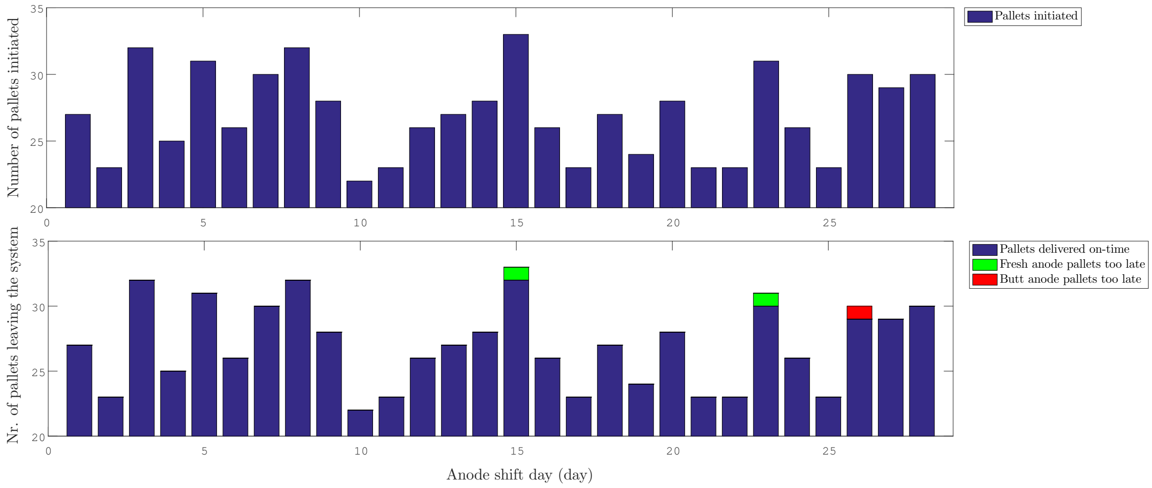


FIGURE 7.2: Pallet distribution during an anode setting cycle for a group of sections that share the same anode shift index.

white-box validation these functionalities are not strictly required. Therefore, we assumed an infinite battery capacity.

Figure 7.2 shows the number of pallets that enters the system and the number of pallets that leaves the systems. In this figure, we observe that the number of pallets initiated is equal to the number of pallets that leave the system. We further see that a small fraction of the pallets is delivered too late but that these pallets still leave the system appropriately. Hence, there are no pallets lost in the system. We examine that the *Section Management* and *Demand Management* correctly handle the transition from new fresh pallets to butt pallets, which ultimately leave the system, based on the arrival and departure of pallets.

The next part of the *Section Management* we validated, is whether AGAPTVs are appropriately dealing with blockades in sections. By visual observation of the model and comparison with cases from practice, we checked whether the AGAPTVs are not traversing paths that are blocked. Figure 7.3 shows how we visually indicated which paths are blocked due to crane blockades. AGAPTVs are not allowed to traverse those lanes. We validated this process by comparing the visuals of the simulation model with media such as videos and photos of potrooms and AGAPTVs. We concluded that the AGAPTVs properly avoid the paths in which the crane is active. Similarly, we validated the metal tapping process.

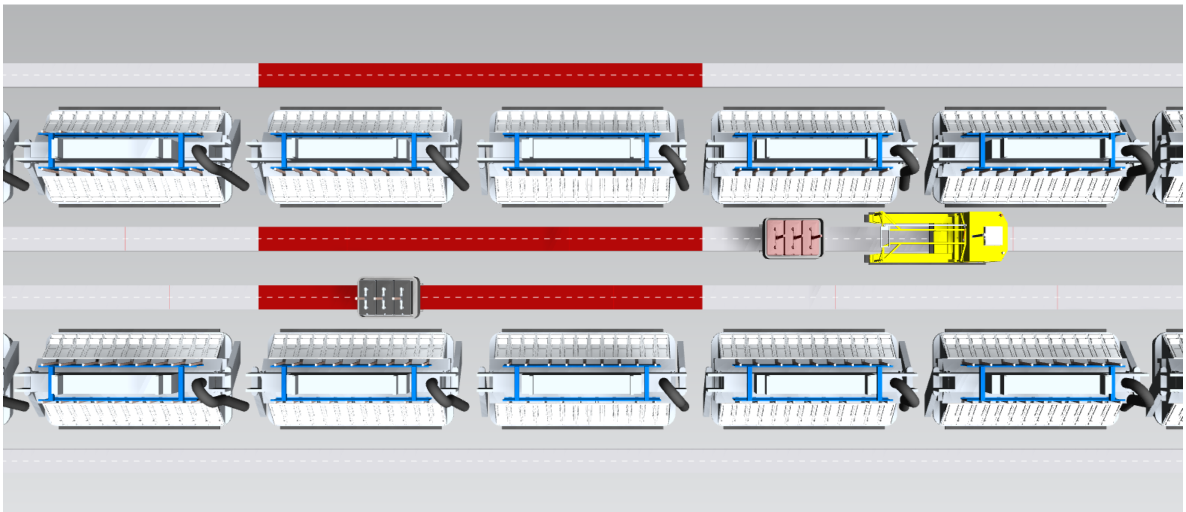


FIGURE 7.3: An AGAPTV cannot traverse blocked paths due to an active crane.

7.3.2.3 Battery Management Agent

The *Battery Management* is validated using:

- The battery consumption during common activities. The battery level should decrease according to the properties as specified in Appendix C;
- Battery charging should take place according to the properties as defined in Appendix C;
- A critical battery charging task should be scheduled once the preferred battery level b_{pref} is being reached. We consider a b_{pref} of $15kWh$. We further examine the automatic charging variant of recharging until at least the battery reaches the level b_{plat}, where b_{plat} equals $32kWh$;
- Recharge until at least the battery reaches the level b_{plat}. This value can for instance be set to the plateau level;
- The vehicle should at least stay for b_{δ_t} minutes once an opportunity charging task is scheduled. For validation purposes, we have set b_{δ_t} to 20 minutes.

Figure 7.4 shows the battery levels of three AGAPTVs which are tracked a period of time. Let us now discuss whether the obtained results accurately represent the reality. Unfortunately, we do not have any historical data regarding the behavior of battery levels, but we discussed the results with a panel of employees of Hencon.

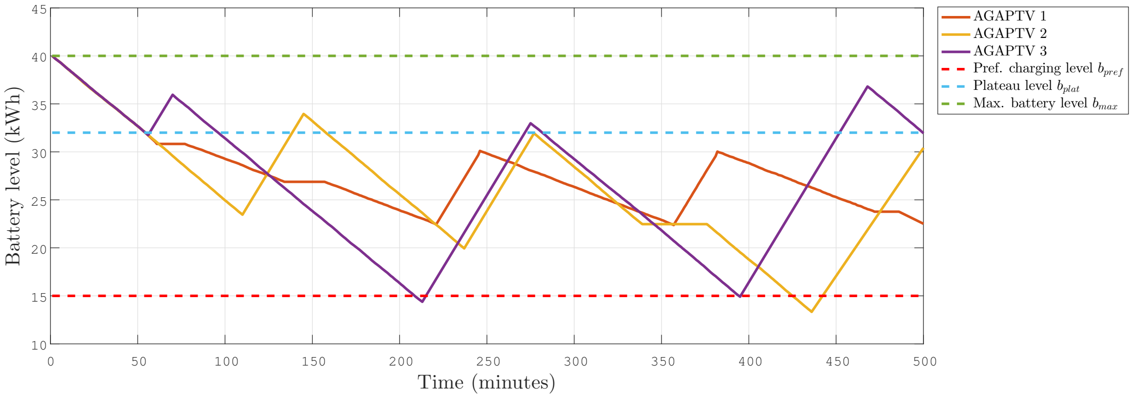


FIGURE 7.4: Battery levels of three AGAPTVs.

First, one remark regarding the data collection in the simulation model. We determined the battery levels at a few moments in time: (1) when a transport job is delivered, (2) when a new transport job is assigned to the vehicle, (3) when an automatic charging task is scheduled, (4) when an opportunity charging task is scheduled.

Figure 7.4 shows that the battery level decreases with roughly $5kWh$ during the transport of goods, which is in line with practice. Likewise, we observe that the battery charging takes places at $18kWh$ which is close to reality. Notice that we assumed a linear increase and decrease in battery levels, while this would be different in practice. For example, charging the last few percentages (e.g., from 80% to 90%) would take significantly more amount of time than charging the same percentage increase starting at a lower level (e.g., from 50% to 60%). However, due to the lack of knowledge regarding the exact battery behavior, we convinced ourselves that the battery behavior in the model fulfills the needs of Hencon.

Furthermore, Figure 7.4 illustrates that when an AGAPTV reached the preferred battery level, a critical charging task is scheduled. The charging task is not interrupted until at least the plateau level is being reached. Also, the opportunity charging approach functions properly, because there are moments in-between the preferred charging level and plateau charging level in which AGAPTVs are charging their batteries for at least 20 minutes.

7.3.3 Black-box Validation

Black-box validation comprises the overall behavior of a model. We examine a selective scope of model parameterizations and experimental configurations. To this end, the input parameters are chosen such that they closely mimic a facility of one of Hencon's customers. We check whether given the input parameters, realistic outputs are obtained.

We first conducted experiments with varying the number of AGAPTVs deployed. This is done in Subsection 7.3.3.1. After that, we performed in Subsection 7.3.3.2 experiments with considering different dispatch rules. The experiments are carried out by using the guide-path input parameters as shown in Appendix W. The demand is generated in a similar manner as done in Subsection 7.3.2.

7.3.3.1 Number of AGAPTVs

We validate the overall system performance by considering the statistics obtained from experiments by varying the number of AGAPVs. Below we respectively discuss the cycle time of pallets in the system when considering one AGAPTV, the cycle time of pallets in the system when considering two AGAPTVs, and the performance on several other indicators with regard to including more AGAPTVs in the system.

The cycle time of a random sample of 250 subsequent pallets is shown in Figure 7.5. In this figure, the pallets are sorted in ascending order based on their fresh pallet pick-up time. Remarkable is that this figure shows steady-state cycles with a length of approximately 30 pallets. In some periods, like the time-window from the 50^{th} pallet until the 120^{th} pallet, the steady-state cycle length is roughly twice the length of a single steady-state cycle. A reason to explain the appearance of steady-state cycles in this manner, is that the shift-based working routine results in periods with high transport demand and low transport demand in cyclic patterns. When a new shift occurs, the demand in the start period of the shift is high because there are many sections that require anode pallets in a short time-window. As all the resulting butt pallets need to be transported back to the rodding shop as well, we expect the demand peak retains for a while after which the demand gradually vanishes away. Consequently, when there are fewer pallets positioned in the potroom and the cranes gradually finishes their tasks, there are fewer blockades on the paths. Fewer blockades yield better routes which decrease the pallet cycle time. Hence, this is an explanation about the decreasing trend in the cycle time within the steady-state cycles.

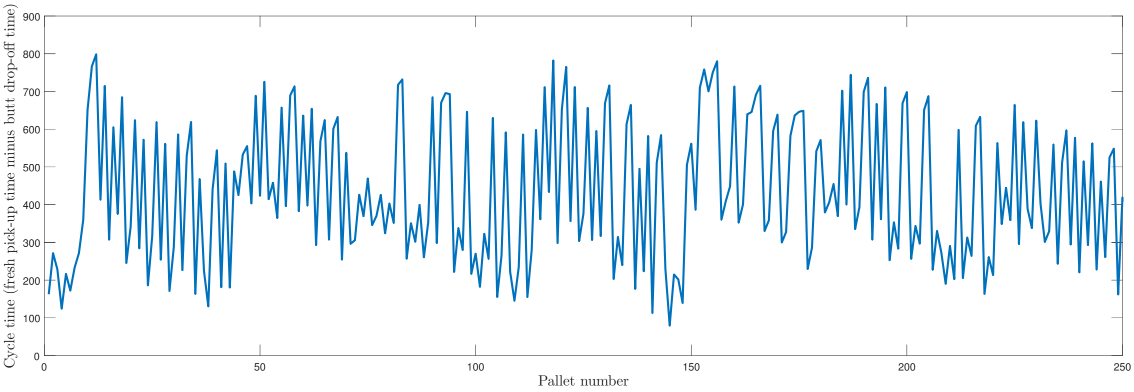
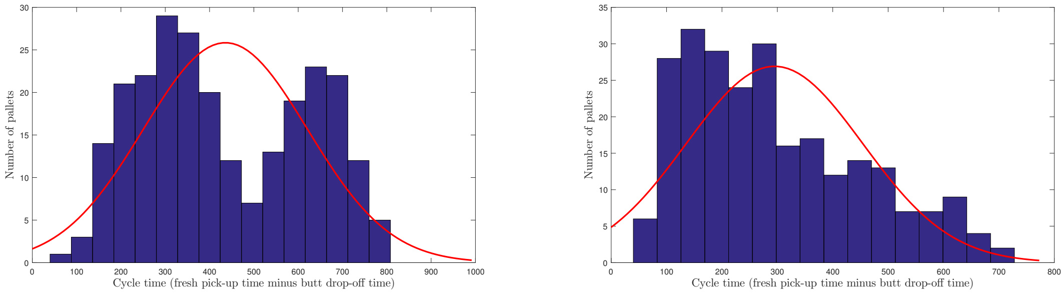


FIGURE 7.5: Cycle time of pallets when considering one AGAPTV.

Furthermore, we can deduce from Figure 7.5 that the pallet cycle times are quite fluctuating. The average pallet cycle time is 435.8 minutes with a 95% confidence interval of $[165.4; 706.1]$. The large width of the confidence interval suggests that the cycle time per pallet might be quite differently. This observation is supported by Figure 7.6a which depicts a histogram of the pallet cycle time. As we can see in this figure, the histogram is not a bell shaped curve. This observation can be explained by the travel differences from the rodding shops to the cells. A relatively high difference between the driving times might be a cause of this fluctuation of the cycle time. We expect the behavior of the system as discussed so far is valid with practice.

Let us now discuss experiments with multiple AGAPTVs in the system. Figure 7.6b gives a histogram of the pallet cycle time with a similar system but now with two AGAPTVs. As dispatch rules, we randomly selected vehicles and jobs. The histogram is different to the one of one AGAPTV because now the figure is more shaped to the left and the average cycle time is shorter. The average pallet cycle time is now decreased to 294.9, which is roughly 140 minutes less in comparison to having one AGAPTV in the system. So, when we add one more vehicle to the system, the pallets are



(A) Histogram of the cycle time of pallets when considering one AGAPTV.

(B) Histogram of the cycle time of pallets when considering two AGAPTVs.

FIGURE 7.6: Anodes positioned in or nearby electrolytic-cells.

on average more than two hours shorter in the aluminium smelter. The 95% confidence width also decreased from 541 to 399 minutes. We believe such a decline in pallet cycle time can be expected because when more AGAPTVs are deployed, it is likely that, for example, the time to pick-up a load decreases.

The results of deploying multiple vehicles in the system is given in Figure 7.7 and Table 7.2. The number of jobs that are delivered too late per anode setting cycle (28 days) is considerably high when there is only one vehicle in the system. More vehicles in the system will decrease this number, but it appears that when reaching a certain threshold of number of vehicles, this number will not decrease anymore and might even increase. Similar results are obtained when considering the average response time per vehicle per trip and the average travel time per vehicle per trip: first the performance increases but when a certain threshold number of vehicles is reached, the performance decreases. These threshold values appear to be different for the presented performance indicators. It is interesting to see this behavior as this is what we would expect. A larger number of vehicles in the system will not always lead to a better performance.

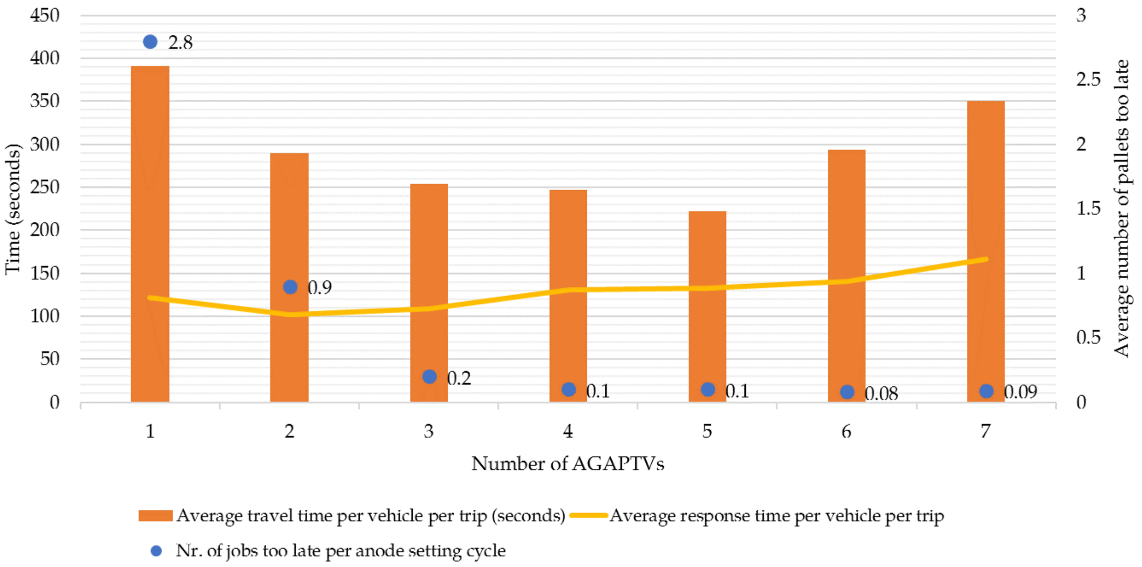


FIGURE 7.7: Several performance indicators with a varying number of AGAPTVs deployed.

7.3.3.2 Dispatch Rules

An important part of the MAS control rules are the dispatching rules. We validate the model by discussing the results obtained with different dispatching rules. The total number of possible experiments that can be carried out is regarding evaluating all possible combinations of dispatching rules is

TABLE 7.2: Simulation output with regard to varying the number of AGAPTVs.

AGAPTVs	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Nr. of jobs too late per anode setting cycle	2.8	0.9	0.2	0.1	0.1	0.08	0.09
Average response time per vehicle per trip (seconds)	122	102	109	131	133	141	166
Average travel time per vehicle per trip (seconds)	391	289	254	247	223	293	350

high. For the purpose of this report, we discuss the performance of the three scenarios of dispatching rules:

1. Workcenter strategy: First Available Vehicle (FAV) & Vehicle strategy: First-Come-First-Serve (FCFS).
2. Workcenter strategy: Random Vehicle (RV) & Vehicle strategy: Random Job (RJ).
3. Workcenter strategy: Nearest Vehicle (NV) & Vehicle strategy: Shortest Travel Distance (STD).

Figure 7.8 shows the result of three performance indicators for each of these scenarios whereby we considered two AGAPTVs in the system. The strategy with the dispatch rule that randomly selects a vehicle or job scores the worst on the average travel time per vehicle per trip, the average response time per vehicle per trip, and the number of jobs delivered too late. However, the difference between the average travel time per vehicle per trip is not significantly worse than the dispatching strategies that select the first available job or vehicle. The number of jobs that are delivered too late is significantly higher with the dispatching strategies that randomly selects a vehicle or job than under the other strategies.

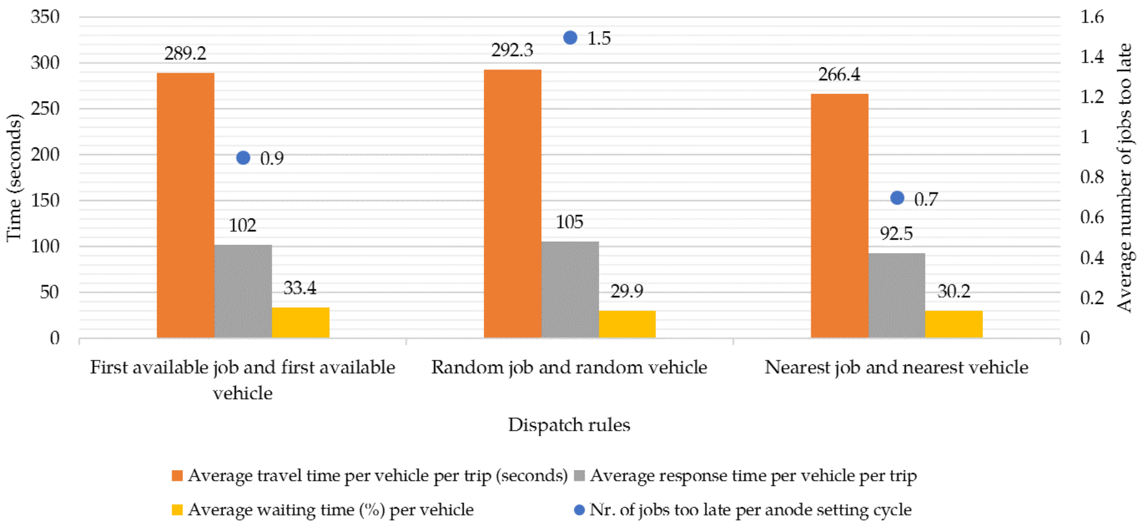


FIGURE 7.8: Histogram of the cycle time of pallets when considering two AGAPTVs.

Notice that we cannot make any general statements regarding the performance in other systems because there are many factors that would influence this. We expect the affect of dispatching rules in relative small system is low, but with the growing tendency of larger potrooms the selection of dispatching rules may play a major role in achieving performance advantages. More experiments should be carried out in a further research to verify this.

7.4 Conclusion

The verification and validation techniques we used, provide us evidence that the simulation model is valid, credible, and reliable for fulfilling its purposes. White-box validation assessed the validity of subsets of the system and black-box validation the validity from a holistic perspective. Despite that there may be some small discrepancies among the reality and the developed simulation model, the users are sufficiently convinced that the model mimics the reality to such a degree that the obtained results are realistic and useful for practice.

Chapter 8

Implementation Plan

This chapter contains an implementation plan of the designed models. The proposed implementation plan is twofold. First, we discuss an implementation plan for the scenario evaluation model. Next, we consider an implementation plan of the MAS planning and control strategies. We propose two implementation alternatives in this chapter. First, the evaluation model without the integration with other systems (Section 8.1). Second, the evaluation model with integration with other systems (Section 8.2). Additionally, we sketch how the MAS system can be integrated with openTCS in Section 8.3. Section 8.4 finalizes this chapter with a conclusion.

Remark that it may be difficult to provide a uniform applicable roadmap for implementing the MAS planning and control strategies to any situation and, therefore, the proposed implementation plan may not be sufficient.

8.1 Stand-alone Evaluation Model

An implementation option is that the evaluation model itself will be used as a separate model that is not necessary integrated with other systems (of clients). That is, we see the model as a stand-alone model. With proper input parameters and little information regarding the client's situation, we can already give an indication of the performance under certain scenarios. An advantage of using the scenario model for this purpose is that no complicated IT-protocols need to be written and that a relatively quick advise can be provided to (prospective) clients. Also, there is limited knowledge required about the customers IT-infrastructure because there is no integration required (yet). The graphical user interface provides the user with relevant information in a friendly manner.

The model is suitable for assessing a variety of different potroom layouts and demand patterns. The model can not only evaluate current potroom layouts but also expose the performance under different potroom layouts. So, the model might open opportunities for fruitful collaborations with other parties. Hencon can use the evaluation model for advising its clients about modifications to their plant layout and adjustments in cell configurations. With the support of the scenario evaluation model, Hencon can support clients in making decisions regarding plant expansion and accessing the impact of different demand patterns. Also, the tool helps in, for example, identifying appropriate battery charging areas. Model parameterizations and sensitivity analysis are an effective means to enable this and convince the customer.

Concerning a periodic use of the model, there are promising directions for future model extensions that may increase the model's applicability and genericness on the long-term. A grasp of fruitful and more practically oriented directions for future model development are (see also Chapter 9):

1. Inclusion of metal bucket transport vehicles (and integration with other unmanned vehicles).
2. The AGAPTV currently plays a supportive role in the potroom environment while there is much potential in developing ways in which they complement each other. Interaction among entities is essential.
3. Strengthen the robustness and applicability of the system.
4. More sophisticated vehicle routing approaches. The release and occurrence of blockades is mostly known upfront. Despite this, the currently used vehicle routing approaches are not properly dealing with this information.
5. Plenty of AGV system design elements are not covered in our evaluation model. For example the concept of tandem configurations.

When one aims to implement the actual operational planning and control rules as a result from a scenario evaluation, the implementation steps as discussed in Section 8.3 should be considered.

8.2 Integrated Scenario Evaluation Model

An alternative implementation option of the evaluation model is an integration with the customer's MES and the openTCS software. The evaluation model itself can then mainly be seen as a hub in-between the MES and openTCS, as shown in Figure 8.1. This figure depicts the communication flows, where the dashed lines represent a feedback loop.

The evaluation model requires information of the potroom environment as specified by the input parameters. This information defines the boundaries in which the evaluation model operates (e.g., layout properties, AGAPTV properties, etc.). Additionally, the evaluation model should obtain transport demand information from the MES. On its turn, the evaluation model uses the demand, potroom, and other model inputs to determine the best settings based on the considered experimental factors as defined by the user.

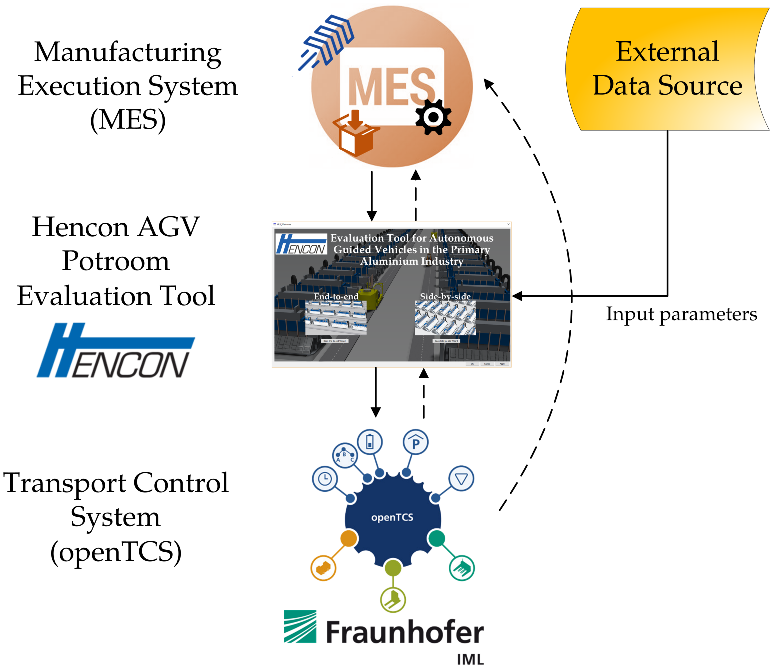


FIGURE 8.1: Implementation architecture of an integrated scenario evaluation model.

The role of the evaluation model in this system is then twofold. The first role is to determine the best suitable operational planning and control strategies. The second role is to pass information through to the next entity (e.g., MES, openTCS, or other IT-systems). To realize this, the model developed so far needs to be extended by a communication shell and protocols to that allow quickly sharing information. To this end, IT protocols need to be developed about how clients' MES communicates with the evaluation model.

An interesting direction for further research with respect to this implementation alternative is the development of a real-time model that can provide support in potroom logistics/environments.

8.3 Multi-agent System and the Operational Planning and Control Rules

The openTCS software plays a major role in the implementation of the MAS and the planning and control rules. OpenTCS intentionally provides a driving model of a transportation system, manages transport orders, and computes routes for vehicles (*The architecture of openTCS* 2017). Furthermore, OpenTCS provides (hardware) drivers for controlling the AGVs. However, as discussed in Chapter 1, openTCS has some limitations such as the absence of evaluating the impact of different settings beforehand.

The MAS and its control rules affect, for example, the dispatcher, scheduler, and router within the openTCS architecture. OpenTCS still functions as a hub in-between the evaluation model and

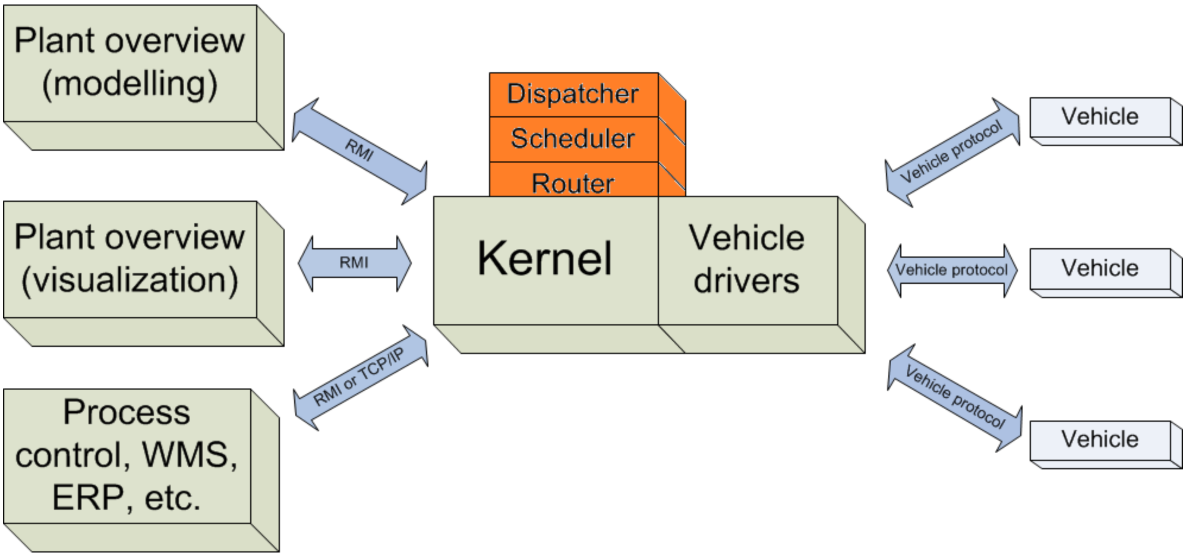


FIGURE 8.2: The architecture of openTCS (*The architecture of openTCS* 2017).

the actual control, but its functions are focussing on controlling the AGV only because our model overtakes the dispatcher, scheduler, and router functionalities.

We suggest to use already existing communication standards (i.e., preferably from openTCS) that allow easy, fast, and secure access through the evaluation model. More specifically, communication protocols should be established for: vehicle routing, vehicle scheduling, parking management, battery management, demand management (through MES), and potroom entities that cause blockades (e.g., additional cranes, buckets, etc.).

8.4 Conclusion

We briefly proposed a few ways of implementing/using the evaluation model, the MAS model, and the planning and control rules. The evaluation model can be used as a stand-alone model by which the only prerequisite is that the user provides inputs. Another implementation option is the integration of the scenario evaluation model, MES, and openTCS.

Chapter 9

Conclusions and Recommendations

This chapter discusses the conclusions of this research. Section 9.1 addresses conclusions with respect to the research questions and contains theoretical and practical implications of our study. Section 9.2 contains areas for further research.

9.1 Conclusions

In Section 1.3.4, we stated our ten research questions. The collective answer to these questions satisfy the research goal of this study. Chapter 2 outlined the context in which this study is framed. In Chapter 3, we reported a literature study on AGV system design, dynamic scheduling techniques in manufacturing environments, multi-agent systems, and operations research applications in the primary aluminium industry. Chapter 4 proposed the designed multi-agent system for planning and control of the AGVs. Chapter 5 continued by discussing the AGV system design. Consequently, Chapter 6 covered the evaluation model of the AGV implementation controlled by the MAS. As part of model verification and validation, Chapter 7 verified and validated the developed evaluation model. Finally, Chapter 8 sketched an implementation plan of the MAS planning and control strategies in AGV systems. For a concise recap of any of the research questions, we refer to the subconclusion in the corresponding chapter.

In this section, we divide our conclusions into two parts. First, we consider a theoretical perspective and discuss the theoretical relevance of our study. Second, we discuss the practical applicability of our study and address how Hencon and its customer may benefit from it.

9.1.1 Theoretical Conclusion

We developed a generic operational planning and control strategy for AGVs involved in anode transportation, within the smelting process of primary aluminium manufacturing. Three models are designed: a MAS, an AGV system, and a scenario evaluation model which is build by using a discrete-event simulation. A conceptual model is build, which is verified and validated by means of several validation techniques. We suggest that the AGV system and MAS designs, as well as the simulation model is more widely applicable than just to our specific research. Below we discuss the suitability of respectively our MAS, AGV system, and scenario evaluation model designs to other types of systems.

9.1.1.1 Multi-Agent System Design

The developed MAS framework by following the Prometheus methodology resulted into a specification of capabilities per agent:

- **Demand Management (DM)**: represents the in- and outgoing demand flow. The data may be provided by the MES but as alternative DM include some heuristics.
- **Section Management (SM)**: monitors pick-up and drop-off locations of the pallets in the sections and thereby considers avoiding collisions due to other ongoing activities.
- **AGV Parking Management (PM)**: assigns dwell points to AGVs.
- **Vehicle Scheduling (VS)**: determines when, where, and which AGV should pick-up or drop-off an anode pallet.
- **Vehicle Routing (VR)**: finds the route an AGV should take.
- **Conflict Resolution (CR)**: monitors AGV movements and is responsible for avoiding collisions and resolving conflicts.

- **Battery Management (BM**: monitors AGVs battery status and determines when and where an AGV should recharge.

The considered instance of agent entities together with its architectural design provides a MAS framework of which the applicability is not necessarily limited to the context of the primary aluminium industry. A key element of our design is the inclusion of a *Section Management* capability that divides the potroom into subsets of controllable areas in which problems are solved locally. Other systems involving the planning and control of AGVs can be equipped with this agent specification as well. The applicability scope is not only limited to AGVs, but the MAS framework can, for example, also be applied to warehousing systems.

9.1.1.2 AGV System Design

The AGV system design is built by using the AGV decision framework of Le-Anh and Koster (2006). We developed an AGV system design that can generically built and of which the applicability scope may be wider than a selected group of Hencon's client base. Our AGV system can be used when one considers using alternative layouts or evaluate the impact of other modifications such as a different vehicle routing approach.

9.1.1.3 Scenario Evaluation Model Design

We developed the scenario evaluation model to assess not only current situations but also to experiment with alternative operational planning and control strategies and AGV system designs. The generic structure of the model allows us to examine plenteous configurations of planning and control rules.

9.1.2 Practical Conclusion

The practical relevance emerges as Hencon can start to employ the scenario evaluation model to not only enhance customers' AGV logistics but also their potroom planning and control strategies. Even with a limited set of input parameters and confined information concerning, for example, anode demand patterns, the model can provide insights into expected yielded performance. During the implementation phase at a client, the evaluation model may be used to find appropriate AGV planning and control rules customized to specific client's needs. Moreover, the software may be used to periodically, based on recent developments at the customer site such as potroom expansions or the placement of additional charging stations, re-evaluate scenarios and configurations. Ultimately, Hencon can then use the developed model as a tool for its full-service providing activities.

We verified and validated the model by means of several techniques. As part of the validation, we considered a smelter layout that closely resembles a real smelter layout. In this particular simulation study, we observed that the cycle time of pallets decreases considerably (more than 30%) when one uses two AGAPTVs instead of one. The number of jobs delivered too late also decreases when one uses two vehicles instead of one. The performance, however, will likely not always increase when one considers more vehicles in the system. Depending on the characteristics of the smelter layout (i.e., input parameterizations) and the considered simulation experiments, performance indicators such as the number of jobs delivered too late could increase when including more vehicles in the system. For that reason, it is important to properly analyze the results obtained from the simulation model.

9.2 Recommendations for Future Research

In this section, we highlight some promising suggestions for further research and development of the models. We have made assumptions and the models' scope is limited. Further research and model extensions are therefore desirable. We divide the recommendations into practical and theoretical relevant directions. Remark that some of the recommendations may be both practically and theoretically interesting but for the purpose of this thesis we focus on highlighting a specific point-of-view:

Practical

1. Although the model is applicable to a wide variety of clients, there is no guarantee that every imaginable smelter can be evaluated. Extension of the evaluation model by considering side-by-side positioned cells seems a suitable next step.
2. An attractive extension is the inclusion of smelter logistics. Modelling smelter operations and involved logistics would enhance the validity of the system. In a further stage, Hencon could consider their fleet capable for these type of jobs with AGV technology as well.
3. Crane movements are not covered in full detail. A noteworthy direction for further research is the detailed inclusion of crane blockades.
4. This study assumes an infinite capacity at the rodding shops (pick-up and drop-off locations), while smelters face space and capacity restrictions. A promising future research direction is the integration of rodding shop activities. Likewise, considering transshipment points that could act as a buffer can lead to performance benefits.
5. The aluminium production process is a complicated process that involves the alignment of many processes which are not all covered in this study. The anode transport now mainly fulfills a supportive task whereby the anodes follow the patterns as desired by the crane operators. An interesting direction would be to examine possibilities to develop a model in which the AGAPTV collaborates more extensively instead of providing a supportive task. A promising line of research is the integration with other internal and external systems (e.g., supply chain wide) towards a more holistic approach.
6. Further research is required concerning the robustness of the system. Despite that a concise sensitivity analysis can be conducted by simulating the effect of randomly passing other vehicles, plenteous other implications such as cell overhaul, bath transport, vehicle maintenance, and the impact of weekend work schedules possibly interfere with the anode changing activities and involved logistics. Additional research needs to be carried out to overcome this and other practical concerns.
7. Extension of the model by incorporating a continuous working approach. To some degree, the model can already satisfy this by parametrization and demand modification, but more emphasis can be given to properly reflecting a continuous workflow approach.
8. The design of a more sophisticated battery management approach that, for example, holistically considers the battery levels of each AGV when making decisions. Furthermore, the selection of locations for battery-charging stations can be investigated in future research.
9. By combining information regarding environmental potroom emissions, insights into the effect of AGVs driving with closed buckets (pallets) in comparison to open buckets can be obtained. It would be interesting to come up with an environmental related model as extension.
10. The comprehensive design of an IT-infrastructure for the MAS and interfaces between external systems.

Theoretical

1. A thoughtless design of experiments can quickly explode the possible solution search space because of the many possible configurations and parameterizations. Some configurations may be excluded on beforehand because they are not considered as valid in practice. However, fine-tuning parameters and methods to find good solutions quickly, still require more attention. To this end, simulation optimization techniques may be an interesting future direction. These techniques try to find the best input factors without accessing each experimental configuration. One then searches for the best solutions with regard to computational time constraints.
2. The model is generic and thus its potential use goes beyond the application area of the primary aluminium industry. Besides that other Hencon software platforms may use technology developed in this study, existing AGV systems such as warehouse management systems can be evaluated as long as they are similarly parameterized.
3. The developed MAS forms as a framework for further research. Different hierarchical MAS structures can be studied as an extension. A promising direction is the inclusion of auction mechanisms for decision-making. More sophisticated methods, for example as zone-partitioning strategy can potentially improve the effectiveness and efficiency of the system.
4. In collaboration with other potroom solutions, the anode transportation tasks can be observed system-wide. More research should be conducted in linking already existing systems together.

5. More research is required in comparing the performance of the designed MAS system with other (analytical) approaches. The performance under varying levels of dynamism and scale can for example be measured against PDPTW benchmarks.
6. Current experimental configurations are basic and can be extended with the latest technologies. We considered, for example, simplistic dispatching rules which can be extended by more sophisticated approaches.
7. The approach used to generate demand usually comes from a MES. Further research can be carried out regarding the validity of the proposed approach for simulating this demand. One could, for example, include a dynamic pallet assignment approach in which multiple pallets are assigned to one position with different reserved time slots.
8. Extension of the simulation model by assessing different vehicle routing strategies on system performance.

Appendix A

Emergence of Automated Guided Vehicle Technology

In recent years, technological developments in the logistics industry have contributed to increasing operations efficiency remarkably. A special role is dedicated to the automation of processes, which brought us, for instance, benefits of higher production rates and increased productivity, more efficient use of materials and a better product quality, improved safety, shorter workweeks for labor and reduced factory lead times. The potential influence of automation within logistic and production environments is currently still a hot topic of discussion due to a number of on-going economic, societal and environmental developments. Despite the promising impact of recent innovative projects, such as the European Truck Platooning Challenge (Dutch Ministry of Infrastructure and the Environment, 2016), there is a continuous desire for higher efficiency of goods transport within the industry.

Companies need to develop new intelligent and flexible approaches for both transport & production planning and scheduling to keep up with current industry trends. Trend overviews from for instance Gartner (see Figure A.1) and DHL (DHL Customer Solutions & Innovation, 2016) indicate an increasing interest and a higher level of maturity regarding AGVs in the near future. Figure A.1 depicts a recent hype cycle from Gartner, and shows there are some years to go before AGVs are getting more mainstream. According to Gartner, expectations about autonomous vehicles have been peaked, however, it would take more than 10 years before having a mainstream adoption of this technology. Additionally, the growing computational power and further enhancements on real-time decision making like the availability of data at increasing levels of granularity, would potentially provide an enormous efficiency improvement. Yet, companies often struggle with attaining and using this potential. Consequently, their degree of competitive advantage could be undermined within the upcoming years. Hencon, in its turn, attempts to be one of the early adopters and embraces AGV technology as one of their unique selling points.

AGVs have now become more commonplace in manufacturing environments (Gosavi and Grasman, 2009). There are plenteous examples of manufacturers and associated transport hubs that use AGVs in their daily operations (e.g. electronic goods and large automobile manufacturers, warehouses and containers terminals). Increasing labor costs associated with human-operated material-handling systems has given a boost to the usage of AGVs (Heragu, 2008). Also new approaches to model and optimize scheduling and routing problems related to AGVs are recently developed. For example, Erol et al. (2012) provides a review of literature related to different methodologies to optimize AGV systems.

Even though AGVs provide a promising application in modern manufacturing and assembly environments, the AGV systems themselves tend to be very expensive and manufacturers are therefore often reserved to incorporate AGVs in their operations. Likewise, AGVs are typically considered to be expensive. In addition, due to the highly dynamic nature of transport creation, assigning transport tasks to AGVs in an efficient manner is not simple. Moreover, transport assignments should be flexible enough to cope with continuously changing circumstances.

To summarize, applications of AGV technologies to increase operations efficiency are slowly getting to a mature level. Even one AGV can significantly reduce the material-handling time and thereby increase throughput and reduce inventory levels (Gosavi and Grasman, 2009). However, in terms of assessing, evaluating and utilizing the full potential of AGVs there are still major barriers to overcome for Hencon. Hencon's clients are for that reason, reluctant to incorporate this technology within their environments. Therefore, it is prudent to thoroughly evaluate the impact AGVs could have on the (prospective) client base. Hencon, as a full-service provider being active in various markets on

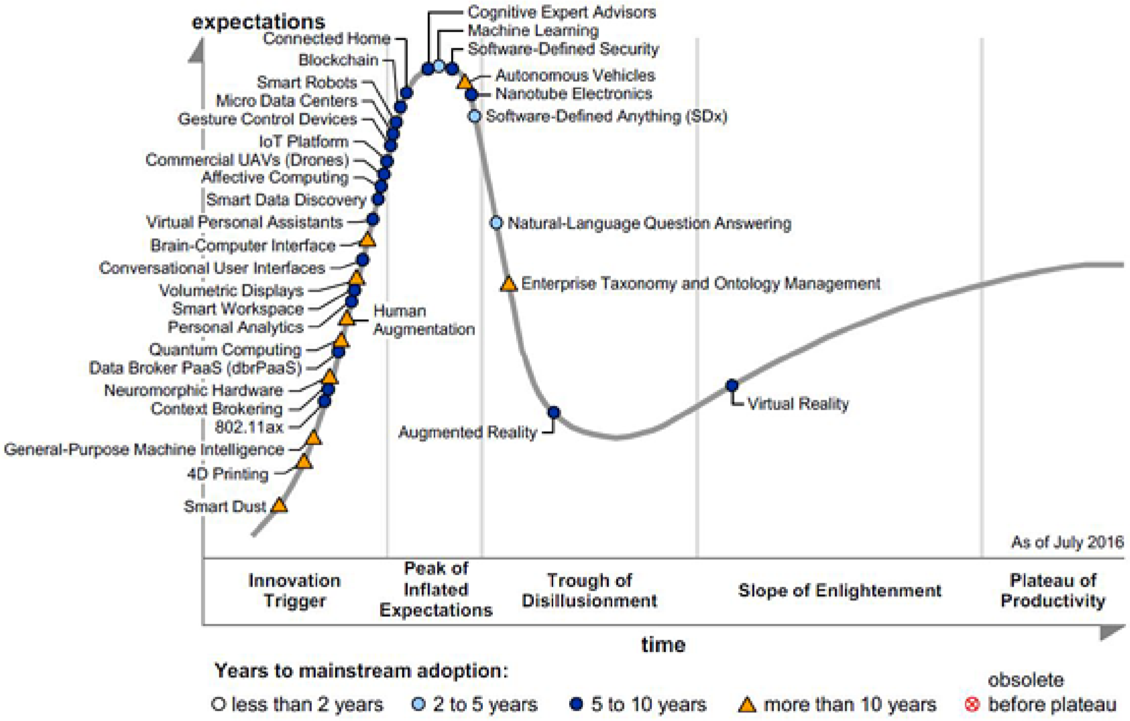


FIGURE A.1: Hype cycle for emerging technologies (Gartner, 2016)

a global level, aims to designate the utilization of this discrepancy in a comprehensive and promising manner. Hencon's goal is therefore to build those AGVs and additionally extend their services by providing their (prospective) clients reliable information about the impact AGV technology has on their manufacturing facilities. By doing that, Hencon ultimately aims to reinforce their market position.

Appendix B

Operational Potroom Tasks

TABLE B.1: Operational tasks in the potroom. Adapted from Eick, Vogelsang, and Behrens (2001).

	Tasks	Vehicles	Machinery	Equipment	Materials
1	Metal tapping	MTV, Truck	CC, PTC	Crucibles, Lids	Metal
2	Anode -, butt transport	APTV		Palettes	Fresh anodes, Bath Spent anodes
3	Anode changing	ACV, CCL HCB	PTC		Bath, Fresh anodes, Spent anodes
4	Anode covering	Drumfeeder, LDF	PTC		ACOM
5	Beam raising	FLT, RRT	CC, PTC	Jacking frame	
6	Bath tapping	BTV, FLT		Bath crucible	Bath
7	Pot maintenance	PTC			
8	Crane filling	PTC		Filling station	Alumina, ACM, AIF
9	AIF feeding	HDF	CC, PTC	Hopper	AIF
10	Alumina feeding	HDF	CC, PTC	Hopper	Alumina
11	Crane maintenance	PTC			
12	Crane transfer	CC, PTC			
13	Pot stoppage	FLT, LFTL, PDC, PTC, Truck, MTV		Crucibles, Palettes	Metal, Bath, Spent anodes
14	Pot startup	PDC, PTC, LFTLT, Truck FLT		Crucibles, Palettes	Anodes, Metal, Bath

ACV = Anode changing vehicle, ACOM = Anode cover material, AIF = Aluminium fluoride, APTV = anode pallet transport vehicle, BTV = Bath tapping vehicle, CC = Construction crane, CCL = Cavity cleaner, FLT = forklift, HCB = Hammer crust breaker, LDF = Low discharge feeder, LFLT = Large 6t forklift, MTV = Metal tapping vehicle, PDC = 160t pot displacement crane, PSUT = Pot Start-Up Tilter, PTC = Pot tending crane

Appendix C

AGAPTV Properties

Automated Guided Anode Pallet Transport Vehicle Properties

Acceleration forwards (loaded)	$0.3m/s^2$
Acceleration forwards (unloaded)	$0.3m/s^2$
Acceleration backwards (loaded)	$0.3m/s^2$
Acceleration backwards (unloaded)	$0.3m/s^2$
Recommended forward speed (loaded)	$1.25m/s$
Recommended forward speed (unloaded)	$1.25m/s$
Recommended backwards speed (loaded)	$1.25m/s$
Recommended backwards speed (unloaded)	$1.25m/s$
Deceleration	$0.5m/s^2$
Emergency brake	$2.4m/s^2$
Maximum capacity	4 anodes
Minimum distance between other vehicles on the track	$10m$
Minimum distance between physical obstacles in plant	$0.5m$
Average battery consumption loaded (3 anodes)	$5.5kW$
Average battery consumption empty bucket	$5.0kW$
Average battery consumption not loaded	$4.3kW$
Average battery consumption loading/unloading operations	$5.0kW$
Average battery life	$6-8$ hours ($40kWh$)
Recharging time	$\frac{batterylife}{2}$, charging is done with $18kW$

Appendix D

System Functionalities: Functionality Descriptors

Demand Management Functionality

Description	This functionality monitors in- and outgoing anode pallets based on the working schema. It obtains information about (expect) arrival and (expected) dispatch times, and anode pallet specifications (e.g., orientation, anode type, amount of anodes, etc.)
Goals	Obtain (expected) arrival time, Obtain departure time, Obtain anode specifications
Actions	Log (expected) anode pallets arrival, Log anode pallets departure, Log anode pallet specifications
Triggers	Anode pallet arrival, Anode pallet departure
Information used	Potroom and cell demand characteristics, Shift schema, Anode pallet arrival time, Anode pallet dispatch time, Anode pallet specifications, Anode and anode pallet database
Information produced	Arrived anode pallets, Dispatched anode pallets, Delayed anode pallets, Anode and anode pallet database

Section Management Functionality

Description	This functionality monitors anode pallet positioning and sequencing in a section of cells. It assigns pick-up and drop-off locations to anode pallets and takes care of avoiding collisions due to other ongoing potroom activities in the section.
Goals	Allocate anode pallet storage location
Actions	Assign anode pallet storage location
Triggers	Loaded AGAPTV arrival, Anode pallet departure, Anode enters/leaves pallet, Butt enters/leaves pallet
Information used	Anode pallet specifications, Anode pallet storage database, Shift schema, Blocked areas database, Arrival database, Dispatch database
Information produced	Anode pallet storage database

AGV Parking Management Functionality

Description	This functionality assigns parking locations to AGVs
Goals	Allocate AGV parking location
Actions	Assign AGV parking location
Triggers	AGV idle, Anode pallet dispatch
Information used	Dispatch database, AGV status, AGV parking database
Information produced	AGV parking, AGV status

Vehicle Scheduling Functionality

Description	This functionality determined when, where, and which AGV should pick-up or drop-off the anode pallet
Goals	Construct pick-up schedule, Construct delivery schedule
Actions	Determine optimal vehicle schedule(s)
Triggers	Anode pallet arrival, Anode pallet dispatch
Information used	Arrival database, Dispatch database, AGV status
Information produced	AGV schedule

Vehicle Routing Functionality

Description	This functionality determines the route an AGV should take
Goals	AGV routing
Actions	Determine optimal routes
Triggers	AGV scheduled for pick-up or drop-off
Information used	AGV status, Guide-path design, Blocked areas database, Anode pallet storage database
Information produced	AGV route

Collision Avoidance & Conflict Resolution Functionality

Description	This functionality monitors AGV movements, takes care of collision avoidance, and resolving conflicts
Goals	Collision- and conflict free routing
Actions	Avoidance of collisions, Conflict resolving
Triggers	(Conflicting) AGV routing, Collision detection
Information used	AGV routing, Collision sensors, Priority rules, AGV status
Information produced	Traffic rules

Battery Management Functionality

Description	This functionality determines when and where AGVs should be recharged
Goals	Maximizing AGV availability
Actions	Determine recharging schedule
Triggers	AGV low power level
Information used	AGV status, Recharging locations
Information produced	Recharge schedule, AGV route task

Appendix E

System Functionalities: Scenario Development

TABLE E.1: MAS Scenario 1: Shift initiated

Key for functionality and data abbreviations:

DM	Demand Management
A.D. Schema	Anode Demand Schema
A.P.D. Schema	Anode Pallet Demand Schema

	Step type	Step	Funct.	Data used and Data produced
1	PERCEPT:	*New shift initiated*		
2	GOAL:	*Obtain anode changing schema*	DM	Shift Schema A.D. Schema
3	GOAL:	*Determine pallet demand schema*	DM	A.D. Schema Cell Specifications Pallet Specifications A.P.D. Schema
4	ACTION:	*Request anode pallet transportation*	DM	A.P.D. Schema
5	SCENARIO:	*New anode pallet transport request (via DM)*		A.P.D. Schema

TABLE E.2: MAS Scenario 2: Anode butt arrivals from cells

Key for functionality and data abbreviations:

DM	Demand Management
SM	Section Management
VR	Vehicle Routing
VS	Vehicle Scheduling
A.D. Scheme	Anode Demand Schema
A.P.S.D.	Anode Pallet Storage Database
A.P.D. Scheme	Anode Pallet Demand Schema
A.P. Specifications	Anode Pallet Specifications
E.A.P.A.T.	Expected Anode Pallet Arrival Time

	Step type	Step	Funct.	Data used and Data produced
1	PERCEPT:	*Anode butt placed in pallet*		

Continued on next page

Table E.2 – continued from previous page

	Step type	Step	Funct.	Data used and Data produced
2	GOAL:	*Update anode pallet database*	SM	A.P. Specifications A.P.S.D. A.P. Specifications A.P.S.D.
3	GOAL:	*Determine if new transport request should be placed*	SM	A.P. A.D. Schema
4	SCENARIO:	*Wait for next anode butt*		
5	OTHER:	*Wait for next anode butt*		
6	SCENARIO	*Anode butt placed in pallet*		
7	PERCEPT:	*Anode butt placed in pallet*		
8	GOAL:	*Update anode pallet database*	SM	A.P. Specifications A.P.S.D. A.P. Specifications A.P.S.D.
9	GOAL:	*Determine if new transport request should be placed*	SM	A.P. A.D. Schema
10	ACTION:	*Request pick-up*	VS	A.P. Specifications E.A.P.A.T. Transport Request
11	GOAL:	*Determine AGV schedule*	VS	Transport Request AGV Status AGV Schedule
12	ACTION:	*Request route*	VR	AGV Schedule
13	GOAL:	*Determine AGV route*	VR	Guide-path Design AGV Schedule AGV Status AGV Route
14	GOAL:	*Update AGV status*	CR	AGV Status AGV Status
15	ACTION:	*Send info to AGV controller*	VR	AGV Schedule AGV Route
16	OTHER:	*Wait for AGV to be at the section*		
17	PERCEPT:	*AGV arrives at section and drops-off the pallet*		
18	GOAL:	*Update AGV status*	VS	AGV Status AGV Status
19	GOAL:	*Update anode pallet database*	DM	A.P.S.D. A.P.S.D.

TABLE E.3: MAS Scenario 3: Fulfillment of new anode pallet transport request (shift initiated)

Key for functionality and data abbreviations:

CR	Conflict Resolution
DM	Demand Management
SM	Section Management
VR	Vehicle Routing
VS	Vehicle Scheduling
A.P. Specifications	Anode Pallet specifications
A.P.S.D.	Anode Pallet Storage Database
E.A.P.A.T.	Expected Anode Pallet Arrival Time
P.C.D.C.	Potroom and Cell Demand Characteristics

	Step type	**Step**	**Funct.**	**Data used and Data produced**
1	PERCEPT:	*New anode pallet transport request*		
2	GOAL:	*Obtain transport properties*	DM	P.C.D.C. Shift Schema A.P. Specifications
3	ACTION:	*Request anode pallet storage location*	SM	A.P. Specifications A.P.S.D. Section Properties
4	GOAL:	*Assign anode pallet storage location*	SM	A.P. Specifications A.P.S.D. Section properties A.P.S.D. Transport Request
5	GOAL:	*Determine anode pallet arrival time*	SM	A.P. Specifications A.P.S.D. Guide-path Design Section Properties Transport Proposal E.A.P.A.T.
6	ACTION:	*Request pick-up*	VS	A.P. Specifications E.A.P.A.T. Transport Request
7	GOAL:	*Determine AGV schedule*	VS	Transport request AGV Status AGV Schedule
8	ACTION:	*Request route*	VR	AGV Schedule
9	GOAL:	*Determine AGV route*	VR	Guide-path Design AGV Schedule AGV Status AGV Route
10	GOAL:	*Update AGV status*	CR	AGV Status AGV Status
11	ACTION:	*Send info to AGV controller*	VR	AGV Schedule AGV Route
12	OTHER:	*Wait for AGV to be at the section*		
13	SCENARIO:	*AGV possible collision detected*		AGV Routing AGV Status AGV Routing
14	PERCEPT:	*Collision is avoided*		

Continued on next page

Table E.3 – continued from previous page

	Step type	Step	Funct.	Data used and Data produced
15	SCENARIO:	*AGV deadlock expected*		AGV Routing AGV Status AGV Routing
16	PERCEPT:	*Deadlock is avoided*		
17	OTHER:	*Wait for AGV to be at the section*		
18	PERCEPT:	*AGV arrives at section and drops-off the pallet*		
19	GOAL:	*Update AGV status*	VS	AGV Status AGV Status
20	GOAL:	*Update anode pallet database*	DM	A.P.S.D. A.P.S.D.

TABLE E.4: MAS Scenario 4: AGV becomes idle

Key for functionality and data abbreviations:

CR	Conflict Resolution
PM	Park Management
VR	Vehicle Routing
VS	Vehicle Scheduling
A.D. Scheme	Anode Demand Schema
A.P.D. Scheme	Anode Pallet Demand Schema
A.P.S.D.	Anode Pallet Storage Database

	Step type	Step	Funct.	Data used and Data produced
1	PERCEPT:	*AGV status is idle*		
2	ACTION:	*Request parking position*	PM	AGV Status
3	GOAL:	*Assign parking position*	PM	AGV status AGV Schedule AGV Parking D.B. AGV Park D.B.
4	GOAL:	*Determine parking arrival time*	PM	AGV Status Guide-path Design
5	ACTION:	*Request route*	VR	AGV Schedule
6	GOAL:	*Determine AGV route*	VR	Guide-path Design AGV Schedule AGV Status AGV Route
7	GOAL:	*Update AGV status*	CR	AGV Status AGV Status
8	ACTION:	*Send info to AGV controller*	VR	AGV Schedule AGV Route
9	OTHER:	*Wait for AGV to be at the section*		
10	PERCEPT:	*AGV arrives at section and drops-off the pallet*		
11	GOAL:	*Update AGV status*	VS	AGV Status AGV Status
12	GOAL:	*Update anode pallet database*	DM	A.P.S.D. A.P.S.D.

TABLE E.5: MAS Scenario 5: AGV reaches low battery status

Key for functionality and data abbreviations:

BM	Battery Management
CR	Conflict Resolution
DM	Demand Management
VR	Vehicle Routing
VS	Vehicle Scheduling
A.P.S.D.	Anode Pallet Storage Database
C.S.D.	Charging Station Database

	Step type	**Step**	**Funct.**	**Data used and** **Data produced**
1	PERCEPT:	*AGV battery status is low*		
2	ACTION:	*Request charging*	BM	AGV status AGV Schedule
3	GOAL:	*Assign charging station*	BM	AGV status AGV Schedule C.S.D. Charging Station C.S.D.
4	GOAL:	*Determine charging station arrival time*	BM	AGV Status Guide-path Design
5	GOAL:	*Update AGV schedule*	VS	AGV Schedule AGV Schedule
6	ACTION:	*Request route*	VR	AGV Schedule
7	GOAL:	*Determine AGV route*	VR	Guide-path Design AGV Schedule AGV Status AGV Route
8	GOAL:	*Update AGV status*	CR	AGV Status AGV Status
9	ACTION:	*Send info to AGV controller*	VR	AGV Schedule AGV Route
10	OTHER:	*Wait for AGV to be at the section*		
11	PERCEPT:	*AGV arrives at section and drops-off the pallet*		
12	GOAL:	*Update AGV status*	VS	AGV Status AGV Status
13	GOAL:	*Update anode pallet database*	DM	A.P.S.D. A.P.S.D.

TABLE E.6: MAS Scenario 6: AGV (possible) conflict predicted

Key for functionality and data abbreviations:

CR	Conflict Resolution
A.P.S.D.	Anode Pallet Storage Database
C.S.D.	Charging Station Database

	Step type	**Step**	**Funct.**	**Data used and Data produced**
1	PERCEPT:	*AGV conflict is detected*		
2	GOAL:	*Resolve conflict*	CR	AGV status AGV Route AGV Schedule Guide-path Design Traffic Rules AGV Status
3	ACTION:	*Send traffic decision to AGV controller*	CR	AGV Status

Appendix F

Collision Avoidance Maneuver

The collision avoidance maneuver should be carried out in case a possible head-to-tail collision must be avoided. By the example illustrated below, we describe the procedure for avoiding a collision between one AGAPTV located in the cross aisle and another AGAPTV in the segment aisle.

Suppose an area of the potroom contains two AGAPTVs of which one AGAPTV is headed from the cross aisle to a segment aisle (see Figure F.1). The other AGAPTV is directed from that segment aisle to the cross aisle where the other vehicle is positioned.

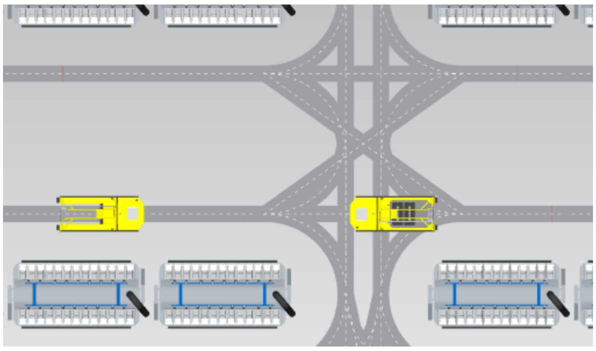


FIGURE F.1: Step 1: two vehicles aim to occupy the same path at the same time

Recall that the zone restrictions should not be violated. Also, the aisle width is not sufficiently large to let two vehicles pass each other. The AGAPTV positioned in the cross aisle wants to enter the segment aisle but on entering the checkpoint of that aisle, the AGAPTV detects the other vehicle is blocking the passage (see Figure F.2).

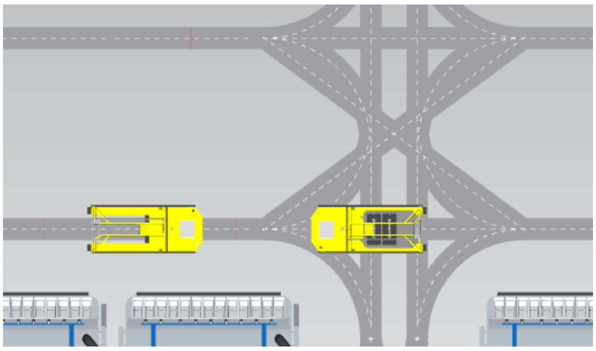


FIGURE F.2: Step 2: vehicle on the right detects the collision at the checkpoint.

When the possible collision is detected, priority is granted according to the defined priority rules. Suppose the AGAPTV currently positioned in the segment aisle gets priority, then the cross aisle has to maneuver away from the passage. To this end, the AGAPTV location in the cross aisle arbitrary selects a path end in the cross aisle that is not planned to be visited by the prioritized AGAPTV. The cross aisle AGAPTV then drives to this point (see Figure F.3), after which the vehicle in the segment can continue its route (see Figure F.4). Once this traveling vehicle has left the cross aisle, the waiting vehicle may continue its route.

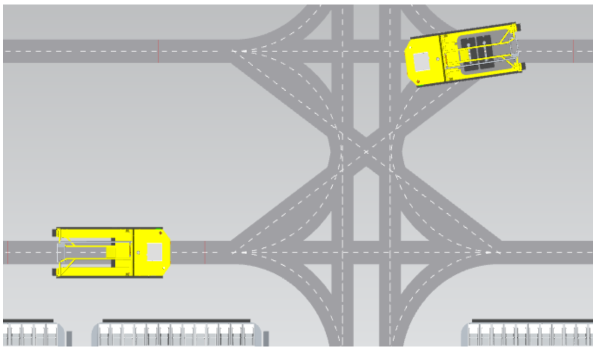


FIGURE F.3: Step 3: Step 3: AGAPTV in the segment aisle gets priority and the other vehicle makes place for this.

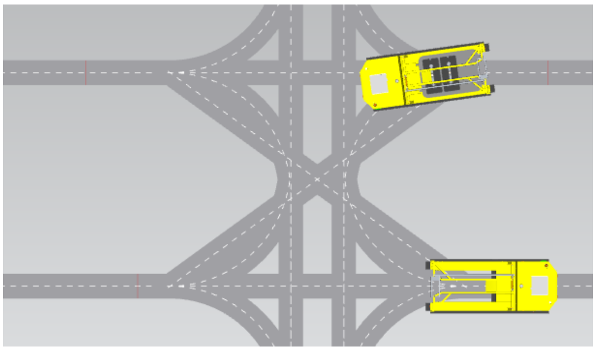


FIGURE F.4: Step 4: both vehicles can continue their route.

Appendix G

Conceptual Model: Model Scope

TABLE G.1: Generic operational planning & control model: model scope

Component	Include/ Exclude	Justification
Entities:		
Agents	Include	Provide MAS functionalities
Rodding shops	Include	Assumption: unlimited supply
Electricity areas	Include	Represented in designated rodding shops
Parking locations	Include	Represented in all rodding shops
Vehicle paths	Include	Guide-path design
Maintenance facility	Exclude	**Assumption**: limited impact on the system performance
Cranes	Exclude	**Simplification**: represented by heuristics and blocking rules
Bath buckets	Exclude	**Assumption**: limited impact on system performance
Activities:		
Anode changing	Include	Input parameter
Metal tapping	Include	Input parameter
Pot tending	Include	**Simplification**: no blocking implications due to limited expected impact on system performance
Metal transport	Exclude	**Assumption**: vehicles can maneuver freely in-between the AGAPTVs
Bath leveling	Exclude	**Assumption**: limited impact on system performance
Fresh pallets pick-up/drop-off	Include	Key influence on throughput
Butt pallets pick-up/drop-off	Include	Key influence on throughput
Empty pallets pick-up/drop-off	Include	Key influence on throughput
Conflict resolution & Collision avoidance	Include	Input parameters; Key influence on throughput
AGAPTV charging	Include	Input parameters; Key influence on throughput
Queues:		
Rodding shop pallet queues	Include	Facilitates consolidation, inflow- and outflow of pallets; **Assumption**: infinite capacity
Segment pallet queues	Include	Required for anode swapping
Electricity areas queues	Include	**Assumption**: unlimited space
Resources:		
AGAPTVS	Include	
Anodes	Include	Consolidated in pallets
Anode pallets	Include	
AGAPTV charging equipment	Include	**Assumption**: always available and unlimited AGAPTV capacity
Anode changing workforce staff	Include	**Simplification**: represented by heuristics
Maintenance engineers	Excluded	Maintenance not being modelled
Personnel in rodding shops	Excluded	**Assumption**: always available

Appendix H

Model Content: Initialization and Reset

Logic Flowchart: End of run
***Trigger**: one setting cycle period ends*

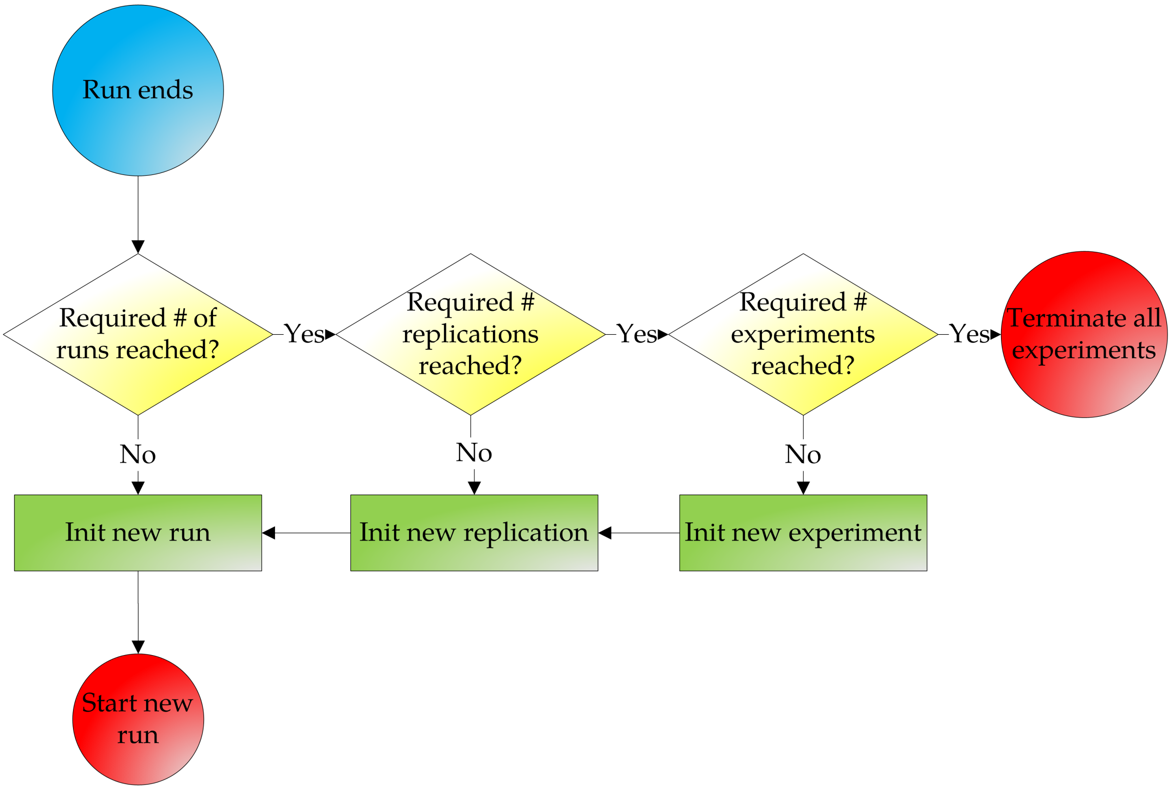


FIGURE H.1: Flowchart: end of simulation run.

- ***Logic Flowchart: New anode shift initiated***
- ***Trigger****: anode shift preparation event*
- ***Info****: starts earlier than the actual anodes need to be changed (at anode shift start time minus the fresh anode pallet release time)*

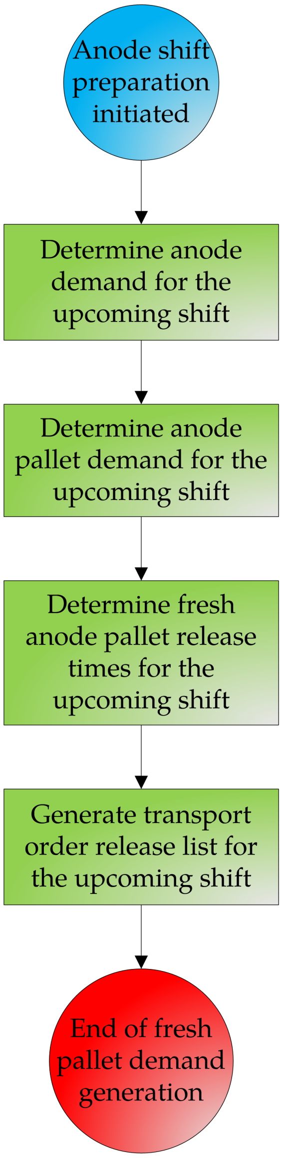


FIGURE H.2: Flowchart: anode shift initialization.

Appendix I

Model Content: Guide-path Construction

The following data are required for constructing the guide-path:

1. Number of potrooms.
2. Number of segments specified per potroom.
3. Number of cells specified per segment (per potroom).
4. Vertical distances specified per potroom:
    (a) (1) cell width.
    (b) (2) distance from base points to the southern part of the first southern cell of the segment.
    (c) (3) distance from base point to southern part of of the northern cell of the segment.
5. Horizontal distances specified per potroom per segment:
    (a) (1) distance from base point to most western cell.
    (b) (2) cell working size length.
    (c) (3) horizontal pallet distance (considering the southern cells, take the distance from the western start point of the cell towards the drop-off position of the pallet).
6. Conveyor belt locations. This can only be specified for the most southern and most northern potroom. For these potrooms, declare whether or not the western and southern outer ends have access to a conveyor belt.
7. Electricity charging station locations. Under the same conditions as the conveyor belt locations.
8. Vehicle safety margin. Safety distance between electrolytic-cell and AGAPTV.
9. Cross road curve safety margin (by default halve cell width). This margin is added to the cross aisle for making the curve via the segment aisles properly.
10. Path width (by default similar to the vehicle width).
11. Graphical scaling factor (by default: horizontal 105% and vertical 110%). Used for visualization purposes of the guide-path. In some cases the default settings are not sufficient for constructing and showing the guide-path, then this factor should be increased.

Construction phases:

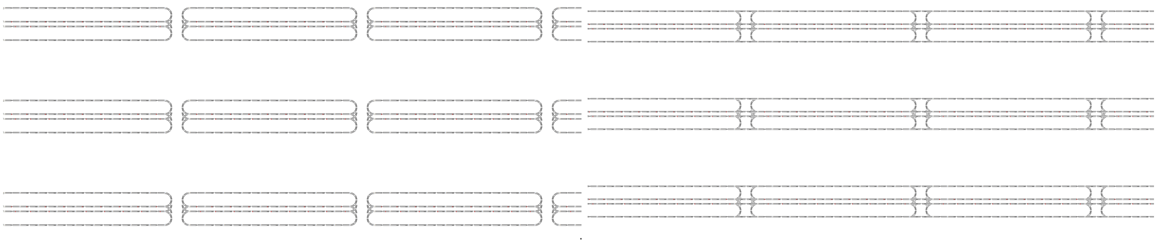
1. Construct the back and center aisle paths (see Figure I.1a). The exact building procedure is not publicity made available.
2. Define pick-up and drop-off sensors in the segment aisles. The exact building procedure is not publicity made available.
3. Construct the cross aisle curves (see Figure I.1b). The exact building procedure is not publicity made available.
4. Adjust back and center aisle paths with respect to the cross road safety margin (see Figure I.2a). The exact building procedure is not publicity made available.
5. Construct horizontal paths between segments (see Figure I.2b). The exact building procedure is not publicity made available.
6. Construct vertical paths in the cross aisle (see Figure I.3a). The exact building procedure is not publicity made available.
7. Construct zigzag paths between the segment ends (see Figure I.3b). The exact building procedure is not publicity made available.
8. Construct advanced cross aisle extensions (see Figure I.4a). The exact building procedure is not publicity made available.

9. Built paths to the conveyor belts. The exact building procedure is not publicity made available.
10. Built paths to the electricity charging stations. The exact building procedure is not publicity made available.
11. Place electrolytic-cells in the potroom. The exact building procedure is not publicity made available.
12. Place conveyor belts in the potroom. The exact building procedure is not publicity made available.
13. Place electricity charging stations in the potroom. The exact building procedure is not publicity made available.
14. Re-scale graphical plant layout for visualization purposes. The exact building procedure is not publicity made available.
15. The user may now adjust the guide-path by manually modifying path properties in the graphical user interface or by running a script. The exact building procedure is not publicity made available.
16. Connecting the individual paths to their neighboring paths. The exact building procedure is not publicity made available.

(A) Guide-path construction phase 1.

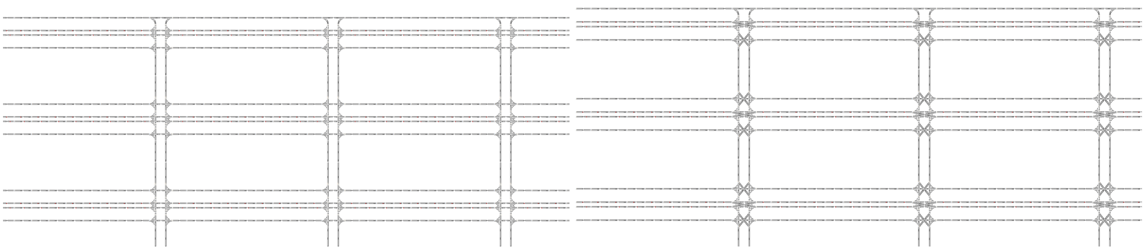
(B) Guide-path construction phase 3.

FIGURE I.1: Guide-path construction phase 1, 3-4.



(A) Guide-path construction phase 4.

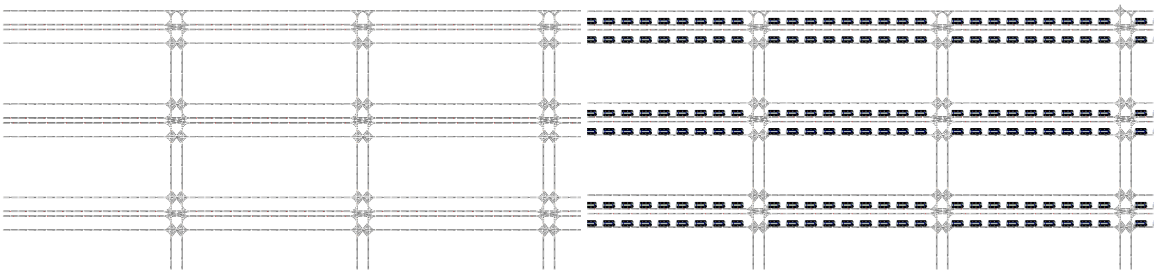
(B) Guide-path construction phase 5.



(A) Guide-path construction phase 6.

(B) Guide-path construction phase 7.

FIGURE I.3: Guide-path construction phase 5-7.



(A) Guide-path construction phase 8.

(B) Guide-path construction phase 10.

FIGURE I.4: Automated guided anode pallet transport vehicle

Appendix J

Model Content: Demand Management - Estimation of the Fresh Anode Pallet Release Time

The latest delivery time denotes the time the operators expect they can start using the anodes in the changing process. When the pallet is delivered before this time, it has to wait in front of the cell before being used. A pallet delivered after this time is not desirable because the workforce then has to wait. Therefore, we introduce an anode pallet release time based on an estimation of when the first anode of the pallet is actually required:

$$\begin{aligned}\text{Fresh Anode Pallet Release Time} = {} & 2 * \text{Average Estimated Travel Time} \\ & + \text{Estimated Time Workforce Needs Pallet} \\ & + \text{Safety Margin}\end{aligned} \tag{J.1}$$

The estimated travel time is the average time required to drive from a rodding shop to the dedicated position and back without considering blocking restrictions and time required for performing the backward placing maneuver. The average is taken over all rodding shops. The estimated time before the workforce actually needs the pallet is calculated by multiplying the mean processing time for changing one anode with the (initially determined) minimum of the anode changing sequence number of the anodes combined in the pallet. An anode sequence number is determined based on one of the used heuristics for constructing an anode changing scheme as we describe later on.

Suppose, the scheme originally proposes that one of the anodes should be changed as n^{th} in the section during the shift, then the anode sequence number of that anode is n. In this example, the estimated time before the workforce needs the pallet (in the shift) equals $(n-1)$ times the mean processing time of one anode change. Lastly, the safety margin could be set by the user and may even be negative in case one wants to examine the impact of early release times.

Recall that we expressed the *fresh anode pallet earliest release time* for pallet p in section s during anode shift a as $FERT_{p,s,a}$ (see Subsection 6.2.3.1). The default starting time of releasing the transport jobs is 4 hours before the actual anode shift starts, this can be expressed as follows:

$$FERT_{p,s,a} = t_{s,a,start} - \Delta t_{r,fresh} \tag{J.2}$$

where, $t_{s,a,start}$ denotes the anode changing shift start time and $\Delta t_{r,fresh}$ the fresh anode pallet release time. As alternative to Formula J.2, one could use a different formula for representing the earliest release time more appropriate by including the travel time from rodding shop and the estimated sequence in which the job is handled by the crane operators. We propose the following alternative for determining the fresh anode pallet earliest release time:

$$FERT_{p,s,a} \approx t_{s,a,start} + \frac{1}{R}\sum_{r=1}^{R} \min(ET_{r,s,c}) + EO_{s,p} + t_{\epsilon} \tag{J.3}$$

where, R = total number of rodding shops, ET = minimum estimated travel time to drive from rodding shop r to cell segment s cell PD point c, $EO_{s,p}$ = estimated time the workforce in section s needs pallet p, and t_{ϵ} = early release safety margin. The travel time is based on a fixed average driving speed of the vehicle (see Appendix C) and without including possible additional rotation maneuvers.

The safety margin is set by the user and we suggest to determine this number based on experimental results, but as a rule of thumb maintain a margin of 30 minutes (influence of blockades, traffic, etc.). The estimated time when the workforce needs pallet p in section s is expressed with:

$$EO_{s,p} = \begin{cases} EO_{s,p-1} + k_{p-1} \cdot EC, & \text{if } p > 1 \\ 0, & \text{if } p = 1 \end{cases} \tag{J.4}$$

In this equation, EC represents the mean service time for changing one anode and k_p indicated how many anodes k need to be swapped on pallet p.

Appendix K

Model Content: Material Flow - Entity Relationship Diagram

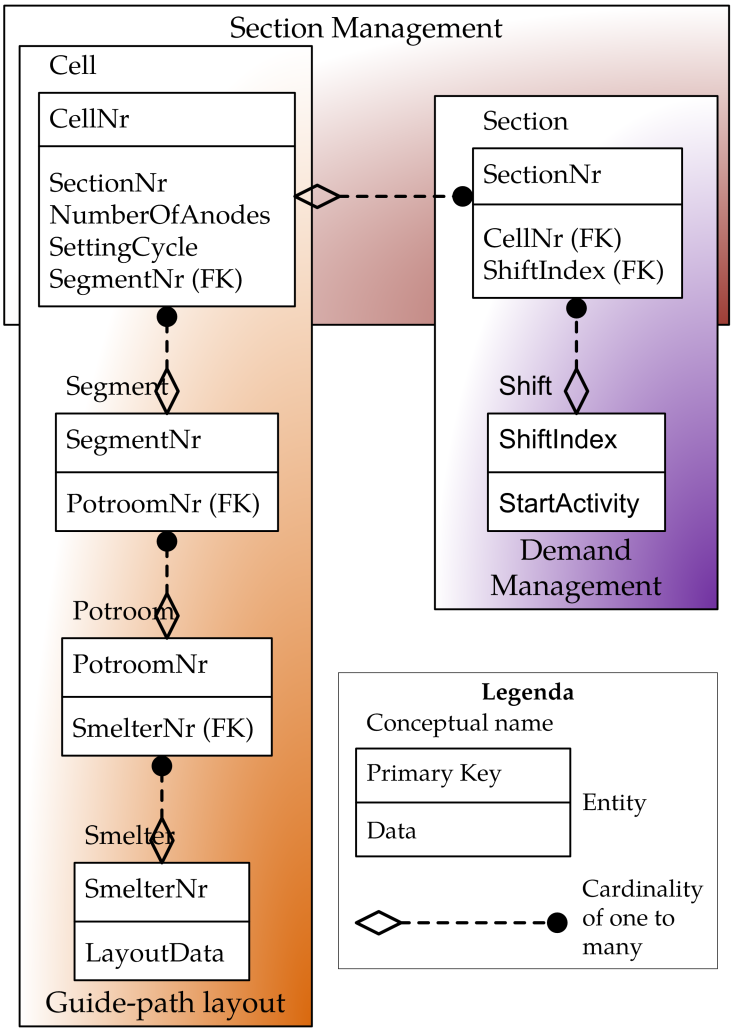


FIGURE K.1: Entitiy relationship diagram representing main components of the demand flow.

Appendix L

Model Content: Material Flow - Anode Demand Generation

The cyclic patterns of all anodes in a section are usually balanced such that the aluminium production process is minimally disturbed and that the expected workload corresponds to the capacity. Incorporating all possible aspects that may influence this demand pattern such as amperes, managers' "practical" experience, and workforce restrictions (e.g., lunch breaks, equipment failures, etc.) would make the model rapidly more complex. Likewise, gathering specific data from customers about their repetitive demand pattern is a time-consuming process and not all customers are capable/willing to present this. Besides that, their used repetitive scheme may not be desirable in terms of achieving a good logistical performance. As the aim of this study is to develop a generic model that must be able to evaluate a large variety of demand patterns, we design the *Demand Management* functionality such that the anode setting cycle scheme can either be manually provided as input or chosen from one of the following four predefined anode demand patterns:

[1] An anode changing scheme per individual electrolytic-cell. The anode changing activities are scheduled such that the first anode of the cell is planned in the first shift, the second anode in the second shift, etc. The designed **Algorithm 1**, as shown in Appendix M, assumes that the setting cycles of all anodes in the corresponding cell are equal. In case the number of shifts is not sufficient to cover all anodes during the anode setting cycle, the next anode is planned in the first shift again etc.

An advantage of this approach is that it is a simple approach that constructs a feasible solution relatively quickly. Drawbacks of the algorithm are that 1) it may result in so-called anode free shifts (a shift in which no anode change is planned for a cell/section), hence, the number of anode changes is not balanced within a section during the entire anode setting cycle, 2) it may result in an overload of scheduled anode changes in a section during the first few shifts (of the setting cycle shifts) and thus an underload during the last shifts, 3) it does not focus on pallet demand but anode demand, and 4) it tend to neglect potline/potroom behavior.

[2] An anode changing scheme for a section of cells by determining a more balanced workload. A modification is made to **Algorithm 1** by remembering the previously assigned last anode shift. The anode shift counter for a cell is not reset when all its anodes are assigned to a shift. That is, the counter proceeds from where it was ended in the previous cell. So, suppose the last anode of a cell is assigned to shift x, then the first anode of the next cell is assigned to shift $x + 1$. When the number of shifts per setting cycle exceeds the shift counter, the counter is reset to the first shift.

An advantage of this construction approach is that it provides an approach in finding a more balanced demand pattern of an entire section instead of individual cell-behavior and, therefore, overcome the first two disadvantages as mentioned for approach [1]. The disadvantage of not focusing on pallet demand but on anode demand only is still not overcome. Also, the potline/potroom behavior is still not fully captured (except when one considers an entire potline/potroom as one section). We suggest to investigate these two deficiencies in further research whereby other parts of the potroom processes such as crane behavior and smelter logistics are considered as well.

[3] An initial anode changing scheme that is randomly constructed and repeats itself every cycle. A random anode changing shift is chosen (from all the shifts during an anode setting cycle) for

each anode. Based on the anode setting cycles, the anode changing scheme prescribes when an anode needs to be changed again.

Albeit one could debate about the validity of this scheme construction approach, it allows us to explore the impact of different setting cycles of anodes in an easy manner.

[4] An anode changing scheme for a section of cells by means of a demand balancing rule in addition to the approach as described in [3]. Likewise, we assume that all anodes in the section have an equal setting cycle. First, employ the approach as described in [3] for all cells in the potroom. Next, the anode changing scheme per section is improved by an iterative procedure. The iterative procedure randomly swaps an anode planned in a busy shift to one of the least busiest shifts (see **Algorithm 2** in Appendix M). A busy shift is a shift that contains the most anode changes and the least busy shift is the shift that contains the least number of anode changes. The procedure is iterated until no further improvement can be achieved.

Remark that under each of the heuristics, the the northern anodes in a cell are the uneven numbers and the southern ones the even numbers.

Appendix M

Anode Setting Cycle Schema Algorithms

Algorithm 1: Basic Anode Changing Scheme Construction Per Cell

```
Data: Anode setting cycle for all cells in the potroom, Shift scheme
Result: Anode changing scheme per individual cell
DetNumShiftsPerSetCycle($shift\ length$, $setting\ cycle$);
forall cells ∈ potroom do
    anode setting shift := $-1$;
    foreach anode ∈ cell do
        anode setting shift := anode setting shift $+1$;
        if anode setting shift = MaxShiftsPerSetCycle then
            anode setting shift := 0;
        end
        AssignAnodeToShift($anode$, $anode\ setting\ shift$);
    end
end
```

Algorithm 1: Basic anode changing scheme per individual electrolytic-cell. The algorithm determines an anode changing scheme for an individual cell based on the setting cycle and shift length. A prerequisite is that all anodes in the cell should have an equal setting cycle.

Algorithm 2: Basic Anode Changing Scheme Construction Per Section of Cells

```
Data: Anode setting cycle for all cells in the potroom, Shift scheme, Potroom characteristics
Result: Anode changing scheme per individual cell
Algorithm 1;
foreach cell section ∈ potroom do
    DetetermineConvergenceLimit(cell section);
    while converge limit is not reached do
        BusyShift := RndBusyShift($anode\ changing\ scheme$);
        BusyCell := RndBusyCell($BusyShift$, $anode\ changing\ scheme$);
        BusyAnode := RndBusyAnode($BusyShif$,$BusyCell$, $anode\ changing\ scheme$);
        LeastBusyShift := RndLBusyShift($cell\ section$);
        SwapBusyWLeastBusy($BusyShift$, $BusyCell$, $BusyAnode$, $LeastBusyShift$, $anode$
          $changing\ scheme$);
    end
end
```

Algorithm 2: Anode changing scheme with equal number of anode changes per shift for a section of electrolytic-cells. Algorithm 1 tends to provide anode peak requests in the early shifts during the entire setting cycle period. Algorithm 2 is an extension of Algorithm 1 and attempts to balance the anode demand during the entire setting cycle period. A prerequisite of this algorithm is that all anodes in the section should have an equal setting cycle.

Appendix N

Model Content: Material Flow - Aggregation of Anode Demand into Anode Pallet Demand

In the section & shift based working routine, transport requests for pallets containing fresh anodes are generated per section of cells. We assume the fresh anode demand is determined after the anode shift has end, which leads to a list of anodes that need to be changed in the upcoming anode changing shift. Our approach and heuristics regarding this transition is explained in the explanation below.

To generate the requests for pallets with fresh anodes, we first determine the required number of pallets with fresh anodes in a section. To this end, we categorize anode and anode pallet demand according to their orientation. Notice that we simplify our model by not sharing anode pallet demand among sections. From the perspective of the crane operator, the anodes of an electrolytic-cell positioned at the back aisle require the same orientation as the anodes of that same cell positioned at the center aisle. The center aisle consists of two driving lanes. We restrict ourselves to dedicating one lane of the center aisle to northern oriented pallets and the other lane to southern oriented pallets. So, a lane is dedicated to serving cells on the opposite side of the center aisle (see Figure 5.1).

The number of pallets with new anodes can be determined as follows. Suppose a cell c is located in a section and a section contains n cells. Each cell c_i inside a section has a number of anodes ranging from $a = 1$ to $a = m$. Anode a inside a cell is characterized by a setting cycle $s_{i,a}$, expressed in days of anode operating time. The number of anodes that need to be replenished per day in one section is then given by:

$$\sum_{i=1}^{n}\sum_{a=1}^{m} c_i * \frac{1}{s_{i,a}} \tag{N.1}$$

Considering the required anode orientation we can split the average number of anodes that need to be replenished per day in one section into either northern or southern demand. We introduce parameters $o_{i,a}^{north}$ and $o_{i,a}^{south}$, which equals 1 in case the anode corresponds to that orientation and 0 otherwise:

$$\sum_{i=1}^{n}\sum_{a=1}^{m} c_i * \frac{1}{s_{i,a}} = \sum_{i=1}^{n}\sum_{a=1}^{m}\left(\frac{c_i * o_{i,a}^{north}}{s_{i,a}} + \frac{c_i * o_{i,a}^{south}}{s_{i,a}}\right) \tag{N.2}$$

Now we have determined the number of anodes that need to be changed within a section, we can determine the number of pallets required. Suppose the anode changing shift occurs once per day, so within that shift all anodes need to be replenished. Further, suppose that all anodes are transported with utilizing the full pallet capacity, except for the last pallet that might be partly filled. If a pallet's capacity equals k, the number of pallets transported to the section during one shift is then:

$$\left\lceil \frac{\sum_{i=1}^{n}\sum_{a=1}^{m}\left(\frac{c_i * o_{i,a}^{north}}{s_{i,a}}\right)}{k} \right\rceil + \left\lceil \frac{\sum_{i=1}^{n}\sum_{a=1}^{m}\left(\frac{c_i * o_{i,a}^{south}}{s_{i,a}}\right)}{k} \right\rceil \tag{N.3}$$

Formula N.3 assumes that the anode changing shift occurs once a day. However, the number of shifts per setting cycle may deviate. Therefore, we extend the formula by including the total duration t_{total} of one shift and divide the setting cycle by this. The assumption that the shift duration may not change during the entire system's life still holds. Also, the measurements units for $s_{i,a}$ and t_{total} should be expressed in the same term (e.g., days). Then, the estimated number of pallets transported to a section for one anode changing shift is given by:

$$\approx \left\lceil \frac{\sum_{i=1}^{n} \sum_{a=1}^{m} \left(\frac{c_i * o_{i,a}^{north}}{s_{i,a}/t_{total}} \right)}{k} \right\rceil + \left\lceil \frac{\sum_{i=1}^{n} \sum_{a=1}^{m} \left(\frac{c_i * o_{i,a}^{south}}{s_{i,a}/t_{total}} \right)}{k} \right\rceil \tag{N.4}$$

where,

$$t_{total} = t_{anode\,changing} + t_{metal\,tapping} + t_{pot\,tending} \tag{N.5}$$

Notice that Formula N.4 is an approximation because the total shifts per setting cycle may not be an integer number.

The resulting number of pallets to be assigned is used in the anode demand aggregation heuristics. The considered heuristics are:

[1] Perform an assignment sweep from west to east per section. The sweep aggregates anodes in pallets starting at the most western part of the section and gradually goes to the eastern part. The starting point is the most western segment, cell, and anode that need to be changed in the shift. An arbitrary side (either northern or southern) is chosen in case the first encountered cells both have anodes on the same vertical position. The sweep goes from west to east and combines anodes into a pallet until the pallet reached its capacity or until there are no changing anodes left. If the pallet capacity is reached and there are still anodes left that need to be assigned to a pallet, a next pallet is initiated continuing the sweep at the next anode.

The sweep advances until all anodes are designated to pallets. In case there are multiple anodes that need to be changed on a cell, these anodes are first assigned to pallets before checking whether the cell on the other side of the center aisle requires anodes to be changed. So, first the operations on one cell are aggregated into pallets after which anodes on the other side of the center aisle are considered. Furthermore, the heuristic prioritizes cells on the previously considered side. That is, once the sweep continues after an anode is assigned there is first checked whether there is an anode on the same side of the center aisle (i.e., either northern or southern cells) that requires changing. This approach limits vertical crane movements. Figure N.1 illustrates an example of how this heuristic works.

The model considers a similar distance between cells within a segment while this might be different in practice. So, the width of cells in the segment is then considered to be equal. On its turn, the aggregation heuristic simplifies the sweep by considering that the northern cells and anodes are positioned on the same horizontal axis as the southern cells and anodes.

To summarize, the heuristic goes as follows:

(a) Start by a new initiating a new pallet. Determine the first position of both the northern anodes and southern anodes.
    i. When the first northern anode is more to the western positioned than the first southern anode, assign the northern anode to the first pallet.
    ii. When the first southern anode is more to the western positioned than the first northern anode, assign the southern anode to the first pallet.
    iii. When the first southern anode is on a similar horizontal position than the first northern anode, assign a random anode to the first pallet.
(b) The 'sweep' point stays at the side of the previously assigned anode. Check whether there are anodes left on the current cell.
    i. In case there are anodes left on that cell, simply sweep according to the heuristic and assign the next anode to the pallet.
    ii. When there is no anode left on that cell, check whether there are anodes on the direct opposite side. If this is the case, the sweep moves towards that side and assigns the next anode according to the heuristic flow (e.g., west-to-east).

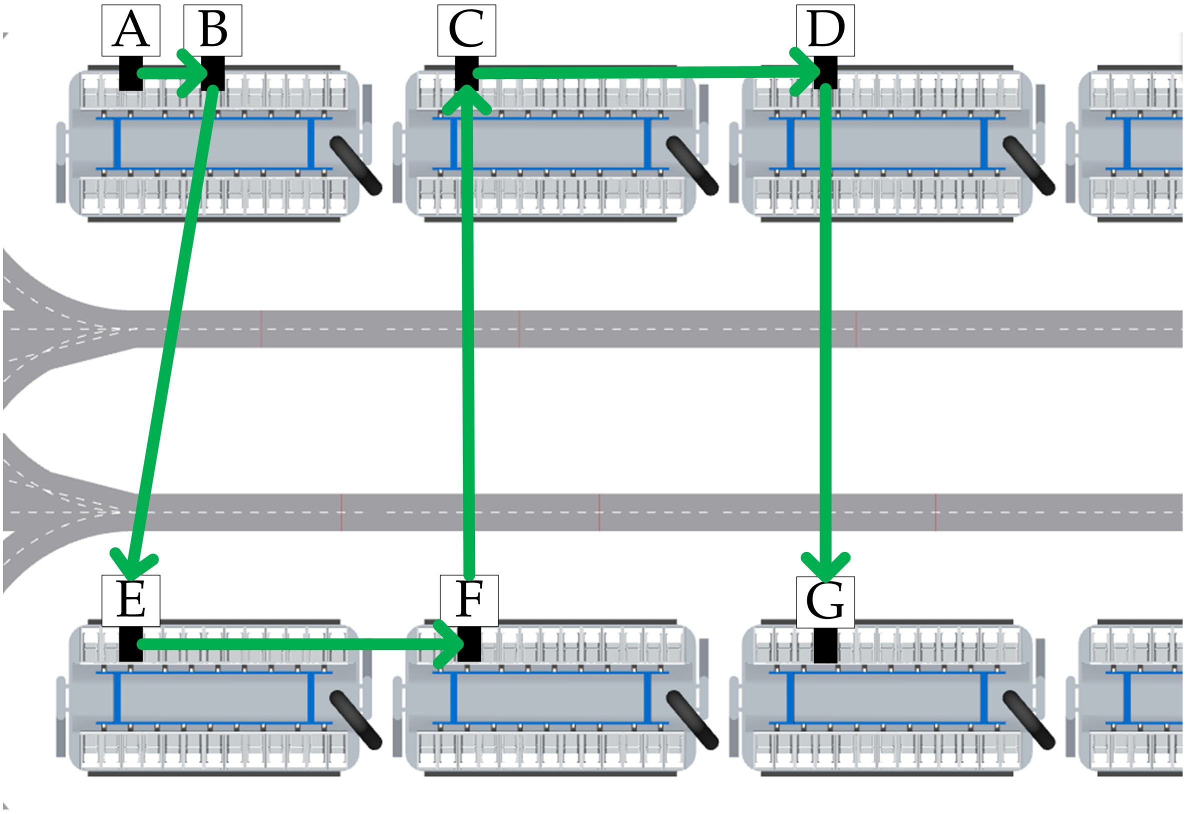


FIGURE N.1: Example of anode aggregation heuristic [2]. Suppose the first randomly chosen anode is anode A, the aggregation sequence is then: A-B-E-F-C-D-G (indicated with the green arrows). When anode E is the first anode, the sequence is: E-A-B-C-F-G-D.

   iii. When there is no anode left on that cell, first determine the horizontal position of the first anode on both sides of the section that requires anodes to be changed. The flow goes to the first cell encountered by the sweep, except in case both cells are on the same position. Then the assignment flow moves towards the cell located on the current side of the flow.

  (c) Continue step (b) until all anodes are assigned to pallets.

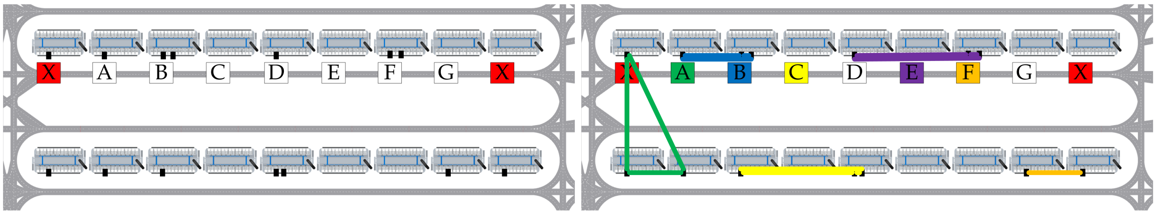
[2] Perform a similar sweep procedure as described in [1] but now start in the most eastern part and sweep to the west.

[3] Aggregate anodes into pallets randomly.

Appendix O

Model Content: Material Flow - Pallet Location Assignment

For constructing the pallet location assignment heuristics, two phases are considered: (1) allocation of pallets to locations and (2) assignment of aggregated changing tasks to pallets. Figure O.1 illustrates this problem with an example. The pallet allocation assignment heuristics designate locations for the pallets, but do not cover the allocation of the pallets to anode changing tasks (Appendix N). This is done in the crane behavior heuristics (Appendix P).



(A) In this example, 14 anodes need to be changed.

(B) The anodes are already aggregated into 5 pallets, but the location of these pallets still needs to be determined.

FIGURE O.1: Example of the pallet location assignment problem in a potroom segment. The outer ends (indicated red) cannot be used due to blocking restrictions. The questions are where to allocate the pallets (indicated black) and from which pallet should the anodes be interchanged.

The following heuristics are considered for allocating pallets to locations:

[1] Allocate the pallets to the most western available positions of the section.

[2] Allocate the pallets on the most eastern available positions of the section.

[3] Distribute the pallets next to each other in the middle of the section. In case of close-ties, choose a random side.

[4] Distribute the pallets evenly in the most outer allowable parts of the section.

[5] Allocate the pallets randomly across the section.

*: under development

Note that assignment heuristics [3], [4], and [5] will likely not be used in practice. However, heuristics [3] and [4] provide a promising benchmark when one aims to compare the logistic performance of pallets positioned (on average) mostly in the inner part of the section or the outer part of the section to the other assignment heuristics. This because the assignment of pallets to the outer cells will likely be preferable for anode transport as the pallets can be dropped-off relatively early in the section. While the assignment of pallets to the inner part of the section would provide an inferior logistic performance. Nevertheless, one should not attach a significant value to these statements regarding the potential performance impact because the potroom performance should be considered from a holistic perspective.

Appendix P

Model Content: Material Flow - Modelling Crane Behavior

The crane behavior addresses in which sequence the crane handles the pallets with anodes. The proposed heuristics are limited to handling anodes per pallet. Thus, they do not allow any interruption of the activities while the swapping of anodes in a certain pallet is started. The heuristics simulate the crane operations flow through the section and result in an initial job handling sequence. Combining this pallet handling sequence with the service times yields an *expected desired delivery time* which is used in the dispatch strategies. The time is an estimation because logistic disturbances (e.g., blocked pallets in the segment aisle or fluctuation in service time) may prevent on-time job execution.

Crane operators conduct their actual anode changing activities based on a First-Come-First-Serve rule. So, based on the actual potroom logistics, the sequence by which the jobs are handled may differ. For example, when a fresh anode pallet arrived earlier than another fresh pallet that was initially scheduled to be handled first. The primary result of the proposed heuristics is not to impose hard pallet placement restrictions, but to 1) designate locations to (groups of) anodes combined in a pallet, 2) determining the handling sequence of the anodes, and 3) react effectively upon logistic disturbances. The heuristics consider fixed positions that may be used, resulting from the pallet location assignment heuristics (see Appendix O). The following heuristics are considered:

[1] Iterate over all pallets, start at the most western pallet and gradually go to the eastern part of the section. Search for the most western anode that needs to be changed in a similar fashion as done in the anode pallet aggregation heuristic [1]. Then, schedule all the anodes of the concerning pallet from west-to-east as well. The process continues with adding the most western anode to the next pallet and so forth.

[2] Perform heuristic [1] but then from east to west.

[3] Assign the aggregated anodes randomly to the pallets. The anode changing sequence is also determined randomly.

Notice that the heuristics further yield the *expected desired delivery time EO* specified per pallet and section. This time is determined by considering the estimated start time when the crane operators need the first anode on pallet (see Formula J.4).

Appendix Q

Model Content: Demand Schema Generation and Heuristics

The demand schema consists of a specification of the anode distribution per cell, section distribution per cell, setting cycle distribution per cell, and shift indexing per section:

Anode Distribution (specified per cell):

[1] Fixed number of anodes for all cells.

[2] Varying number of anodes for each cell conform a uniform distribution.

Section distribution (specified per cell):

[1] Every potroom gets an unique section number, starting in the first potroom. So, all cells in a potroom will be considered as one section.

[2] Every segment gets an unique section number, starting in the first potroom first segment. So, all cells in the same segment will be considered as being in one section.

[3] Each potroom is split in a number of s sections which roughly contains the same number of segments. This heuristic requires parameter s that denotes the number of sections in a potroom. The model is limited to examining a similar s for each potroom.

Setting cycle distribution (specified per cell):

[1] Random setting cycle per potroom, based on a uniform distribution.

[2] Random setting cycle per section, based on a uniform distribution.

[3] Random setting cycle per cell, based on a uniform distribution.

Notice that the heuristics with the random distributions can also be used to obtain fixed setting cycles by considering an equal lower and upper bound. The setting cycles are round to integer values.

Shift indexing (specified per section), indicates which section perform their activities synchronously. That is, when the shift index of a section is similar to the index of another section, both sections will start their shifts and activity type at the same time. The following heuristics are included:

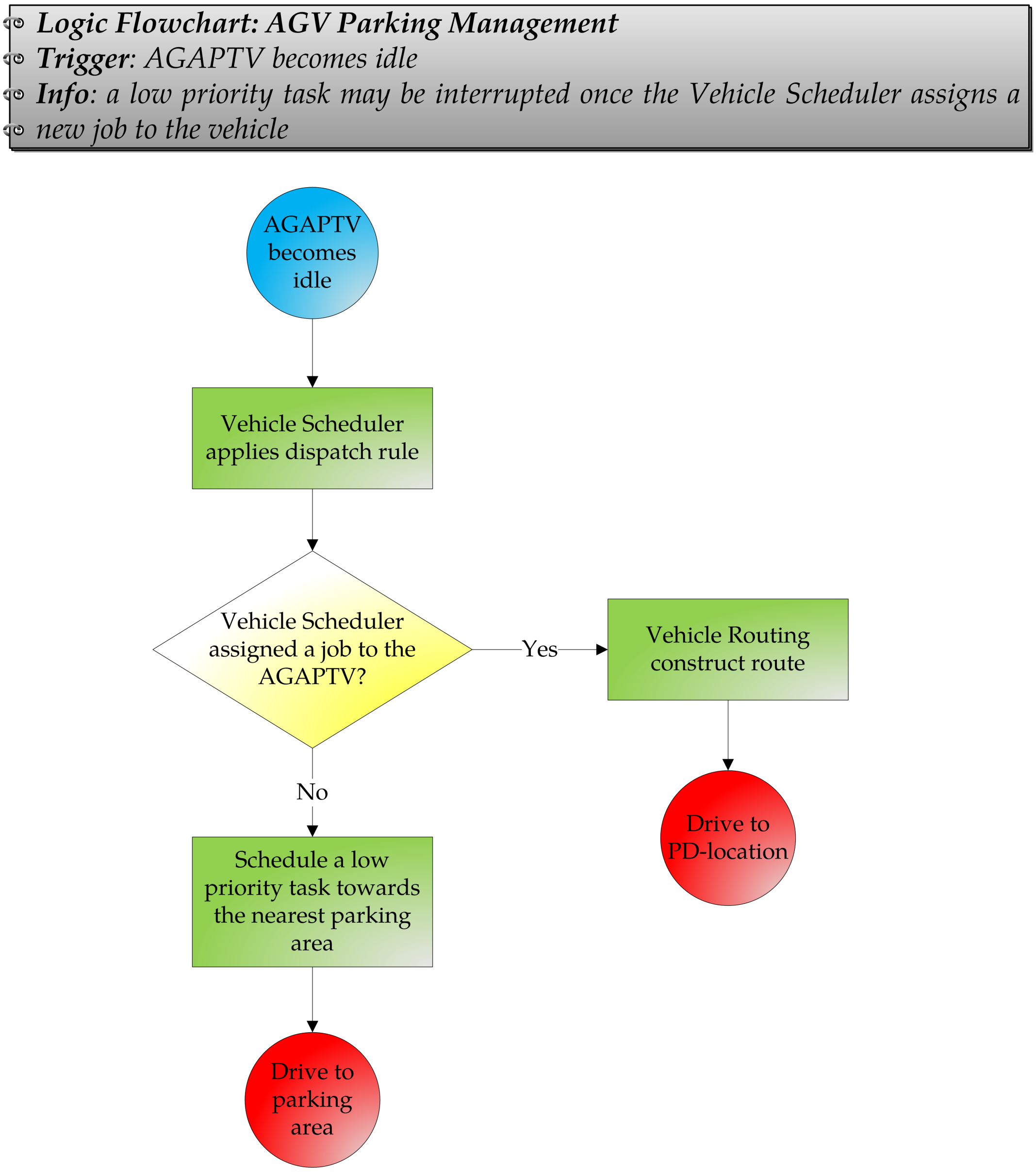
[1] Continuous numbering per section, starting in the first potroom the first section and ending in the last potroom last section. The numbering starts with assigning the activities: anode changing - metal tapping - pot tending sequentially. There is no reset when the numbering is at the end of a potroom.

[2] Continuous numbering per section in a similar manner as [1] but then the numbering resets at the subsequent potrooms.

[3] Split the potroom into three subparts that roughly contain the same number of sections. The most western part is the first shift index, the middle part the second index, and the eastern part the third index. In case of an unequal distribution, the section is designated to a random shift index.

Appendix R

Model Content: AGV Parking Management



- ***Logic Flowchart: AGV Parking Management***
- ***Trigger**: AGAPTV becomes idle*
- ***Info**: a low priority task may be interrupted once the Vehicle Scheduler assigns a*
- *new job to the vehicle*

FIGURE R.1: Logic flowchart AGV Parking Management with trigger idling AGV.

Logic Flowchart: AGV Parking Management
***Trigger**: AGAPTV with a low priority parking task reaches its parking destination*
***Info**: a low priority task was scheduled but it turns out that there was no job interruption; this opportunity is used to charging the battery*

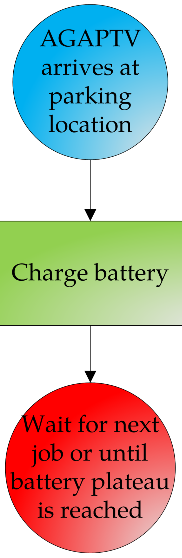


FIGURE R.2: Logic flowchart AGV Parking Management with trigger arrival at parking location.

Appendix S

Model Content: Vehicle Scheduling - Vehicle-initiated Dispatching

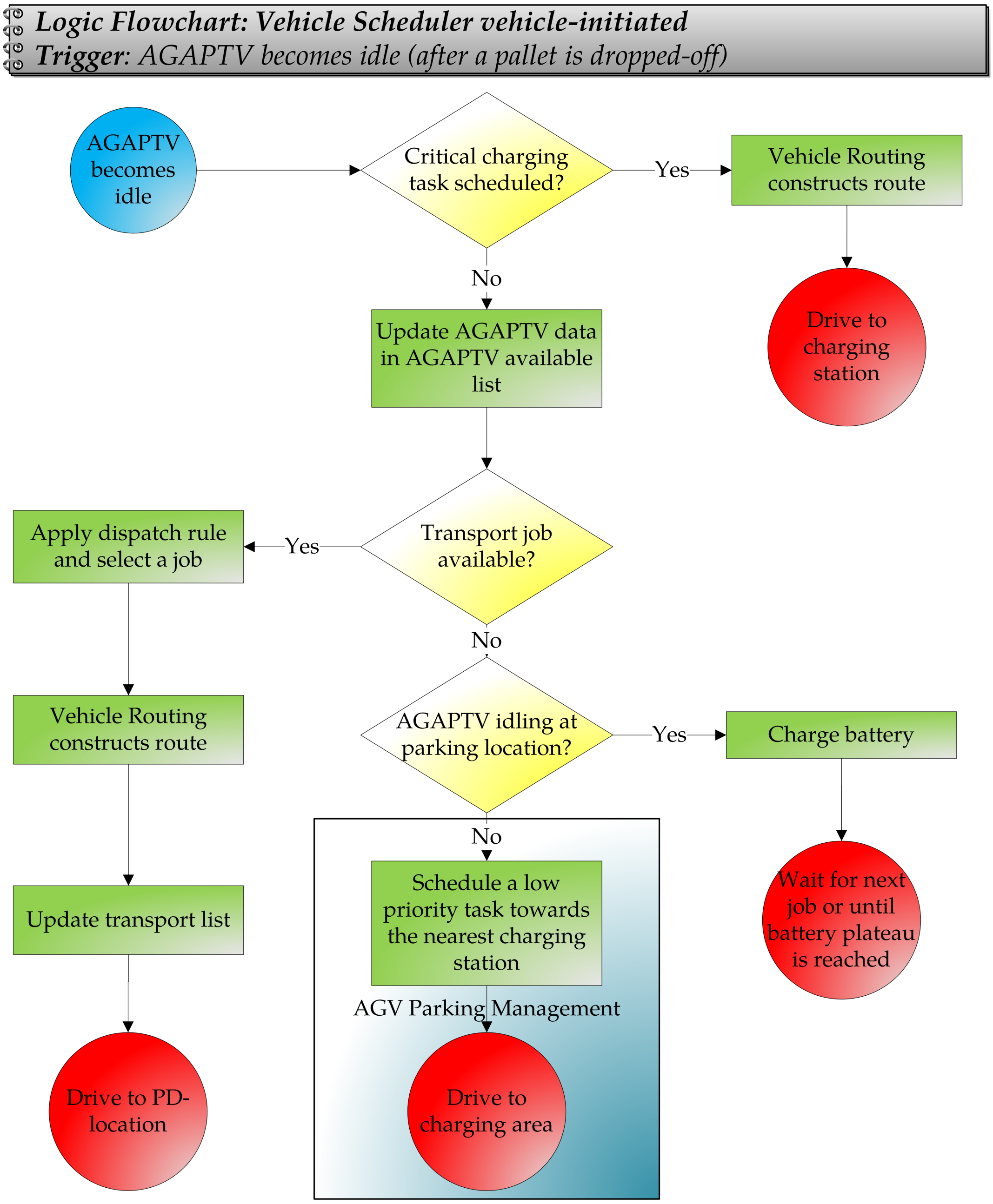


FIGURE S.1: Logic flowchart Vehicle Scheduling with as trigger a dropped-off pallet.

Logic Flowchart: Vehicle Scheduler vehicle-initiated
Trigger*: AGAPTV becomes idle (at charging station, when battery plateau level is reached under the automatic charging task)*

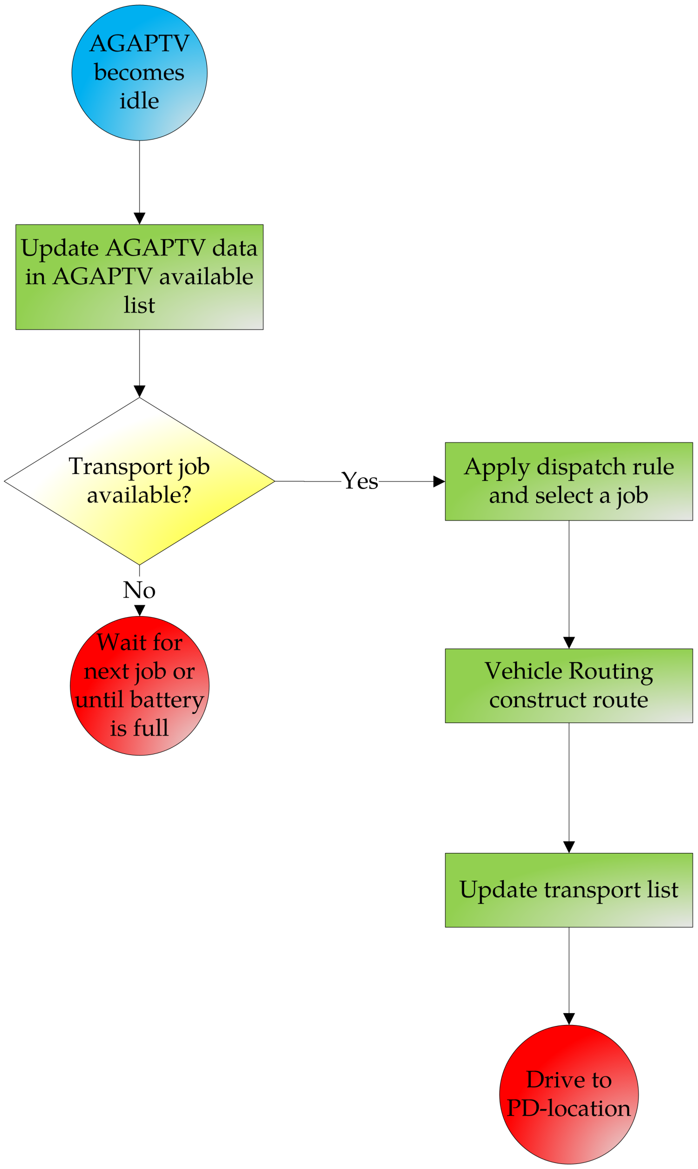


FIGURE S.2: Logic flowchart Vehicle Scheduling with as trigger battery plateau level reached under the automatic charging task.

Appendix T

Model Content: Vehicle Scheduling - Workcenter-initiated Dispatching

Logic Flowchart: Vehicle Scheduler workcenter-initiated
Trigger*: pallet transport request initiated (transport request released in the system)*

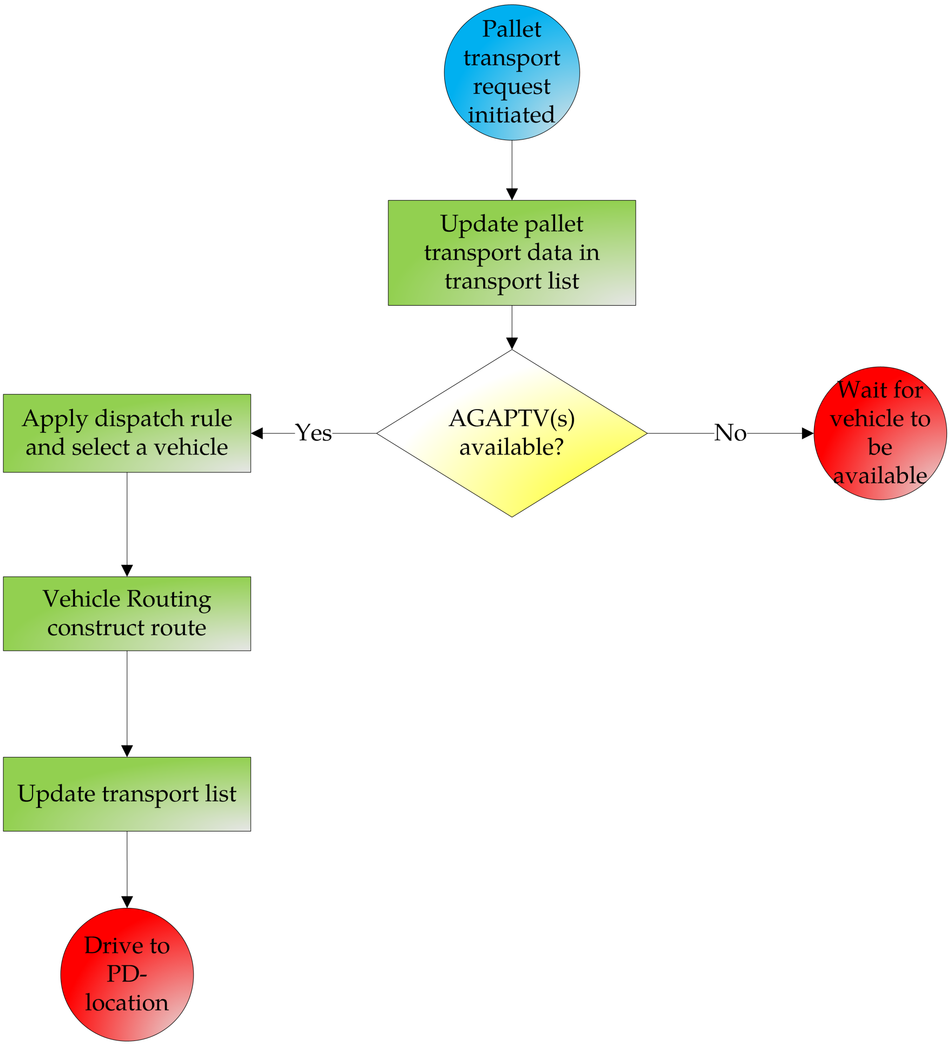


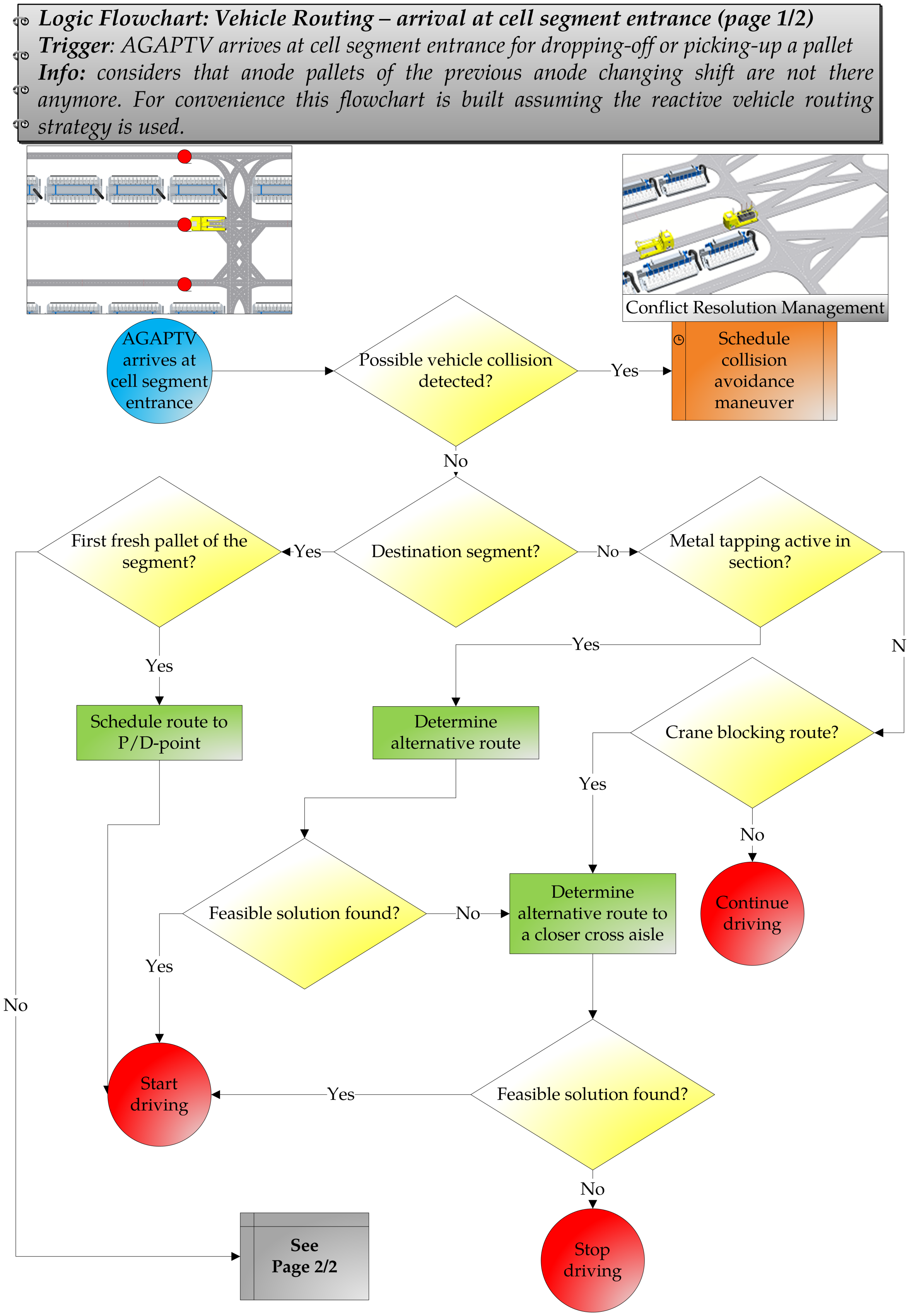
FIGURE T.1: Logic flowchart Vehicle Scheduling with as trigger an initiated pallet transport request.

Appendix U

Model Content: Vehicle Routing

This appendix contains five flowcharts concerning the Vehicle Routing functionalities:

- Figure U.1 presents the process flowchart regarding the arrival of an AGAPTV at a cell segment entrance;
- Figure U.2: shows a subchart of the flowchart of Figure U.1;
- Figure U.3: depicts the logic flowchart of the pro-active vehicle routing approach;
- Figure U.4: presents the logic flowchart of the reactive vehicle routing approach;
- Figure U.5: presents the logic flowchart of the determination of alternative vehicle routes.



Logic Flowchart: Vehicle Routing – arrival at cell segment entrance (page 1/2)
Trigger: AGAPTV arrives at cell segment entrance for dropping-off or picking-up a pallet
Info: considers that anode pallets of the previous anode changing shift are not there anymore. For convenience this flowchart is built assuming the reactive vehicle routing strategy is used.

FIGURE U.1: Process flowchart Vehicle Routing: AGAPTV arrives at a segment entrance (part 1 out of 2).

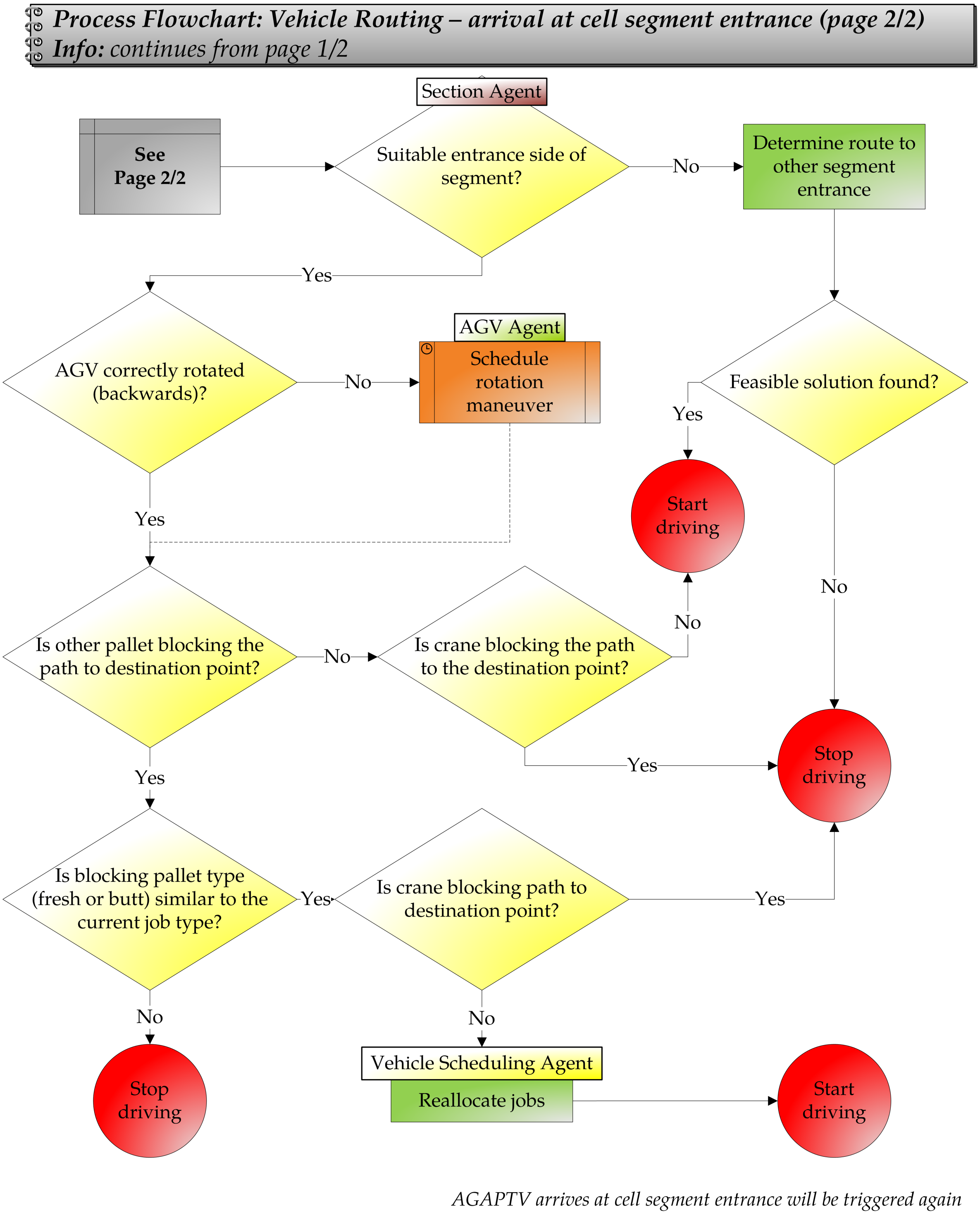


FIGURE U.2: Process flowchart vehicle routing: AGAPTV arrives at a segment entrance (part 2 out of 2).

Logic flowchart: pro-active vehicle routing based on blocking event

Trigger*: blocked path restriction update (via anode changing and metal tapping activities)*

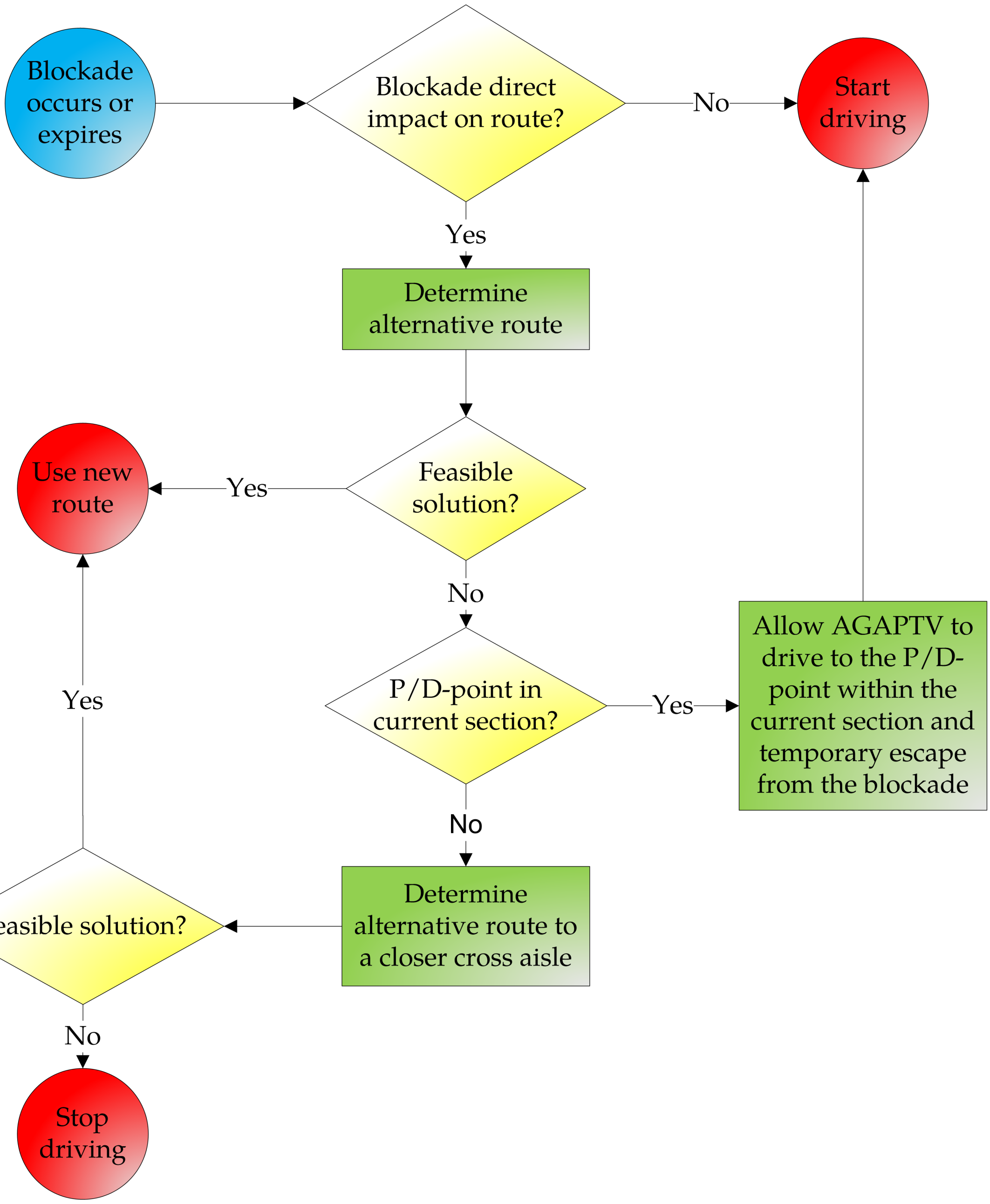


FIGURE U.3: Logic flowchart proactive vehicle routing.

Logic flowchart: reactive vehicle routing based on blocking event
Trigger: *AGAPTV's next path is blocked (due to anode changing and metal tapping activities)*

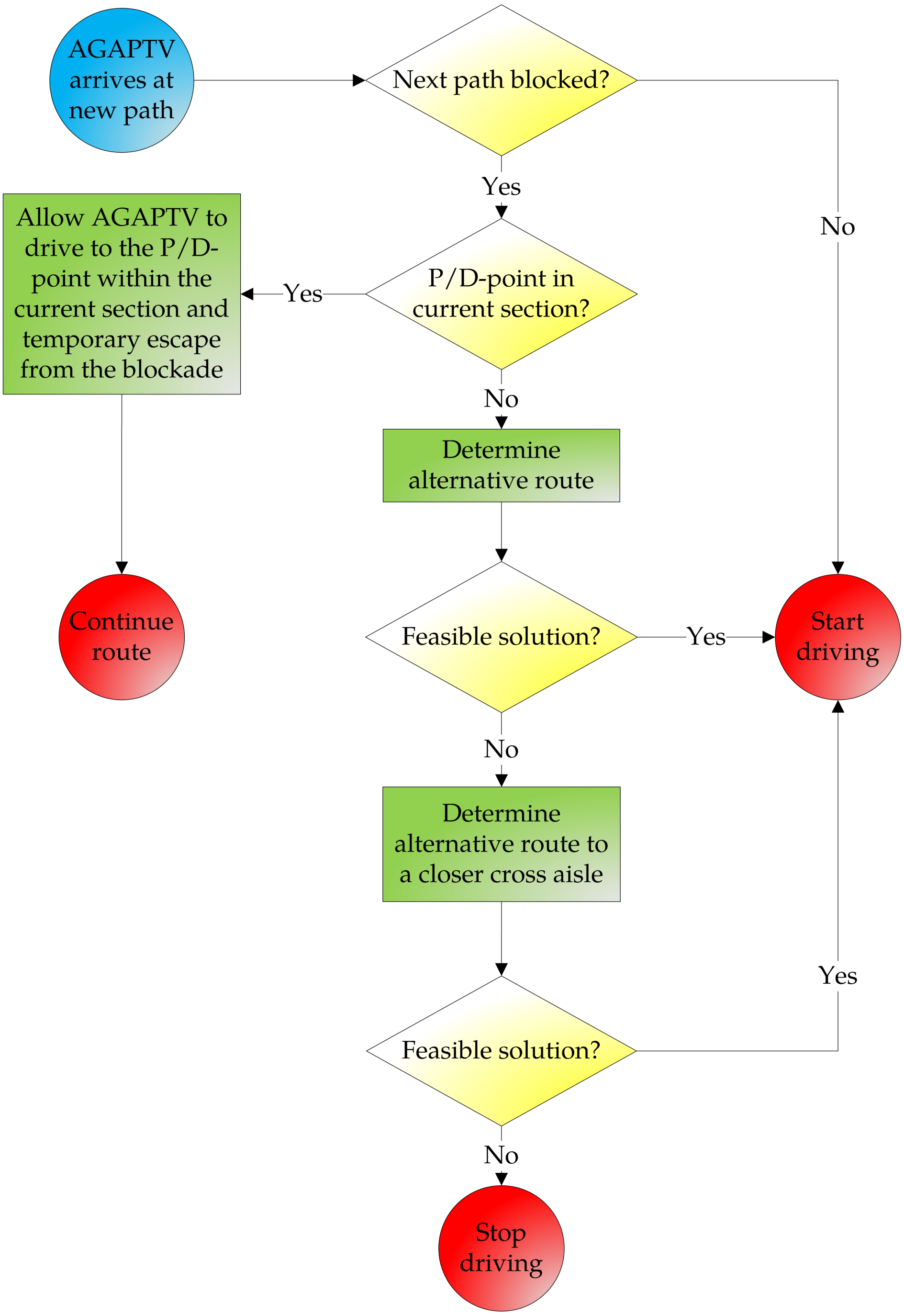
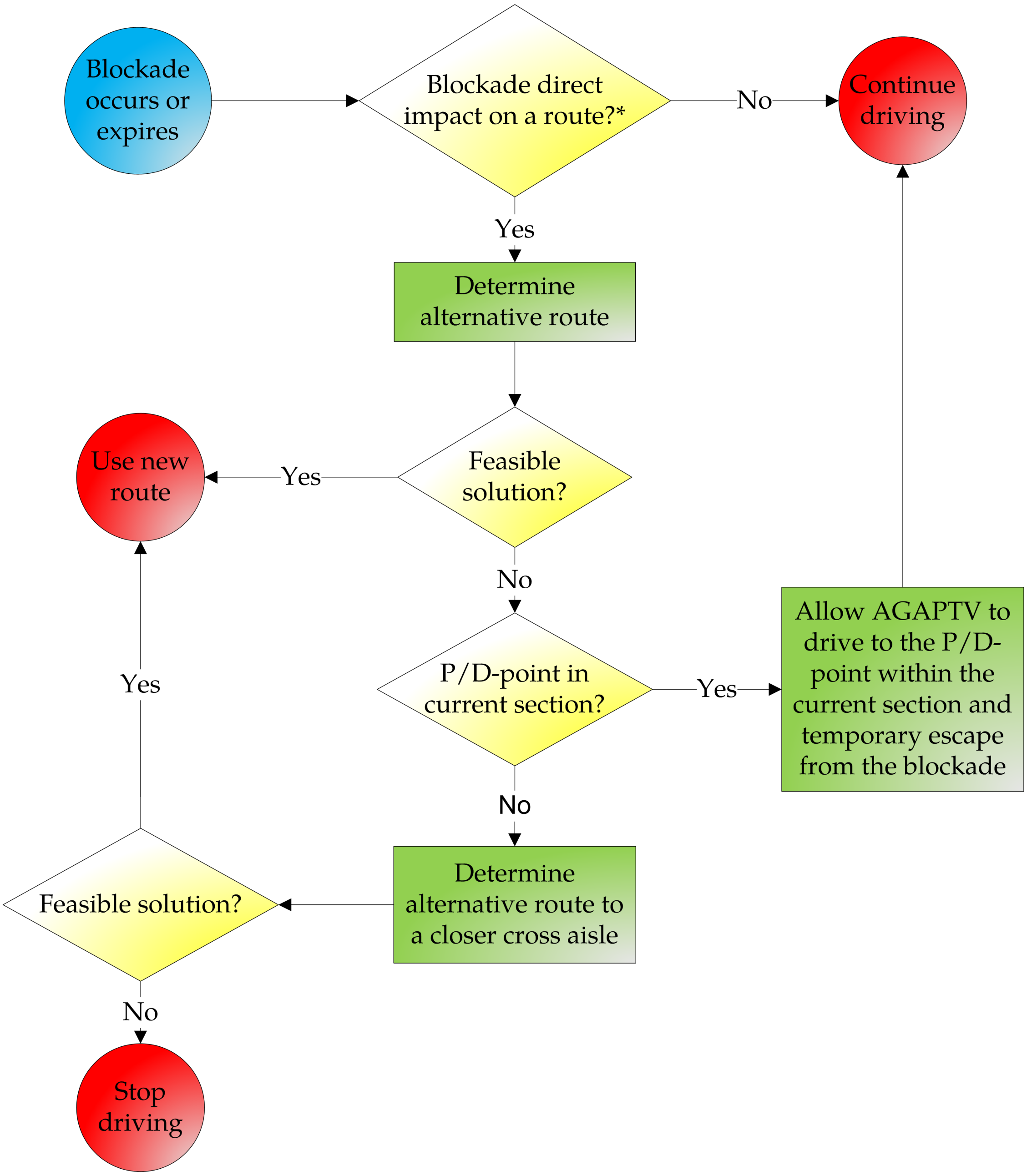


FIGURE U.4: Logic flowchart reactive vehicle routing.

Logic flowchart: pro-active vehicle routing based on blocking event

Trigger*: blocked path restriction update (via anode changing and metal tapping activities)*

Info*: number of arising blockades may be large and thus resulting in considerable computation time*



**: impact may be positive or negative*

FIGURE U.5: Logic flowchart vehicle routing: determination of alternative route.

Appendix V

Model Content: Collision Avoidance

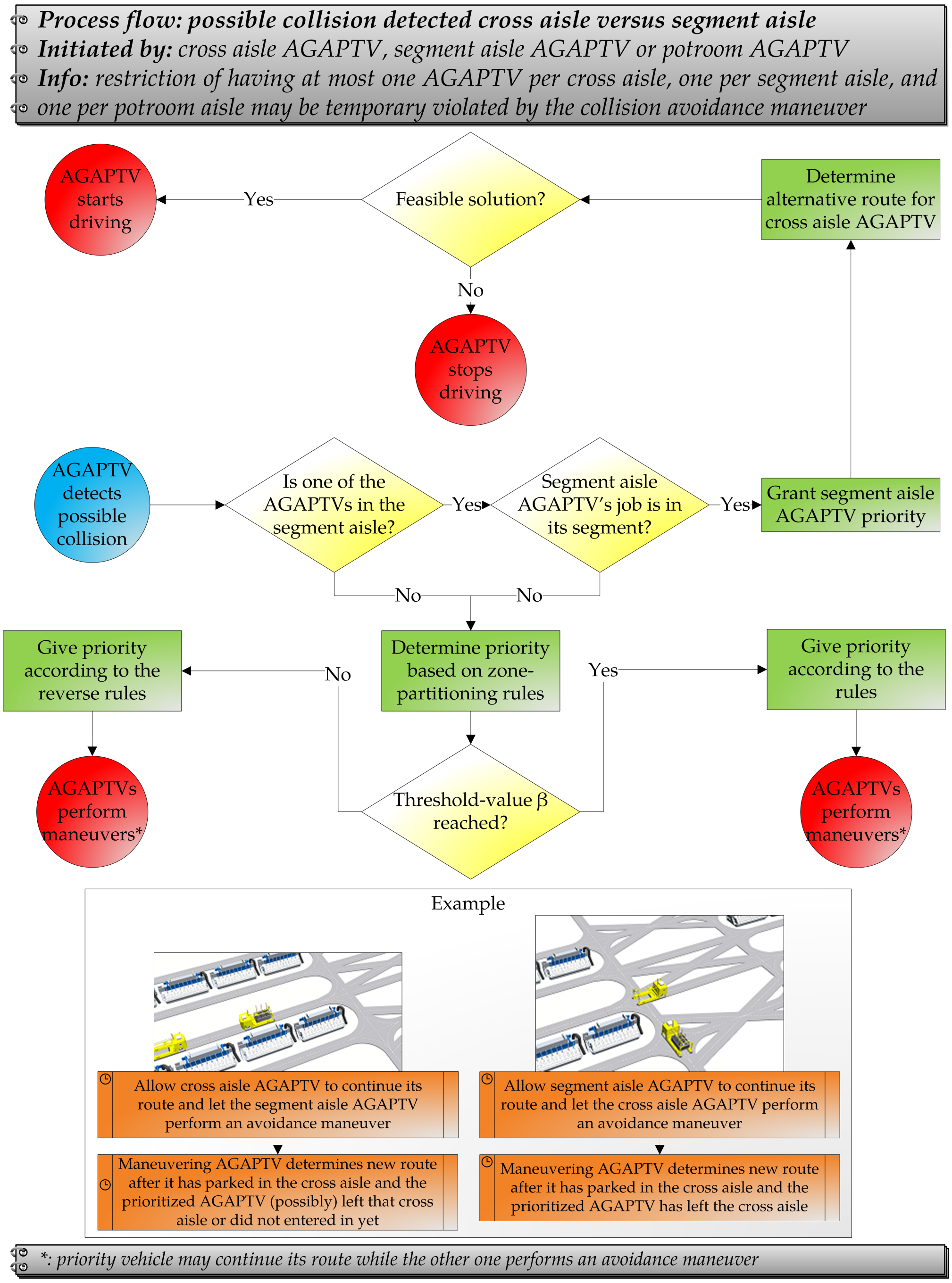


FIGURE V.1: Flowchart collision avoidance MAS.

Appendix W

Model Validation: Factory Layout

The smelter layout considered for model validation as shown in Figure W.1 is build by using the model building parameters. Recall that the Cartesian coordinate system is used in a 2D-perspective in which the base point denotes the most south-western point of the first cell in the first potroom. The following model building parameters are used:

1. Number of potrooms: 4.
2. Number of segments per potroom, potroom 1-2: 5 and potroom 3-4: 7.
3. 18 cells per segment.
4. Cell width (vertical distance) of the end-to-end cells are: $5m$.
5. Vertical distance from base point to southern backaisle first cell: potroom 2 $50m$; potroom 3 $100m$; potroom 4 $150m$.
6. Cell working size length (horizontal distance) of the end-to-end cells are: $10m$.
7. Vertical distance from base point to most western cell is $100m\times$ number of segments from base point.
8. Horizontal distance from base point to sensor position: $6m$.
9. Safety factor in-between center aisles: 0.1
10. Safety margin for cross roads in-between segments $\frac{5}{3}$ m
11. Conveyor belt at potroom 1 segment 5 western end and a conveyor belt at potroom 4 segment 3 eastern end.

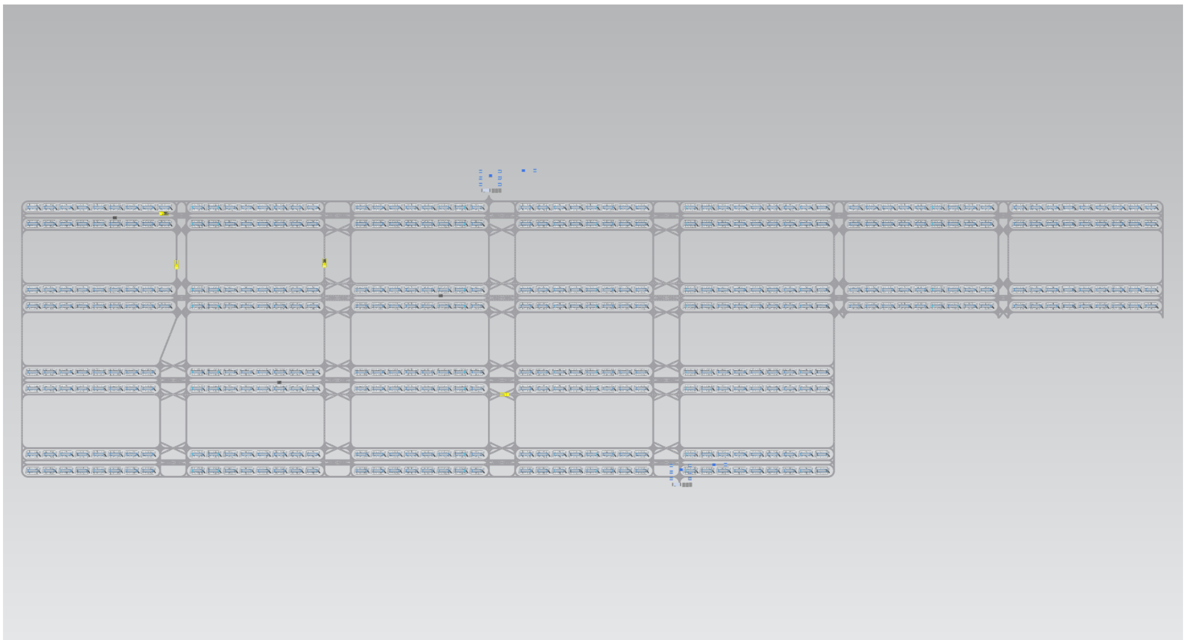


FIGURE W.1: 3D screenshot of the considered factory layout in model validation.

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