MASTER THESIS

MIXED TRAFFIC SOLUTIONS FOR AUTOMATED HUB-TO-HUB LOGISTICS

A SIMULATION STUDY

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PREFACE

This thesis is dedicated to my dad, who sadly will not be at the big moments in my life anymore, but would have been so proud of my achievements.

Dear reader,

What a journey it has been. Literal blood, sweat and tears have been put into the thesis that is lying before your eyes. I will be honest with you; I had some doubts if I was able to finish this thesis. Mainly, because I found my passion in a different career path then I expected when I started studying in 2023. While becoming active during my student time, I found my passion in organizing events. That is why, while still doing my thesis, I started working in this field, which gives me a lot of energy and joy. My thesis got to the background of all that was happening around me, but I am so glad that I pushed through and can present what I have been working on (for quite some time).

This thesis is supervised by three people who contributed a great deal to this research. Berry, with your creativity you always encouraged me to think outside the box. I will cherish all the drinks, barbecues, beer brewing, and other activities you organised. Martijn, your in-depth knowledge of the subject sometimes confused me by suggesting complex approaches to adapt. This helped me to stay critical and has contributed to adding more value to this research. Matteo, you had a never-ending patience with me, even when you did not hear from me for months, you always excitingly continued guiding me with building my simulation, debugging, and detecting errors in the coding. I really appreciate your enthusiasm for my research and your contribution to it.

There are a couple of people that I want to thank for supporting me through the process of finishing this thesis. First, my aunt Anna, really the only blood-related family that I have left. Thank you for always supporting me, never pushing me, and never judging me. Thank you for contributing to all of my student years, you encouraged me to follow my dreams and to take all the time I needed, but with one promise: one day I would finish my master's degree, and here we are.

Roy, thank you for being my chosen family and providing me with a second home where I was always welcome in need of a place to study. Rogier, thank you for rubber-ducking with me and giving me breakthroughs when I got lost in coding. To the boys of 'WatSchuurChaBroek', thank you for all the fun times and teamwork in completing the master courses. Daan, thank you for always providing me with motivation.

Lastly, a special thanks to two people in particular that got me through the last couple of months, helping me carry the really heavy weight of 'de laatste loodjes'. Lieke, thank you for giving me a call every day to give me the motivation to go on and checking up on me even in the chaos of your own life. You are truly the best and keep on slaying every day! Jurian, you may not understand what I was doing, or why I was doing it, but you never stopped believing in me and always cheered me up when I was in a total mental breakdown. I could not have survived without you.

I am looking back on ten years of lots of fun, getting to know people who became my closest friends, and learning very much about myself and what I want to achieve in life. Now I am saying goodbye to the University of Twente, the place I got to know thoroughly by being involved in all aspects of student life, the place that kickstarted my career at the event office, a place I got to call home. Even though I am not a student or employee anymore, I will always stay connected.

Jiska Chang
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MANAGEMENT SUMMARY

Supply chains consist largely of the transport of freight, often using different modalities such as water, rail, air, and road. Freight needs to be transported between the different modalities within the supply chain: from container terminals to distribution centres, or from airports to warehouses. We define short-haul intermodal transportation - transport between modalities as barge, truck, train, or plane, or between terminals and distribution centres, warehouses, or logistic services providers - as hub-to-hub transportation. This research investigates how hub-to-hub logistics can be automated, to reduce daily costs and to make more efficient use of available transport. An approach to enhance the efficiency of hub-to-hub transport is the implementation of Connected Automated Transport (CAT). CAT means transportation solutions for passengers or freight utilizing automation and connectivity.

In this research we focus on the impact of the implementation of CAT on hub-to-hub environments in mixed-traffic situations, answering the following research question:

> *What characteristics of hub-to-hub environments impact the implementation of Connected Automated Transport and how to design and implement logistics concepts of varying degrees of mixed traffic in these environments?*

The characteristics of hub-to-hub environments contain repetitive internal transportation flow between the different Logistic Hubs (LH) located in a designated area that is connected to different modalities. The transport takes place on public roads, which complicates the implementation of CAT in these environments. This research explores the various levels automation and different dimensions of connectivity within Connected Automated Transport (CAT), aiming to implement the highest degree of both dimensions in hub-to-hub logistics. Different logistic concepts are explored to gradually implement CAT on public roads and these logistic concepts are categorized in a taxonomy for traffic separation. The taxonomy identifies four dimensions of operation: full separation, separation by space, separation by time, and no separation. The dimension of connectivity increases through the dimensions of operation and consequently challenges arise with the implementation of the logistic concepts.

This research focuses on the impact of separating conventional and autonomous traffic by time. A conceptual model is constructed to analyse the impact on hub-to-hub environments. The different characteristics of the hub-to-hub environment are translated into building blocks, each with different input variables. With these building blocks, various hub-to-hub environments can be constructed. The conceptual model introduces a connected system (CS) designed to link all environmental characteristics to a system overseeing the internal transportation flow, utilizing autonomous vehicles (AVs). To separate conventional and autonomous traffic, time windows (TWs) are allocated to autonomous traffic to operate on public roads. Meanwhile, these are closed to conventional traffic.

To evaluate this concept, a business case of XL Businesspark (XL Park) is introduced that has all the characteristics of a hub-to-hub environment, with two modalities (water and road), two types of LHs (terminal and warehouses), and the option to close off the environment since only one main road is going in and out of the environment.

These characteristics, together with gathered container arrival data of the terminal in the XL Park, are used as input for the simulation model. Experiments are designed based on the AV schedule considering different TWs in amount, duration, and timing. The results show that one-hour TWs are more efficient than half-hour TWs and the best moment to schedule the TWs is during the night. However, the operation of AVs outside working hours requires more adjustments to the environment. LHs must remain accessible for AVs, and the handling of containers during working hours implies that containers transported the first night would be stationed at the LH throughout the day, waiting to be picked up again the subsequent night.

For the XL Park, more implementation challenges are elaborated upon since the implementation of a CS needs the collaboration of all LHs in the environment and adaptations need to be made to all barriers the AV encounters en route to the LHs and back.

ABBREVIATIONS

CAT	Connected Automated Transport
AV	Autonomous Vehicle
LH	Logistic Hub
KPI	Key Performance Indicator
CTT	Combi Terminal Twente
TT	Terminal Tractor
CS	Connected System
TW	Time Window
XL Park	XL Businesspark Almelo

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1. INTRODUCTION

This chapter introduces the research of mixed traffic solutions for automated hub-to-hub logistics. In Section 1.1, the research motivation is explained. Section 1.2 describes the research problem with the background of the business case. In Section 1.3, the research design is given, and the research questions are formulated.

1.1 RESEARCH MOTIVATION

Logistic companies struggle to keep their supply chain cost-effective, flexible, reliable, and sustainable. Reasons for these struggles are changing demand patterns, increasing competition, and increasing service requirements. The logistics supply chain is a complex network that connects the supplier to the product manufacturer, all the way to the end customer, by integrating (multimodal) transportation, logistic hubs, and service providers. Processes need to be efficient, and costs need to stay low to keep up with the competition.

The supply chain consists largely of the transport of freight, often using different modalities such as water, rail, air, and road. Therefore, freight needs to be transported between the different modalities within the supply chain: from container terminals to distribution centres, or from airports to logistics service providers. We define this type of intermodal transportation as hub-to-hub transportation. Besides moving freight between two transport modalities, characteristics of hub-to-hub logistics are routine work or daily transport between two hubs. It is useful to investigate how hub-to-hub logistics can be automated to reduce daily costs and to make more efficient use of available transport.

An approach to enhance the efficiency of hub-to-hub transport is the implementation of Connected Automated Transport (CAT). CAT refers to using automation and connectivity in new transportation solutions for passengers or freight. Automated vehicles are vehicles that have safety-critical functions and can operate without direct driver input. Connected is defined as exchanging information wirelessly. According to ERTRAC (2019a), connected automated driving is seen as one of the key technologies and major technological advancements influencing and shaping our future mobility and quality of life. CAT in its ultimate form, as fully unmanned and automated vehicles, will also enable completely new transport systems to be realised (European Commission, 2018). At this moment, laws and regulations hold back the implementation of CAT on public roads, due to the (lack of) acceptance of self-driving vehicles by other road users. Consequently, researchers focused only on confined areas or dedicated roads for the application of CAT. This research will investigate mixed traffic situations, to define different logistics concepts that can be implemented in a hub-to-hub environment and test which logistics concept has the best impact on the conventional traffic and the current situation of the public roads.

To illustrate our work, a case study around XL Businesspark Almelo is analysed. This business park features an inland terminal (CTT Almelo), a transport company (Bolk), and several warehouses in a semi-private environment. Between these companies, several types of goods are transported regularly. We investigate the logistics and traffic flows at this business park and translate these into a simulation environment. With this simulation, we study the impact of the different logistic concepts of mixed traffic. The best and safest strategy for implementing autonomous vehicles (AVs) into public roads will be derived from these findings. In summary, understanding the challenges faced by logistic companies sets the stage for exploring innovative solutions. As we delve into the specific problem associated with hub-to-hub logistics in the next section, we will uncover the key considerations that drive the need for connected automated transport.

1.2 PROBLEM DESCRIPTION

The first implementation of autonomous transport in heavy-duty freight transport was in confined areas, which are simple and closed-off environments, where the tasks are repetitive and traffic management is fully controlled. According to the ERTRAC (2019b) roadmap for Automated Freight Vehicles, shown in Figure 1.1, the next step for research into the highest degree of automation is AVs on dedicated lanes, roads, and areas, followed by research into hub-to-hub environments. The difference between a confined area and a hub-to-hub environment is that, within a hub-to-hub environment, transport is partly taking place on public roads. Much research is dedicated to examining the efficiency and cost-effectiveness of autonomous transport. However, the biggest barrier to implementing autonomous transport within hub-to-hub environments is the prohibition of AVs on public roads. Specific rules and regulations may apply for highly automated freight transport, such as speed limits (ERTRAC, 2019b). A hub-to-hub environment with partly public roads is a good case to perform tests and pilots in real operations, to see what about the environment, e.g., the infrastructure, the traffic management, and the logistics systems, needs to be adapted.

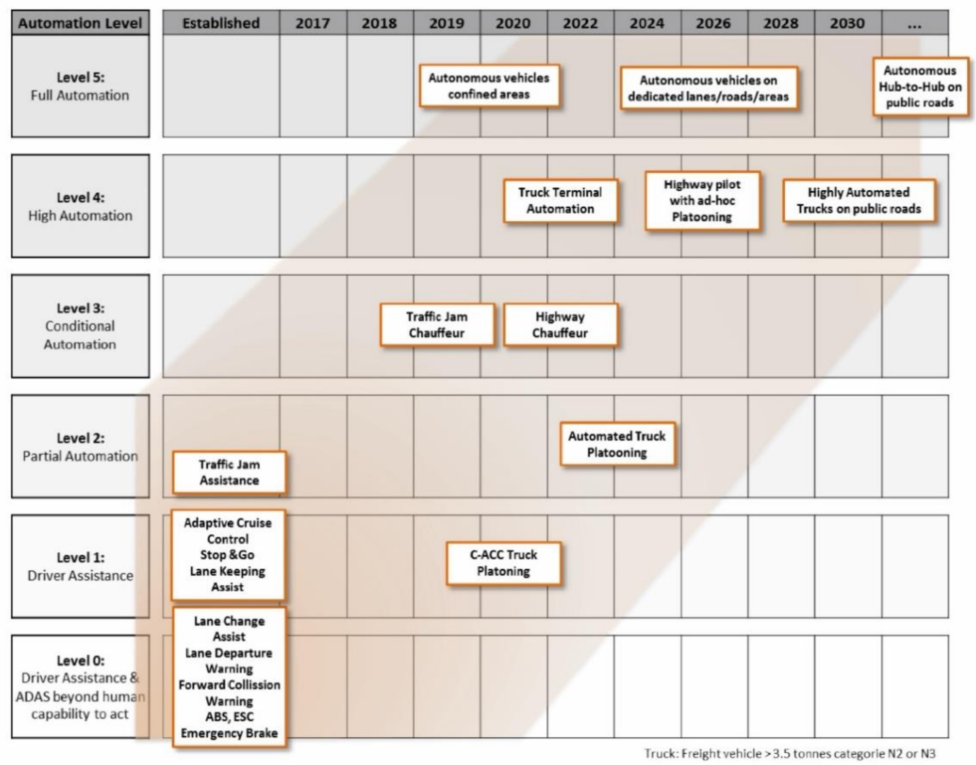

Figure 1.1 ERTRAC (2019) roadmap for Automated Freight Vehicles

One of the research gaps in hub-to-hub logistics is insight into the best strategy for implementing AVs on public roads. To be able to get AVs to drive on public roads, this thesis investigates the impact of automated transport on the current traffic situation in a business case. The goal is to determine an implementation strategy where other road users can get used to AVs in a safe and controlled environment, the next section will introduce the business case used as a tool to test the implementation strategy.

1.2.1 Business case background

Toward**s** in**t**ellig**e**nt int**er**-hub logi**s**tics (STEERS) is a research project conducted in the Netherlands. The STEERS consortium consists of different business partners (Combi Terminal Twente, Bolk Transport, Distribute), the University of Twente and the Hogeschool Arnhem and Nijmegen, as well as branch partners (Port of Twente, XL Businesspark Almelo) and the Regio Twente. These partners are joining forces to explore the real-life challenges associated with the logistics operation in hub-to-hub logistics and to investigate the potential of intelligent and connected technology to address such challenges. This project will investigate the requirements for the application of automated vehicles in “business park transport” and simultaneously explore the potential of intelligent hub-to-hub transport. In this case, a “business park” is an area that contains a container terminal and different logistics hubs, where daily hub-to-hub transport takes place.

The consortium sees the advantages of CAT regarding sustainability, safety, and efficiency at business parks. The transportation of containers in a business park can be defined as hub-to-hub transport. Furthermore, the business case of XL Businesspark Almelo (XL Park) can be used to see how CAT can be implemented into daily hub-to-hub transport. This research focuses on how automated transport can gradually be implemented, with the business park as an example and provides insights into the interaction of automated vehicles with conventional vehicles.

As we've identified the barriers to implementing autonomous transport in hub-to-hub environments, Section 1.3 delves into our research design, outlining the systematic approach we undertake to address these challenges and answer crucial questions regarding the implementation of CAT in hub-to-hub environments.

1.3 RESEARCH DESIGN

This research focuses on the following research question:

> *What characteristics of hub-to-hub environments impact the implementation of Connected Automated Transport and how to design and implement logistics concepts of varying degrees of mixed traffic in these environments?*

To investigate the requirements for the application of automated vehicles in hub-to-hub environments, we first need to define this environment. Various concepts of hub-to-hub logistics are explained using examples from the literature, helping to identify the characteristics of hub-to-hub logistics that impact the implementation of CAT. The varying degrees of CAT are described and a taxonomy for the implementation of CAT into hub-to-hub environments is made. One of the logistics concepts of the taxonomy is tested by a simulation model, using a business case of a hub-to-hub environment. This research answers the following sub-questions:

How can we define hub-to-hub logistics, and what characteristics influence the implementation of Connected Automated Transport (CAT)?
The first step of this research is to understand the environment in which CAT is to be implemented. Literature is used to describe the definitions of hub-to-hub logistics and to explore different concepts of environments and their layouts. The examples are used to identify the characteristics of the environments that may influence the implementation of CAT within these environments.

What different logistic concepts of mixed traffic can be defined, and can a taxonomy be made from these concepts?
In the context of mixed traffic, conventional and AVs share the same (public) roads. To construct different logistics concepts of mixed traffic, the dimensions of connectivity and automation within CAT are explained. A taxonomy will be made with the highest degree of automation, and different dimensions of connectivity, creating a roadmap to gradually implement mixed traffic on public roads. The taxonomy outlines degrees from solely conventional traffic on the roads to completely integrated AVs into conventional traffic. Different concepts are constructed within the levels, to separate the types of traffic by space or by time, e.g., different roads and hours. This research will test these logistic concepts, to determine which concepts have the most positive effect on the hub-to-hub environment.

How to design a generic conceptual model to study the impact of CAT on various types of hub-to-hub environments?
Hub-to-hub environments have varying characteristics, so to create a generic model that applies to all hub-to-hub environments, we will look at various building blocks that together form a conceptual model. All these building blocks will be adaptable to the characteristics of hub-to-hub environments to be simulated. In this way, the model can be generalized and has added value for future research.

What are the environmental characteristics of the XL Park and what do the logistics flows look like?
For our business case, we investigate the XL Park. Different Logistics Hubs (LHs) are located in this business park, among which is a container terminal, CTT Almelo. From the container terminal, the containers are transported to LHs in the business park. We will define the characteristics of this hub-to-hub logistics and map out all logistics flows within this environment. With this information, we can design a simulation model of the XL Park.

What is the impact of the logistics concept of CAT on hub-to-hub environments based on the results of the simulation of the XL Park?
With all the different elements gathered in this research, the building blocks for the simulation are turned into a simulation of the XL Park. Utilizing the taxonomy of logistics concepts, experiments are conducted within the simulation of the XL Park based on different key performance indicators (KPIs). The results of the simulation will be evaluated, and recommendations will be written about what the implementation plan for CAT at the XL Park should look like. Lastly, future changes to the business park are identified.

1.3.1 Research Outline

The research questions are answered in chronological order. Figure 1.2 shows the connection between the topics of this research.

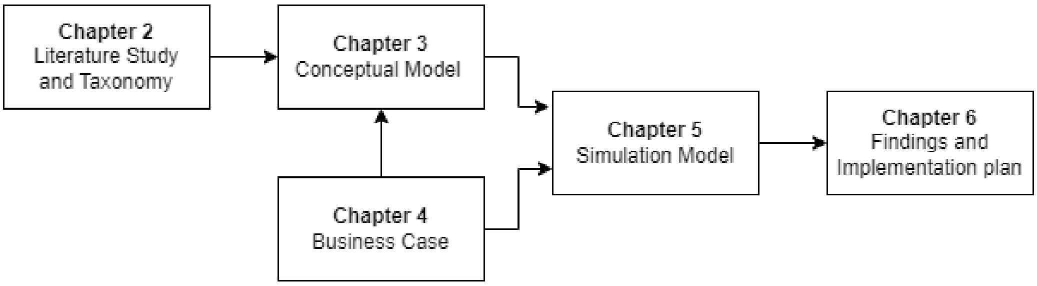

Figure 1.2 Research Outline

To summarize, the first step of this research is to define the characteristics of hub-to-hub environments and explore the varying dimensions of automation and connectivity of CAT. These insights are the foundation to construct the taxonomy for the implementation of CAT on public roads, which is used as the basis for the next steps of our research. With the characteristics of hub-to-hub environments, a conceptual model is designed, with building blocks that can be used to simulate any type of hub-to-hub environment. The conceptual model is designed to assess the impact of the different logistics concepts of the taxonomy. The business case is introduced, describing the characteristics of that hub-to-hub environment as inputs for the conceptual model. With the conceptual model and business case together, the computer model is built, and different experiments are carried out to test the impact of CAT implementation in a hub-to-hub environment. With the results of the experiments, the findings are translated into an implementation plan for the business case specifically and general challenges and guidelines for implementing CAT.

2. LITERATURE STUDY

This chapter describes the literature study on hub-to-hub logistics and CAT. Section 2.1 discusses the literature for hub-to-hub environments. Several examples of these environments are given and definitions for this research are formulated. Section 2.2 explains the different dimensions of connectivity and various degrees of automation of CAT and explores examples of current operational AVs of freight transport in their environment. The findings of these sections are merged into a taxonomy, formulated in Section 2.3.

2.1 HUB-TO-HUB LOGISTICS

The definition of logistics is the process of planning, implementing, and controlling operations for the efficient and effective transportation and storage of goods. It covers all the transportation within a supply chain, from the supplier to the end customer and includes inbound, outbound, internal, and external movements. Logistics hubs play an important role in transport logistics, especially regarding the management and handling of transport. Not only the transport logistics hubs (the large-scale gateways for the import and export of goods) are of major importance, but there are also a large number of smaller, just as important logistics hubs, like logistics hubs of freight forwarding networks (Huber et al., 2015). The complexity of the operating environment has a strong influence on the level of external support that an automated vehicle will need to ensure safe operations (Shladover & Bishop, 2015).

The ERTRAC roadmap (2019b) describes four types of environments for transport logistics, from “simple” environments to more complex environments:

1. Confined Area
2. Hub-to-Hub
3. Open roads
4. Urban Environment

Confined areas are private areas with fully controlled traffic management. This makes it possible to use unmanned or remotely supervised vehicles as an intermediate step to fully autonomous vehicles. A control tower can monitor and supervise the control of the vehicles (ERTRAC, 2019a). Examples of transport in confined areas are unloading a barge and moving the containers to the stacks on the quay, moving a container within a distribution centre, or transportation within logistic centres, a port, a terminal, factories, or warehouses. The movement of goods in a confined area can be seen as transportation within a hub or “intra-hub transportation”.

This research will focus on the second environment. Hub-to-hub transportation is the transportation between these confined areas. A hub-to-hub environment has a relatively controlled environment and is rather similar to a confined area in terms of solutions and technology. Hub-to-hub environments may have dedicated infrastructure for transport, such as non-public roads reserved for more efficient terminal equipment, but commonly transportation also takes place on public roads (Heilig & Voß, 2017). The characteristics of hub-to-hub environments are a relatively simple environment, repetitive tasks, partly public roads, and party-controlled traffic management (ERTRAC, 2019b).

Open roads are defined as public roads, often highways including city and country borders. Urban Environments are the most complex environments, busy city roads with multiple traffic signs and often traffic congestions. These environments are out of the scope of this research.

A logistics hub (LH) is a centre that manages field-based logistical activities to provide goods distribution and customer services in a designated area. The LH plays a key role in developing company businesses via a strengthened logistical connection between companies and customers (Wen et al., 2016). LHs are generally defined as linking points, infrastructure facilities and nodal points, in logistics networks. Accordingly, the hub executes not only storage activity, but also processes of ordering, bundling, and unbundling. There is a distinction between distribution LHs and transport LHs. Distribution LHs hold inventories, where goods can be stored for a longer period and these hubs often link few sources with many sinks (Huber et al., 2015). Transport LHs have less of a storage function, but often do have a buffer to support the main function of the hub, namely the transhipment of goods. These hubs usually connect many sources with many sinks (Huber et al., 2015).

A hub-to-hub environment can have different layouts, as depicted in Figure 2.1. Janic et al. (1999) describe five types of networks, from which three fall in the definition of a hub-to-hub environment. A common feature of all these networks is that the transportation flows that are originally widespread within an area are bundled to become more suitable for transport by regular and relatively frequent transport. Hub-to-hub logistics can be a "point-to-point" network when the transport flow is between two hubs. Another layout can be the "hub-and-spoke" network, where one central hub exchanges between transit units, which are the spokes. At the spokes, the loading units enter or leave the network (Janic et al., 1999). A hub-and-spoke network often has long distances between the hubs, but this layout can also be found in smaller hub-to-hub environments. A combination of these two layouts is the "trunk line with collecting/distributing forks" network. From different "collecting forks", the transport units enter the network to a "begin terminal", where the units change the modality and go to the "end terminal", from where they leave the network with the "distribution forks".

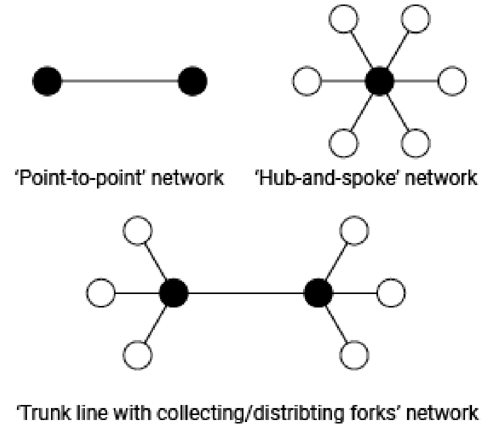

Figure 2.1 Hub-to-Hub Environment Layouts

Duinkerken et al. (2006), summarise the operations of a hub-to-hub environment as follows:

1. The punctual (neither early nor late) collection of containers from their point of origin
2. The punctual delivery of containers at the desired point of destination
3. The possible bridging of discrepancies in both these tasks by "buffering on wheels" or in a transport stack ("on ground")

The coordination of these operations requires efficient and collaborative planning techniques and means to communicate in real-time between the different hubs (Heilig & Voß, 2017). Hub-to-hub environments can form a complex transportation network, which can represent a major source of errors and delays if not handled efficiently. Consequently, the main objective of efficient hub-to-hub logistics is to minimize transport delays, or ideally eliminate delayed transport (Heilig & Voß, 2017). An important performance criterion for that main objective is the transportation time of loading units between their origin and destination hub, including the handling at the destination hub (Duinkerken et al., 2006; Janic et al., 1999). The infrastructure and environment of hubs play an important role in assessing the performance of hub-to-hub environments and may lead to different decisions regarding the modal split. In some hub-to-hub environments, automated transport over dedicated roads may not be feasible, especially in environments where the distance between hubs is high (Heilig & Voß, 2017).

Further performance indicators often take the form of averages and distributions, including vehicle occupation rates, number of empty trips, vehicle loading rate, number of vehicles waiting to load or unload and the equipment utilization at the terminals (Duinkerken et al., 2006). Janic et al. (1999) describe twenty different performance indicators, including cost, safety, dependability and reliability. Chapter 5 will discuss these performance indicators more elaborately when describing the model design. Having established the significance of hub-to-hub logistics, let's now delve into specific examples and characteristics of these environments.

2.1.1 Environment Examples

The literature encompasses numerous instances of hub-to-hub environments, each designated by distinct names and accompanied by varied definitions. This section provides an overview of the diverse environments identified in the literature.

Inter-Terminal Transportation

The first example of hub-to-hub transportation is inter-terminal transportation. Inter-terminal transportation is described as the container transport between various terminals and the various modalities, and the transport between these modalities and other service centres. Inter-terminal transportation refers to any type of land and sea transportation moving containers and cargo between organizationally separated areas (e.g., container terminals to empty container depots) within a seaport (Heilig & Voß, 2017).

Transportation Network

Also called: (closed) transport systems, freight forwarding networks, freight transport systems, logistic networks, or bundling networks. This network connects origins to destinations, supplier to buyer, purchaser to supplier, different transport modes, or hubs to hubs, where the exchange of loading units takes place. This exchange occurs repetitively and is according to a schedule or arrangements between the hubs. The transport vehicles are owned by one of the parties involved in the exchange, making them responsible for the organisation of the transport services (Janic et al., 1999).

Logistics Centre

A Logistics Centre is the hub of a specific area where all the activities relating to transport, logistics and goods distribution, for both national and international transit, are carried out. In short, the Logistics Centre is simply a village planned and built to best manage all the activities involved in freight movement. The most important infrastructures inside a Logistics Centre are the warehouses and the intermodal terminal. To encourage intermodal transport for goods handling, a Logistics Centre should preferably be served by a variety of transport methods (Europlatforms, 2004).

Logistics Clusters

A logistics cluster is an area located outside a city and can also be defined as an “intermodal yard” or “dry port”. Such an area is connected to road, rail, cargo aeroplanes, and/or to a seaport, operating as a centre for the transhipment of cargo between modalities. Preferably, a research centre is established in a logistics cluster for cooperation among companies, students, and researchers (Sheffi, 2012).

Logistical Hotspots

In the Netherlands, freight transportation often involves the utilization of various modalities such as barges, trucks, and trains, and these operations frequently rely on logistical hotspots. These hotspots serve as key nodes for the seamless transfer of goods between different modes of transportation, effectively making them hub-to-hub environments, where terminals, airports, and stations are defined as hubs.

Logistical Ecosystems

Regional (Dutch) logistical ecosystems are based on the idea that one robust logistical hotspot is more than a collection of individual companies with logistical operations. The environment covers a more elongated area, called the “regions” of the Netherlands. The most important aspect is that within these ecosystems, the government, industry, and academia closely work together in the triple helix context, to strengthen the logistical operations. Hub-to-hub logistics in environments like this are more complex with greater distances over public roads.

Business Park

In Dutch, a business park is defined as a collective name for an area with a main function to develop economic activities. A business park is an area mostly on the outskirts of a city, intended for the settling of commercial companies. For logistical reasons, business parks are often located along railways, waterways and/or motorways. The layout of a business park is aimed at optimal spatial development. Depending on the location and the environmental factors, settlement conditions can be imposed that are aimed at maximizing the economic added value of the area. The definition of a business park in English is an area where company offices and light industrial premises are built, which is not the same as the Dutch definition, the Dutch definition is more focused on the logistical collaboration of the companies.

Industrial Symbiosis

Industrial symbiosis is a network to foster eco-innovation and long-term culture change (Lombardi & Laybourn, 2012). The strength of industrial symbiosis lies in value-added destinations for non-product outputs. The waste of one company can be another company's treasure. Resulting in daily transport between the companies, exchanging these transactions. This is not a literal example of a hub-to-hub environment, but it can result in daily hub-to-hub transport.

From the examples of environments found in the literature, the characteristics are defined that have an impact on or are influenced by the implementation of CAT within these environments.

2.1.2 Environment Characteristics

The characteristics of hub-to-hub environments influence the automation of hub-to-hub transport. From the description of hub-to-hub environments and environmental concepts, the similarities and differences are described. The role of each characteristic in this research is defined, as well as the impact on the implementation of CAT.

The first characteristic is the transport between the hubs. Within each example, the transport is between the same hubs, resulting in fixed transportation routes. This characteristic is an advantage for the automation of hub-to-hub transport since the automated vehicles only have a limited set of possible routes. The infrastructure can be adjusted to the automated vehicles, or the vehicles can have fixed routes programmed.

The second similarity is the repetitive transport, which adds to the first characteristic. Next to the fact that the transportation is between the same hubs, it is not coincidental transport but a repetitive transport flow. Automated transport would make this repetitive transport more efficient, by executing the jobs without human interaction needed.

Most environments exchange freight between modalities, which means that unloading and loading activities take place. Besides being moved by vehicles, the loading units are handled by other systems, for example, quay cranes for (un)loading barges, or ground handlers at airports. Automating the transport also means cooperating with these systems, adjusting the vehicles to the systems, or the systems to the vehicles.

All examples describe an area or park where the transport takes place. The hubs are located near each other, which results in short-distance transport. This is an advantage for automated transport, if the vehicles are fuelled by electricity, the loading periods are easier to schedule between the different transport jobs.

Even though the hub-to-hub environment can be in a business park or designated area, the transport is mostly over public roads. This makes it difficult to change the infrastructure to support automated vehicles. The vehicles need to be designed in a way that they can interact with the current infrastructure and traffic.

Besides driving on public roads, the vehicles need to leave and enter the confined areas of the hubs, often closed off by gates. For this characteristic, the confined areas need to be adapted to an automated vehicle. The gates need to cooperate and interact with the vehicle, preventing any delay in the transportation process by creating waiting times at the gates.

There are some differences between the examples as well. Most examples are about the transport of containers but, for example, industrial symbiosis is about any type of transport. This can be energy, gas, water, or any type of industrial "waste". This impacts the design of the automated vehicle regarding what kind of freight is transported.

Most hub-to-hub environments have as their main function the exchange of loading units between modalities within an area. Often, one of these hubs is responsible for the transport between the hubs. For example, a container terminal is responsible for the transport of the containers to a distribution centre or logistic service provider where terminal tractors can be used for this transport. If the hub-to-hub environment is between two or more hubs and the hubs are not logistic service providers, an external party can be employed for the transport. With the automation of transport, the ownership of vehicles can be a pivotal factor. To guide the AVs, a connected system (CS) needs to be in place, to determine the order of transportation jobs and corresponding routes to the hubs for the AV. The different hubs need to share all their information with this system and thus with the owner of the vehicles. Companies could be hesitant to share their information due to confidentiality concerns. Clear definitions of these characteristics are crucial, as they will be consistently used throughout the remainder of this research.

Definitions of characteristics

These are the definitions of the characteristics used for the remainder of this research.

Logistics Hub (LHs)	A port, a terminal, a warehouse, a factory, or any other business that is connected to the transportation flow in a hub-to-hub environment with a logistics operation such as distribution, transport, or storage.
Hub-to-hub environment	The connection of different LHs in a designated area by repetitive transportation flow between the hubs.
Transportation flow	The transport of freight over different modalities, for example, water, air, and land. This research refers to internal and external transportation flow. Internal transportation is within the hub-to-hub environment, which is the focus of implementing CAT, and includes the transport between different modalities. External transportation flow proceeds from different hubs in the environment to hubs outside the environment and vice versa.
Freight	The freight is the load or cargo that is transported from hub to hub. This research focuses on container transportation.
Modality	The type of vehicle of external transportation. This can be a barge, truck, train, or plane.
Designated Area	The hub-to-hub environment is often located in a designated area. This area must be accessible to various modalities and the infrastructure needs to support heavy freight. This research will focus on designated areas that can be closed off to external transportation.
Private Roads	Private roads are the roads in confined areas, where AVs are allowed to drive. The roads can be monitored or designated for the AVs.
Public Roads	Roads for conventional traffic, which the AV needs to use for hub-to-hub transportation.
Confined Areas	Private, closed-off areas where roads are fully monitored and AVs can be used. Confined areas are defined as hubs or LHs for the remainder of this research.

The business case described in Chapter 4 describes the transportation flows between a terminal and multiple LHs in a designated area. This is identified as an example of a hub-to-hub environment. The next section will dive into the concept of CAT, where the dimensions of connectivity are explored, the levels of automation are described, and examples of operating CAT systems are shown to see the current status of research in this field.

2.2 CONNECTED AUTOMATED TRANSPORT

The development of CAT plays an important role in the logistics transportation sector. CAT is one of the key technologies for future transportation. The main drivers for higher levels of automated driving are safety, efficiency, sustainability, comfort, and accessibility. CAT in its ultimate form, as fully unmanned and automated vehicles, will enable completely new transport systems to be realised. These systems will reduce energy consumption and favour the use of electric or fuel-cell-powered vehicles. Also, CAT can be used to design more flexible systems that can make it more cost-effective to use the most energy-efficient mode of transport (European Commission, 2018).

2.2.1 Connectivity

Connectivity means that real-time data is exchanged, making processes controllable. Connected vehicles are vehicles that use any of several different communication technologies to communicate with the driver, other cars on the road, roadside infrastructure, and the “Cloud”. This technology can be used not only to improve vehicle safety but also to improve vehicle efficiency and commute times. A connected vehicle can have different dimensions of connectivity (Shladover, 2018):

> *Vehicle to Vehicle*; communication between vehicles can result in collision warnings or enable cooperative adaptive cruise control. An example of vehicle-to-vehicle connectivity with connected automated vehicles is truck platooning. In this concept, the truck in front is manually driven, and the other trucks in the platoon are connected, following the front truck. This results in a smaller distance between the trucks, increasing lane capacity, and decreasing emissions.
>
> *Vehicle to Infrastructure*; vehicles can communicate to the infrastructure if there is a traffic jam or provide other detailed traffic information. Vehicle-to-infrastructure connectivity can enable electronic toll collection and parking payments, or traffic signal priority requests.
>
> *Infrastructure to Vehicle*; this is for example real-time traffic signals, green wave speed advice, traffic and weather condition information, real-time routing advice, end-of-queue warnings, etc.
>
> *Vehicle to Pedestrian*; this includes any vulnerable road user that carries a device that can communicate with the vehicles.
>
> *Vehicle to Anything*; this can be compared to the “internet of things”, in which virtually every device can be connected to any other device.

Connected vehicle systems are a fundamental means of enabling the road transportation system to function as a well-integrated system combining infrastructure, vehicle, and user elements (Shladover, 2018). The development of connected systems and automated systems have been proceeding along somewhat independent paths, but there should be a strong synergy between them since they provide complementary contributions to improving transportation system performance and safety. Where connectivity integrates the vehicles and the infrastructure into a system whose performance can be adjusted to satisfy a variety of societal goals, automation overcomes one of the major impediments to transportation system performance and safety (Shladover, 2018).

2.2.2 Automation

Over the last few years, there has been rapid adoption of automation and predictive analysis and these innovations should have a major impact on the organization of the logistics sector: automation should bring efficiency improvements that are driven by the associated cost savings (ERTRAC, 2019b). Automation means the use of electronic or mechanical devices to replace human labour (Shladover, 2018). Fully automated, autonomous, or “self-driving” vehicles are defined as “those in which operation of the vehicle occurs without direct driver input to control the steering, acceleration, and braking and are designed so that the driver is not expected to constantly monitor the roadway while operating in self-driving mode.” (NHTSA, 2013). SAE International (2018) defined six levels of automation. In levels 0 to 2 the driver monitors the driving environment, in levels 3 to 5 the automated system monitors the driving environment.

Level 0: No automation, the driver of the vehicle is in control.

Level 1: Driver assistance, the vehicle has a single automated system, with features that provide steering or brake/acceleration support to the driver.

Level 2: Partial Automation, which means advanced driver assistance systems and the vehicle can control both steering and accelerating/decelerating.

Level 3: Conditional automation, these vehicles have "environmental detection" capabilities and can make informed decisions for themselves, such as accelerating past a slow-moving vehicle. However, the driver must remain alert and ready to take over control if the system is unable to execute the task.

Level 4: High automation, these vehicles can intervene if things go wrong or if a system failure occurs. These cars do not require human interaction; however, the driver has the option to manually override.

Level 5: Full automation, the dynamic driving task is eliminated, and these vehicles can drive without a driver.

CAT is expected to improve safety in all transport modes. Human error is a major cause of accidents and increased and correct use of CAT will substantially reduce these accidents (European Commission, 2018). Next to carrying out specific tasks more reliably, CAT has a lower overall cost level. Depending on the level of automation, it is possible to perform tasks completely without an operator or at least ease the workload of the operator. When tasks are carried out without errors and under favourable conditions, CAT can lead to multiple advantages such as less to no costs for personnel, reliability in container tracking, optimum and careful handling of vehicle and load, less energy consumption and less wear and tear, no accidents due to more precise vehicle navigation, as well as faster vehicle navigation leading to faster transhipment (Götting, 2000). In autonomous control, particular focus is placed on smart logistics entities which can interact with each other (Hribernik et al., 2010). The next section goes deeper into the practical applications of CAT.

2.2.3 Autonomous Vehicles

For the automation of logistical processes in the supply chain, different automated systems can be utilized. Two primary types of automated vehicles are Automated Guided Vehicles (AGVs) and Autonomous Vehicles (AVs). While AGVs are guided by marked lines or wires along a route, indicating a predetermined path, AVs demonstrate a higher level of autonomy, capable of navigating without the need for designated lines or marks, relying on sensors and GPS for independent navigation AGVs are most often used in industrial buildings, like factories and warehouses, and are used in applications with repetitive movements of materials over a distance, regular delivery of fixed loads, or processes, where tracking the goods is important. Examples of these applications are the handling of raw materials, work-in-process movements, pallet handling, finished product handling, trailer loading, roll handling, and container handling. AVs are more suitable for this research, as the focus involves the use of public roads without the need for guides. The advantages of AVs include labour cost savings, predictable and continuous operation, high reliability, and reduction of error rates of transport processes due to the high degree of automation (Schmidt et al., 2015). AVs are widely used within industrial buildings because of the controlled environment and fixed jobs.

The same applies to confined areas, where AVs can closely be monitored from a control tower, so unmanned and remotely supervised vehicles can be used. Within these confined areas specific regulations may apply to enhance intermodal freight transhipment (ERTRAC, 2019a). To accommodate the increased supply of containers, terminal operators should achieve a high level of productivity and container throughput, ideally at low costs. One means of achieving this is to provide an advanced level of automation in container terminals, especially in high-wage countries (Schmidt et al., 2015). Ports and terminals can use multiple autonomous systems, for instance, automated ship-to-shore cranes, automated stacking cranes, and automated freight transport carriers. Operating examples of these autonomous systems are described in the next section.

2.2.4 Examples of AV applications

AVs are already applied in confined areas and even some tests are executed on public roads. This section describes some examples of these AVs.

Maasvlakte 2, Rotterdam

The container terminals at the Maasvlakte 2 in Rotterdam are the world's most automated terminals, operating largely autonomously, and with remote operators. The automated systems in the port are automated quay cranes, automated barge cranes, automated stacking cranes, and AGVs. The AGVs transport the containers between the different cranes. The environment the AGVs are driving in is fully automated, so there are no other road users. The automated quay cranes can handle 45 containers per hour, whereas conventional quay cranes can handle 25 containers. The remote crane operators monitor the cranes from the control tower.

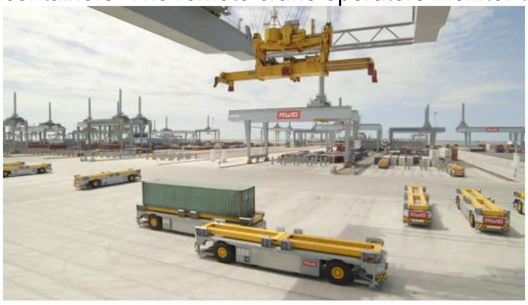

Figure 2.2 AV at Maasvlakte 2

BASF, Ludwigshafen

BASF is a big chemistry company, working in six segments: chemicals, materials, industrial solutions, surface technologies, nutrition & care, and agricultural solutions. At their site in Ludwigshafen, AGVs that transport innovative tank containers are driving around in a mixed-traffic environment. The tanks filled with liquid or gaseous chemical products are transported from the train station to the plants. The vehicles are electronically connected to a transponder lane, allowing them to find their way with centimetre accuracy. The AVs at the BASF site are the first driverless vehicles to drive on a road shared with other road users. To ensure traffic safety, the AVs are equipped with sensors on all sides of the vehicle to identify obstacles. Furthermore, cameras send real-time images to the control centre, where employees can intervene at any time.

Figure 2.3 AV at BASF

Volvo Vera, Götenborg

The AV "Volvo Vera" takes care of the repetitive transport flow between a logistics centre of DFDS and a terminal in Götenborg. It drives over short distances with a maximum speed of 40 km/h. Currently, in this first test project, the vehicle is observed by an operator in a control tower. A part of the route runs on the public road in the industrial area. The autonomous transport solution will be further developed in terms of technology, management, and adaptions to the infrastructure before the vehicles are fully operational. In addition, the necessary safety measures are taken to meet social requirements for a safe route for self-driving transport.

Figure 2.4 The Volvo Vera

Yangshan deep-water port, Shanghai

This terminal is similar to the Maasvlakte 2. The port of Shanghai implemented automated systems the same way, and now the whole terminal is fully automated. There are no workers present at the terminal, in fact, it is forbidden for people to walk around the terminal. The workers sit in a control room, monitoring the operations of the terminal.

Figure 2.5 Yangshan Terminal

In the next section, we will categorize the findings of various logistic concepts into a taxonomy for traffic separation, placing the characteristics of these operational examples within the dimensions of the taxonomy.

2.3 TAXONOMY

This section will describe a taxonomy that serves as a framework for categorizing various logistic concepts for traffic separation in CAT systems. The transition to fully mixed traffic on public roads is not going to happen by itself. To ensure that the regulation will be adapted, it must first be demonstrated that AVs go hand in hand with conventional traffic.

Elvik et al. (2019) describe the implementation of CAT systems as a process developing along four dimensions. The first dimension defines the levels of automation, explained in Section 2.2.2. The second dimension is about the domains of operation, in which three levels can be identified:

1. Automated vehicles can only operate in designated areas where other traffic is not permitted.
2. Automated vehicles are allowed to operate on some public roads where non-automated traffic is also found.
3. Automated vehicles are allowed to operate on all parts of the road system.

The third dimension is about whether traffic is being monitored and regulated by a traffic centre or not, and the fourth-dimension concerns how fast vehicles at different levels of automation will penetrate the market. This research will focus on the second dimension of the implementation of CAT systems, this dimension is particularly relevant for the next step in research following the ERTRAC (2019) roadmap introduced in Section 1.2 and shown in Figure 1.1.

With the levels of the second dimension of operation in mind, a taxonomy for different logistic concepts is designed. A taxonomy is a classification scheme to organise information into categories so that it can easily be accessed (Laudon & Laudon, 2014). This systematic classification of concepts in hierarchical categories is based on shared characteristics or attributes to understand relationships and compare differences and similarities between them.

This taxonomy describes different logistics concepts for traffic separation, which represent the first category in the hierarchy. The concepts describe various approaches to segregate autonomous and conventional traffic. The second category represents four different dimensions of operation in which traffic can be separated. These levels represent specific characteristics to categorize the logistics concepts, composing the third category, which implement the level of operation in practise. Within the dimension of operation, the levels of connectivity from Section 2.2.1 are taken into consideration as criteria. A visual representation is shown in Figure 2.6. The next sections elaborate on the classification of the characteristics, criteria, logistics concepts, and challenges within each dimension of operation.

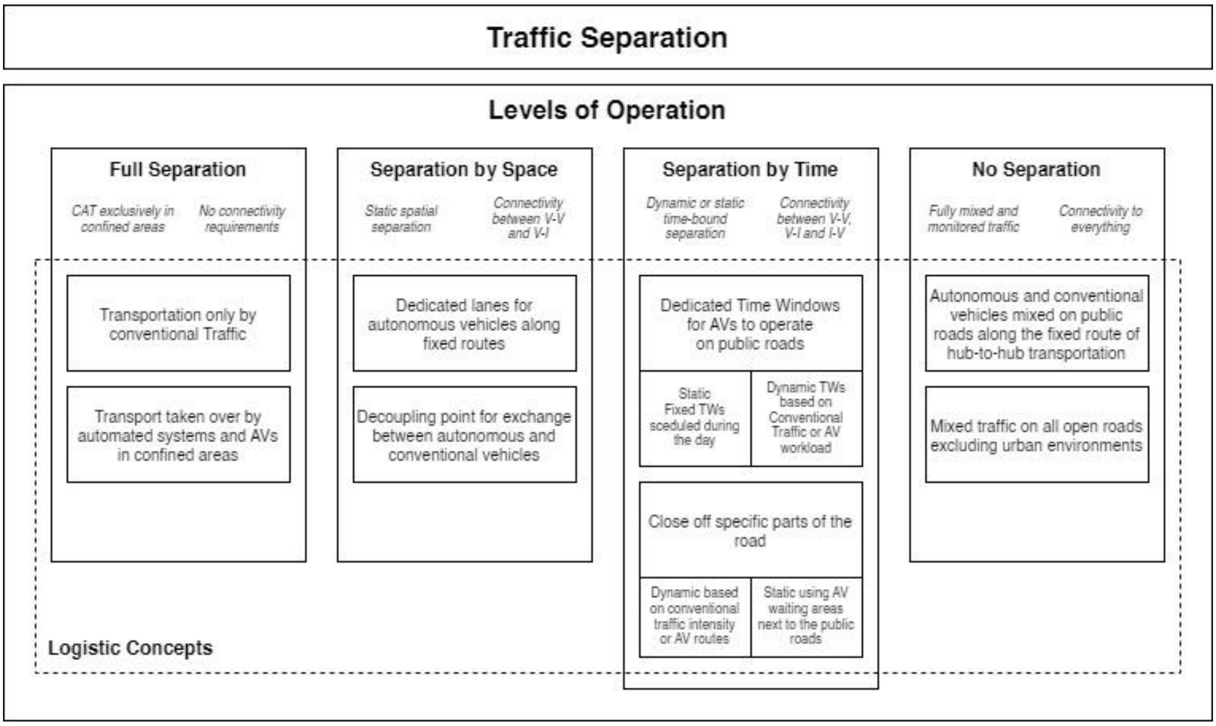

Figure 2.6: Taxonomy of Traffic Separation

2.3.1 Full Separation

The current situation of public roads: only conventional traffic is allowed, which means that all vehicles must have a driver. Therefore, AVs cannot be used for hub-to-hub transport. However, in the private areas, the confined areas of the hubs, AVs can be applied, together with other automated systems to improve the logistical processes within the hub, where the vehicles and systems are monitored. On public roads, no connectivity is needed, whereas in confined areas the connectivity is regulated by the operation of a private monitoring system.

Characteristics: No AVs allowed on public roads. Confined areas for exclusively AVs and automated systems. Monitoring of CAT systems.

Criteria: No connected system on public roads.

Logistics Concepts: Transportation is done by only conventional traffic and cooperating systems are handled with human interference.

Transportation over public roads is done by conventional traffic and in confined areas taken over by automated systems and AVs. An example of this logistics concept is the Yangshan deep-water port in Shanghai, given in Section 2.2.4.

Challenge: Automation of hub-to-hub transportation is not possible.

2.3.2 Separation by Space

AVs can be separated from conventional vehicles by dedicating roads to one type of vehicle. Since hub-to-hub transport mostly consists of fixed routes, along these routes dedicated lanes can be built, so conventional traffic and autonomous traffic can operate completely separated from each other, which is a static way of separating by space. On the dedicated lanes, connectivity is needed between the AVs for collision control, and between the vehicle and infrastructure to ensure the vehicle stays on the dedicated lane and follows the correct route. Another way of separating traffic by space is a decoupling point. In clusters, parks, or terminals that could become closed-off areas, a dedicated spot can be constructed for the handover between conventional traffic and AVs. Conventional traffic can park here, and trucks can decouple the trailers. AVs pick up the trailers to transport the last mile on fully autonomous roads to the destination. People can be moved by autonomous shuttles or other autonomous solutions. The decoupling points should be designed to separate the AVs and conventional vehicles, so connectivity is only needed between AVs for collision control, and between AVs and the infrastructure to ensure the designated spot for decoupling.

Characteristics: Static spatial separation. Dedicated lanes. Decoupling points.

Criteria: Connectivity between vehicle to vehicle and vehicle to infrastructure on dedicated lanes and in decoupling points.

Logistic Concepts: Public roads separated for conventional and autonomous traffic by dedicated lanes along fixed routes. Decoupling point for transportation handover between conventional and AVs in designated hub-to-hub areas.

Challenges: Investments in realizing a new road infrastructure, the building of a decoupling point, designing a planning tool or connected system for transition between conventional and autonomous transportation at the decoupling point, and adaptions to the environment to support AVs.

2.3.3 Separation by Time

AVs are using the same public roads as conventional traffic, however, not at the same time. This separation can be static or dynamic. Static separation in time can be achieved by closing the roads at specific times for conventional traffic, so AVs can do their job. These specific times can be divided over different time windows (TWs) scheduled during the day. To indicate what type of vehicle is allowed on the public roads, traffic lights or other traffic signs can be implemented. The TWs can also be scheduled dynamically, responding to the intensity of conventional traffic or the workload of the AVs. When conventional traffic is monitored, roads can be closed off in off-peak hours and AVs can operate without interrupting and delaying conventional traffic that cannot enter public roads during these TWs. When the workload of AVs is monitored, TWs can dynamically be initiated when enough workload for the duration of the TW is piled up, or the duration of the TW can dynamically be adjusted to the in-stock workload.

Another option is to dynamically adjust the route of the AVs. If an AV makes its route, only close off the road the vehicle is driving on for conventional traffic. This way conventional traffic can always enter the hub-to-hub environment but does not get mixed with AVs. This option can also work the other way around; letting the AV dynamically select the roads to their destination to avoid close contact with conventional traffic. Traffic needs to be closely monitored, so AVs can adjust their routes to the roads with the least traffic. When it is not possible to choose from multiple routes, an option would be to let the AVs leave the roads en route to make room for conventional traffic when needed. For this, waiting areas should be available or built. When the roads are free of conventional traffic, the AV can continue its route.

Within the logistics concepts of this operation level, connectivity is more complex by dynamic approaches. Vehicles need to be connected to vehicles, connected to the infrastructure, and infrastructure needs to be connected to the vehicles, so it can interact with the vehicle when roads are about to close for that type of vehicle, or when routes need to change because of change in parameters for the dedicated road user.

Characteristics: Dynamic or static time-bound separation, time windows for conventional and AVs, response to conventional traffic intensity or AV workload, dynamic route adjustment.

Criteria: Connectivity between vehicle to vehicle, vehicle to infrastructure, and infrastructure to vehicle.

Logistic Concepts: Dedicated TWs for AVs and conventional traffic, fixed over the day of dynamically initiated based on intensity of conventional traffic or AV workload.

Closing of part of the road for a specific type of vehicle, dynamically based on conventional traffic intensity or based on AV routing. Static by using AV waiting areas next to public roads.

Challenges: Investments in new road infrastructure or traffic signs for closing roads, designing an efficient schedule or dynamic system for TWs, adaptions to environment to support AVs, planning tool or connected system to assign workload to AVs.

2.3.4 No Separation

Conventional traffic and autonomous traffic use the same roads at the same time, interacting with each other through different connected systems. Hub-to-hub transportation can be done by a collaboration of conventional and AVs, interchanged by human-operated systems or automated systems. To achieve this operation level, AVs should be connected to everything, this level of connectivity exceeds the capability of one connected system that can operate in a designated area. The AV should be able to make decisions on its own, taking into account all connected and unconnected elements in its current environment. Which cannot be achieved by one connected system within a designated hub-to-hub environment.

Characteristics: No spatial or time-bound separation. Mixed traffic in all parts of the transportation system. Collaboration of human-operated and automated systems. Full integration into the existing road system.

Criteria: Vehicle connectivity to everything.

Logistics Concept: Mixed traffic of autonomous and conventional vehicles on public roads along the fixed route of hub-to-hub transportation. The Volvo Vera described in Section 2.2.4 is an example of research into a logistic concept within this level of operation.

Mixed traffic of autonomous and conventional vehicles on open roads, all public roads including highways, excluding complex urban environments i.e. within city limits.

Challenges: Adaptions to road infrastructure to support AVs, improving connectivity in entire hub-to-hub environments, and acclimatization of human drivers to AVs on shared roads.

2.3.5 Challenges

While each level of the taxonomy outlines ways to achieve traffic separation, challenges accompany each solution requiring careful consideration of costs and time investments. The various challenges across the different separation dimensions entail aspects such as infrastructure development or adjustments and the need for a planning tool or connected system. However, the most crucial challenge involves a smooth integration of AVs into the existing road infrastructure, where human drivers coexist. This challenge encompasses aspects of providing accurate information to human drivers about the existence of AVs on the shared road and available roads or designated TWs to enter specific roads or areas. Ensuring a clear understanding among human drivers about the presence and behaviour of AVs is crucial for minimizing disruptions and enhancing overall road safety. These challenges must be addressed to ensure the successful implementation of CAT systems into real-world transportation scenarios. In addition to the connectivity levels mentioned in the taxonomy, hub-to-hub transportation introduces an overarching challenge. All hubs must be seamlessly connected to the vehicle to control AVs' transportation jobs effectively. Connectivity remains a crucial aspect at all levels, playing a significant role in the necessary environmental changes.

Current research into CAT systems is done within the dimension of separation by space, and the first steps of research are taken into the integration of an AV on a road with no separation. However, the separation by time is a new research concept and will be the topic of this research. By focusing on dynamic and static time-bound separation, scheduling, and route adjustments, this research aims to contribute valuable insights into the evolving environment of CAT systems. For this research, a CS will be designed to operate and control the transportation flows of the AVs. The environment of a business case will be introduced in Chapter 4 and used to test the logistical concepts of the dimension 'Separation by Time'.

2.4 CONCLUSIONS

This Chapter answers the research questions for the literature study and explains existing concepts of hub-to-hub environments and CAT systems. Hub-to-hub logistics is defined as the transportation flow between confined areas, with dedicated infrastructure for transport, including private areas for transition between modalities and public roads between the different hubs. These environments can be of different layouts, with exchange of transport between different modalities and transport between different LHs, in some sort of designated area. Most importantly, the transportation flow between these hubs is repetitive with fixed routes between the LHs. This makes the hub-to-hub environment suitable for the implementation of CAT.

CAT can be distinguished between connected and automated, but the synergy between the two comes with the data that connected technology can provide to automated systems to improve their performance and safety. Connectivity is an important factor in the implementation of CAT in hub-to-hub environments, the AVs need to be connected to the infrastructure of the environment, and other vehicles, and in addition to that, a CS should be implemented to direct the AVs to the LHs and monitor the transportation flow. In this research the AVs are of the highest level of automation, full automation, meaning the AV drives autonomously over the public roads. From these findings, a taxonomy is made with different dimensions for implementing CAT in hub-to-hub environments. The first dimension is the current situation where only conventional traffic is allowed on public roads. The second dimension is the separation by space where AVs and conventional traffic do not make use of the same roads. The third dimension is the separation by time, AVs and conventional traffic make use of the same roads, only not at the same time. The fourth dimension is fully mixed traffic where all vehicles, autonomous and conventional are driving on the same roads, at the same time. Within each dimension, various logistic concepts are categorized and the challenges for the implementation of these logistic concepts are identified.

3. CONCEPTUAL MODEL

This chapter develops a generic conceptual model, existing of various building blocks that represent the characteristics of a hub-to-hub environment. Section 3.1 introduces simulation studies and explains their significance in the context of this research. Section 3.2 described the conceptual model framework, with the problem situation, general project objectives, outputs, inputs, and the scope of the model. In section 3.3 we dive further into the model content.

3.1 INTRODUCTION

Simulation is an indispensable tool for understanding, managing, and improving complex systems. It is used by many organisations to plan future scenarios and to improve current operations. The definition of simulation, as stated by Robinson (2008), describes an imitation of a system as it progresses through time. The purpose of a model is to understand, change, manage, and control reality (Pidd, 2009). The purpose of a simulation is to obtain a better understanding of a system and identify improvements. It involves predicting the performance of a system under specific inputs.

There are two concepts of simulation: static and dynamic. A static simulation imitates a system at a point in time, while a dynamic simulation, which will be the focus of this research, imitates a system as it progresses through time. In general terms, a system is a collection of parts organised for some purpose (Coyle, 1996). An operating system is discussed as a configuration of resources combined to provide goods or services, encompassing diverse functions such as manufacturing, transportation, supply, and service (Wild, 2002).

More specifically, this research employs a discrete-event simulation, which is used for modelling queuing systems. A system is represented as entities flowing from one activity to another. All events are separated by time, queues result when entities arrive at a faster rate than they can be processed by the next activity.

The simulation process can be more elaborately defined as an experiment using a simplified computer-based imitation of an operational system. This aims to enhance understanding and improve the system over time. Variability in a system, combinatorial complexity (number of combinations of system components), and dynamic complexity (interaction of components in a system over time) are reasons to translate a system into a simulation model.

Simulation models enable us to explicitly represent a system's variability, interconnectedness, and complexity. As a result, it is possible with a simulation to predict system performance, to compare alternative system designs and to determine the effect of alternative designs and policies on system performance. These factors, inherent in real-world systems, pose challenges to traditional analytical approaches, making simulation a powerful alternative for system analysis and design.

Conceptual modelling is the abstraction of a simulation model from the part of the real world it is representing ("the real system"), which may or may not, currently exist (Robinson, 2017). A conceptual model is defined as a non-software-specific description of the computer simulation model, describing the objectives, inputs, outputs, content, assumptions and simplifications of the model (Robinson, 2008). The system description is a description of the problem situation and the system in which the problem situation resides (Robinson, 2011). For this research, the characteristics of hub-to-hub environments are used to frame the conceptual model.

This research is built upon hub-to-hub logistics and different hubs are defined. These hubs are used as the basis for different building blocks within the simulation model. Designing general building blocks for the simulation model makes it easier to expand the model when new hubs are added to the environment. With the building blocks, other hub-to-hub environments can easily be built, by changing the number of blocks and changing the input variables. We use the characteristics described in section 2.1.2 to determine which building blocks are needed for a generic model.

3.2 CONCEPTUAL MODEL FRAMEWORK

Robinson (2008) describes a structured approach to conceptual modelling. This approach consists of the following five steps:

1. Understanding the problem situation
2. Determining the modelling and general project objectives
3. Identifying the model outputs (responses)
4. Identify the model inputs (experimental factors)
5. Determining the model content (scope and level of detail) and identifying any assumptions and simplifications.

These steps are taken to construct the conceptual model.

3.2.1 Understanding the problem situation

Understanding the problem situation is central to the formulation of the modelling objectives (Robinson, 2008). The starting point in any simulation study is driven by the need to improve a problem situation. To develop a proper conceptual model, a thorough understanding of the problem situation is needed. The problem situation derived from the preceding gives the requirements for the conceptual model. Chapter 2 outlines environmental characteristics impacting CAT implementation, presenting various levels of mixed traffic to facilitate the integration of AVs on public roads.

Problem situation: Most hub-to-hub environments contain public roads used for container transport from one hub to the other. To automate this container flow, the use of AVs is required, but not allowed on public roads. The taxonomy categorizing various logistic concepts for CAT implementation encompasses four dimensions of operation. Within the dimension of separation by time, no research has been conducted. This conceptual model is developed to test the logistic concepts in this dimension, aiming to minimize the impact on both conventional traffic and container transport.

Separation by time implies that conventional traffic and AVs share the same roads but operate at different times. To achieve this, roads will be closed for conventional traffic while AVs are using the roads for transportation. For this, Time Windows (TWs) are implemented, permitting only AVs on the public road. These TWs have an impact on the flow of conventional traffic, and the results of the experiments should analyse this impact. The experiment design involves variables such as the number of TWs and the duration of the TWs. Rather than defining different scenarios, we pre-define configurations of TWs for the experiments to investigate the impact of different TWs on the current situation.

3.2.2 Determining the modelling and general project objectives

The simulation study aims to provide insight into the impact of the implementation of AVs on different hub-to-hub environments. The impact will be assessed through the following KPIs:

1. Fraction of delayed traffic
2. Terminal time of containers
3. Call time
4. Utilization of the AV
5. Jobs left in the CS

The research objective is to minimize the impact on conventional traffic while implementing AVs on public roads, but the main operation of transporting containers to the LHs should also be taken into consideration. System changes influence the routing of conventional traffic, which can be measured by the fraction of delayed traffic. Terminal time, call times of containers, and AV utilization serve as metrics to monitor the core operation of transporting containers from hub to hub.

3.2.3 Identifying the model outputs (responses)

The output variables of the simulation model are defined by five different KPIs.

Fraction of Delayed Traffic

The fraction of conventional traffic waiting for the roads to open to access the roads and continue their route, i.e., private cars and trucks. This indicates the impact of delay caused by implementing CAT in the hub-to-hub environment.

Terminal Time

Terminal time represents the period that the containers spend in between hubs while being on route(s) between origin(s) and destination(s) (Janic et al., 1999). In this research, two types of terminal times are distinguished: the time between arriving at the terminal and arriving at the LH, and the time between leaving the LH and leaving the terminal. The terminal times are the transportation times plus the time the container is waiting at the terminal to be transported. Terminal time influences the total delivery time and thus the total delivery cycle of the containers. Minimizing the terminal time will increase the terminal efficiency and reduce the space needed to store the containers (Janic et al., 1999). Higher terminal times indicate more delay in the delivery time of the containers, which can occur if AVs can only transport containers in limited time intervals.

Call time

The Call time is used instead of testing due dates. When a container has a due date, it can be tested if the due date is met and what the difference in arrival time and due date is. Due dates are not known in this research, so the delivery time is tested with a call time. The call time is the time between a container being ready for pick up and the time a vehicle arrives to pick up the container. In this model, two types of call time exist. The time between the arrival at the terminal and being picked up by the AV, and the time between the container being ready at the LH and being picked up by the AV.

Utilization

To find the most efficient length of the TWs, the utilization of the AVs is measured.

Utilization = the fraction of time a vehicle is occupied.

The duration of the TWs should be adjusted to the workload of the AV. The roads are closed when the AV is driving, so the duration should not be longer than needed, since this causes delay for all other traffic. The duration should also not be too short, this causes delays in the delivery time of the container or even unfinished jobs. The utilization is measured by two factors. The first is the time the AV carries a container, meaning the AV is loaded. The second is the time the AV is assigned a job, so the time the AV is driving empty (unloaded) to pick up a container is also considered. The time the AV is unloaded and has no job assigned is not considered as utilization.

Jobs Left

If the CS is efficient and the number of AVs and TWs are sufficient for the workload of the internal transportation, all containers should be transported during the TWs. To determine the efficiency, the number of containers left in the CS at the end of the day is counted. This visualizes the queue at the terminal of containers waiting for internal transport every day.

3.2.4 Identifying the model inputs (experimental factors)

The model inputs are described by the characteristics of the hub-to-hub environment.

Environment

Firstly, the environment plays a crucial role. This encompasses the infrastructure of roads, connections to hubs, and the various modalities within the environment. Modelling the environment close to reality is essential for obtaining accurate results.. The following environmental inputs include:

- Infrastructure of roads (water, land) that connect the hubs and external roads
- Different hubs and their location
- Different modalities within the environment
- External and internal transportation generators
- Conventional traffic generator

LHs

LHs serve different functions in the environment, but not all functions are crucial for modelling the hub-to-hub environment. The following inputs are vital for analyzing internal transportation in the system:

- Switch between modalities within a hub
- Number of container handling systems (for example cranes at a terminal, or docks at a warehouse)
- Storage space
- (De)couple times
- (Un)loading times
- Connections to other hubs and the frequency (destinations)
- Opening hours

Transportation flow

The transportation flow is generated by different generators such as barge, truck, train, or plane generators. Modalities transport containers into the system, initiating internal transportation. Important inputs for modelling this aspect include:

- Arrival intensity of modalities
- Freight (number of containers that the modalities transport)
- Destination frequency

AVs

For the implementation of CAT in the hub-to-hub environment, a system needs to be in place to connect the AV to the hubs and to the containers it needs to transport. This system also connects the external transportation flow to the internal transportation flow.

To implement the separation of time between conventional traffic and the AVs, TWs are determined when AVs can access the road or not. This is defined as the AV schedule, which is an experimental factor aimed at designing the most efficient AV schedule with the least impact on conventional traffic. The three factors that influence the AV schedule are:

- Duration of TWs
- Amount of TWs
- Moment of the day for the TWs

In addition to the schedule, the number of AVs is determined. This can be a fixed number as a constraint by the environment or vehicle owner, or this can be an experimental factor to determine the optimal amount with the optimal schedule of the AV. The AVs also need a home base where they are stored and charged.

3.2.5 Scope, assumptions, and level of details

The primary focus of the model is the impact of the AV on public roads, while also providing a foundation for possible further research in hub-to-hub environments. Therefore, the current situation should be modelled as close to reality as possible. In the conceptual model, some assumptions are made, when real data is not known or uncertain. Simplifications are made when variables do not impact the goal of this research and keep the model simple for experimenting, due to a time constraint for this research.

Container information

In cases where obtaining real data is challenging, certain assumptions are made. All containers have a destination, determining the incoming barge and truck flow. The container input is generated by a distribution, which gives the simulation a stochastic input. The containers only have a destination, but lack a due date, which means the lateness of container delivery is not considered. However, the goal of the simulation is to minimize the terminal time, which means the containers get to their destination at the earliest possible time. The difference in modelling with due dates would be in the order the containers are picked up to be transported.

Assumptions input variables

The different building blocks of the simulation are modelled in detail and the input variables at the terminal and LHs are based on real data. However, these variables are set to fixed values for simplification of the model. At the terminal, the handling time of the crane for putting the containers on the chassis is not taken into consideration and assumed this does not influence the system. Also, we assume that when a barge arrives at the terminal, there is always a crane handler present, since the barges are scheduled, and the arrival time is known by the terminal. When loading a barge, truck or chassis, the crane can always reach the right container. Moving containers to reach the right one does not take extra time in this model. Containers that are leaving the system by barge do not have a specific barge assigned to them. After a barge is unloaded, all containers waiting to be transported are loaded onto the barge.

The decoupling times at the LHs are not taken into consideration, these values depend on the model of the AV and how the system of coupling and decoupling the chassis is designed. Next to that, these values do not impact the traffic situation, which is the focus of this research.

External transportation flow

The model does not contain external hubs facilitated by the environment, since the transport is not regulated by the AVs. Containers will get the “exit” destination when entering the system. The containers can re-enter the system if they are returned by a truck to the terminal and loaded on a barge to leave the system indefinitely. This flow to external hubs is taken into consideration because it impacts the traffic flow. Likewise, the LHs have an external truck flow with their suppliers and clients, which is generated by a distribution. To make sure this container flow will not cause any system delay, the container pick-up is modelled in a way that the container is always available when a truck arrives at the terminal or LH to pick up the container for external delivery. For the same reason, when a container arrives in the system with an external destination, a truck will always be available to pick up the container. In the real system, these trucks are scheduled by the companies, and this is not modelled in further detail.

AV Operation

When an AV delivers a container at an LH, the most efficient flow is to take back a container of that same LH. When there are no containers available at the current location, the AV does not consider the closest location to pick up a container but selects the container with the earliest arrival time anywhere in the environment. The cargo of a container is considered irrelevant to the traffic flow and therefore not taken into consideration. It is assumed the cargo does not influence the speed of the vehicle. The charging time and place of the AV are not taken into consideration: we assumed that the AV can be charged in idle times, e.g., during the time windows in which it is not allowed to drive. AVs are assumed to be able to (de)couple chassis to transport the containers without an operator.

3.3 MODEL CONTENT

The next step in conceptual modelling is determining the model content. The general overview of the building blocks with their inputs is shown in Figure 3.1. The input variables can differ for each LH and the building blocks can be added multiple times to the model. The input variables can be adjusted separately to the real system's settings. The arrows represent the infrastructure of the roads.

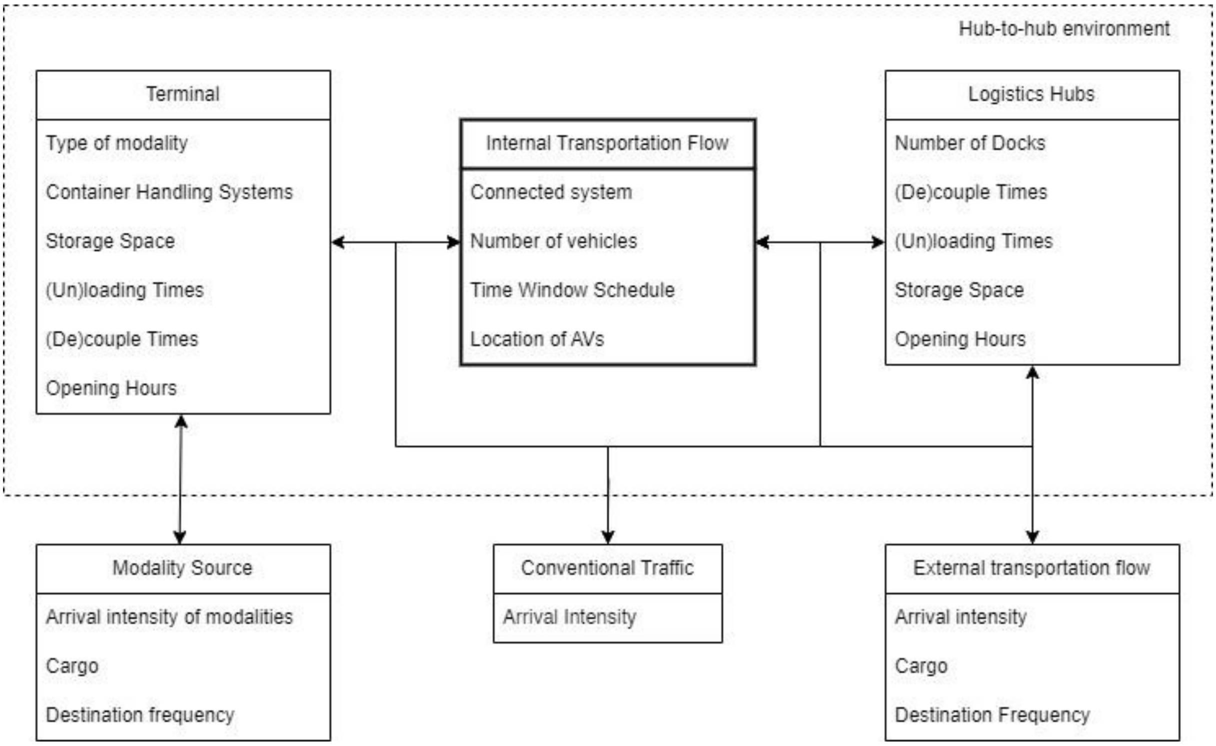

Figure 3.1 Building Blocks and Input Variables of the model

To implement CAT systems into hub-to-hub environments, the internal transportation flow needs to be regulated by a connected system that interacts with the AVs, the LHs, and the containers, to determine the work of the AV. Next, the implementation of the CS in the model visualised above will be explained.

3.3.1 Connected System

The CS can be viewed from two perspectives, the interaction with the containers and the interaction with the AVs. Figure 3.2 compares the CS interaction of the container with the CS interaction of the AV. The container arrives at an LH and the process after container arrival involves the following steps:

1. The container is placed in the CS.
2. The system checks if the TW of the AV is active. If not, the system waits until the TW of the AV.
3. If the TW of the AV is active, the system checks if an AV is idle to pick up the container for transport. If not, the system waits for an idle AV.

The AV interaction starts at the beginning of an TW and the idle AV checks the CS for containers that need to be transported. If the CS is empty, the system waits for a container arrival. The container and AV interaction with the CS merge when both an AV and a container are available during a TW, and the AV gets assigned to a container. The AV picks up the container for transport to its destination. After the transportation process, the container is processed at the destination, and the AV becomes idle. An idle AV checks if the TW is still active before checking the CS for a new job.

Colour coding in Figure 3.2 visualizes these connections between the AV and container, where blue represents waiting for container arrival, green denotes waiting for the start of the TW, and orange signifies waiting for the event of an AV becoming idle. The yellow blocks represent the container handling processes, including transportation and handling at the LH. The check for active TWs can be left out if a logistic concept without TWs is implemented. The process of an AV becomes simple and connects with the CS every time it becomes idle.

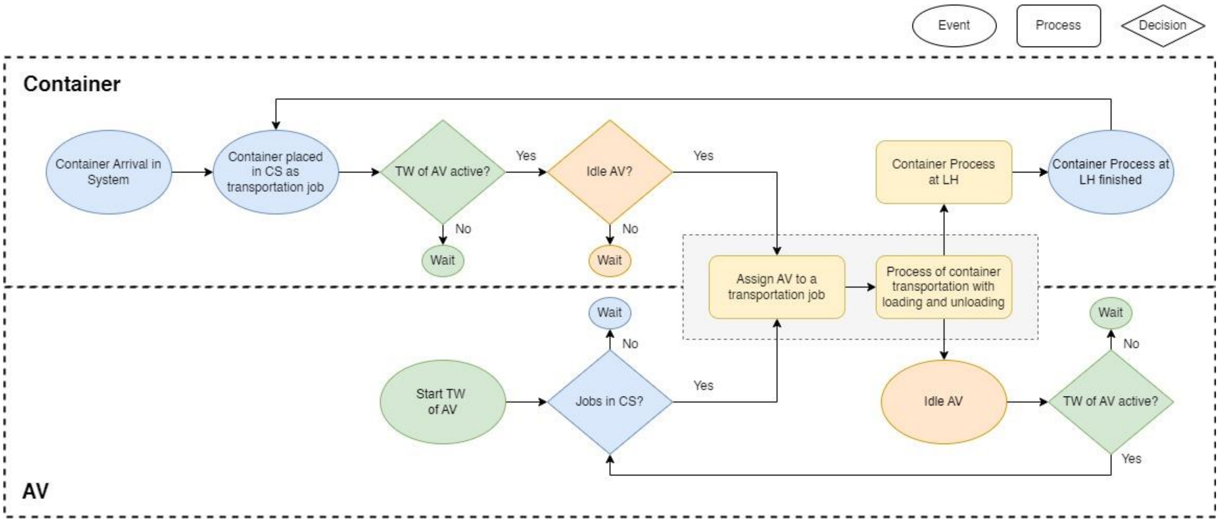

Figure 3.2: Overview of container and AV interaction with the CS

Figure 3.3 illustrates the detailed process of the interaction of the AV with the CS. At the start of the AV TW, the AV, while idle, checks the CS for jobs at its current location. When no jobs are available at that location, the AV checks the CS for available jobs at other locations. Available jobs are sorted on arrival time, and the job with the earliest arrival time is assigned to the AV. The job gets removed from the CS and the AV picks up the container for transport to its destination. When the AV is unloaded and the AV TW is still active, the AV will check the CS for the next job. When there are no available jobs in the CS, the AV needs to wait for a container arrival to trigger the CS, this is represented by the dotted line in Figure 3.3, as the AV does not influence this event, since it is triggered by an external connection to the CS. When the TW is finished, the AV goes back to its idle area to wait for the next TW to start.

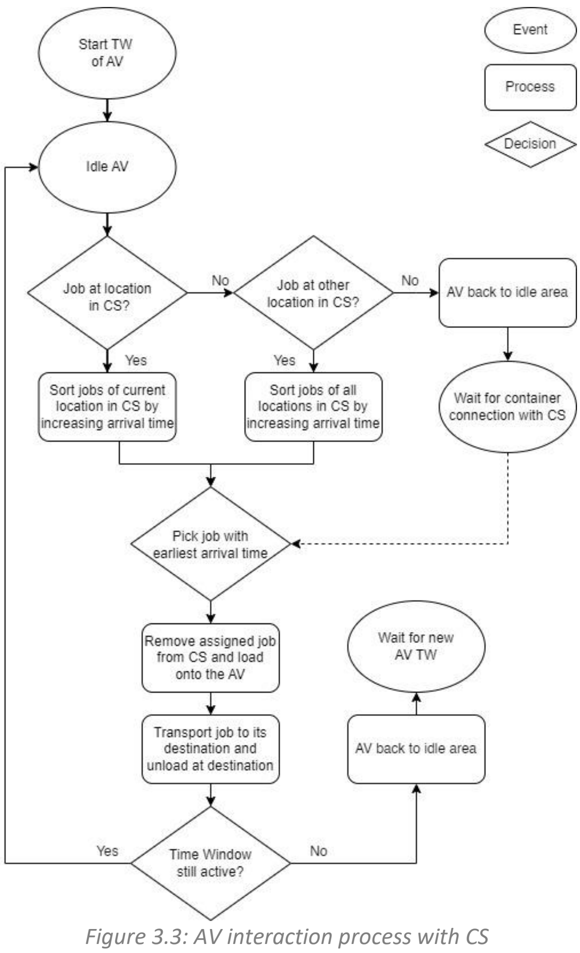

Figure 3.3: AV interaction process with CS

Figure 3.4 illustrates how the containers interact with the system. The containers arrive in the system through external transportation. If the container has a destination within the hub-to-hub environment, the container is placed within the CS. The container remains in the storage area of the arrival hub until it gets assigned to an AV for transport. This is indicated by a dotted line since this event is triggered by an external connection of the AV with CS. Once the container is assigned to an AV, it is picked up at its location and transported to its destination. After the process at its destination is finished the container needs to go back to its arriving hub, it is put back into the CS and waits until it gets assigned to an AV again. At its destination, it is put in the storage space until transportation out of the system.

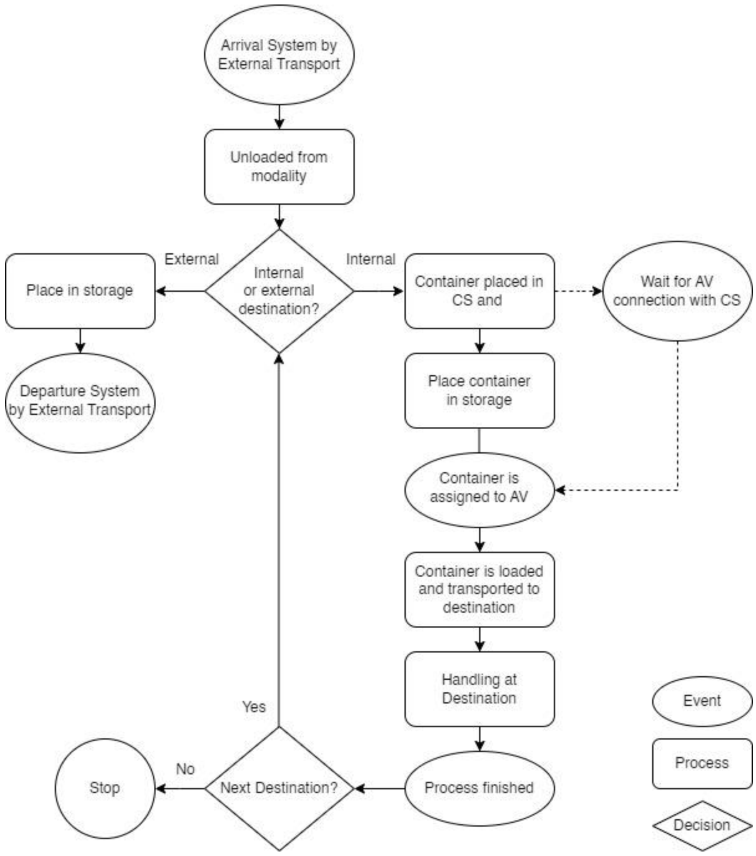

Figure 3.4: Container interaction process with CS

3.4 CONCLUSIONS

Simulation serves as a powerful tool to understand, manage, and improve complex systems. It models a system as it processes through time, enabling the examination of possible future scenarios. This research develops a discrete-event simulation of a hub-to-hub environment to evaluate the system performance after the implementation of CAT. Simulation is an appropriate tool to experiment with future scenarios in the complexity of a stochastic system, while it processes through time.

The challenge of implementing CAT in hub-to-hub environments is that most hub-to-hub environments contain public roads used for container transport from one hub to the other, which raises challenges for automating these flows while AVs are restricted on public roads. The simulation addresses the third dimension of the taxonomy, where AVs and conventional traffic are separated by time on public roads, and studies its impact on conventional traffic. TWs are introduced where AVs are allowed to drive on public roads while conventional traffic is parked until the end of the TWs.

The KPIs defined to evaluate the impact on the system are the fraction of delayed traffic, terminal time of containers, call time of containers, and jobs left in the CS at the end of each day. The research objective is to minimize the impact of delayed traffic while being able to handle the internal transportation flow within reasonable handling times.

The model inputs are defined per building block which are designed by the characteristics of hub-to-hub environments. The building blocks described with their input variables are the hub-to-hub environment, LHs, transportation flows and a CS. Assumptions made in the model include container information, input variables, external transportation flows, and the operation of the AVs.

The model content provides a visualization of the entire system and illustrates the connections between the building blocks. Central to this structure is the CS, which regulates the internal transportation flow. Both containers and AV connect to the CS when they are available for transportation, and through the CS, a container gets assigned to an AV. The detailed processes outlined for AV interactions with the CS and container movements offer clarity on system dynamics.

4. BUSINESS CASE

This chapter describes the business case of XL Park in Almelo. The implementation of automated transport is currently investigated in this hub-to-hub environment. Section 4.1 introduces the XL Park and the vision of the park is described. The characteristics of the hub-to-hub environment of the XL Park are determined in Section 4.2 and specific challenges for implementing CAT in this environment are established in Section 4.3. The information from this business case is used as input for the conceptual model described in Chapter 3, so the impact of the implementation of CAT can be tested on an existing hub-to-hub environment.

4.1 INTRODUCTION XL PARK

The XL Park is an up-and-coming industrial area located in Almelo, in the east of the Netherlands. This XL Park is accessible via road, water, rail, and air and its ideal location in the European traffic network allows for an efficient logistic flow of goods. The XL Park was built on the Twentekanaal, which allowed Combi Terminal Twente (CTT) to expand its business from Hengelo to Almelo. With a container terminal present, the park became more attractive to companies and logistic service providers.

4.1.1 Case description

The XL Park is still in development, which means opportunities arise to make future-proof logistics decisions within the park. The goal of the XL Park is to get into the top three logistical hotspots of the Netherlands out of a list of the existing 28. The XL Park is in the Twente region (Almelo – Hengelo – Enschede). The election for "best logistical hotspot" is an initiative of logistiek.nl. Every year, several experts (34 last year), e.g., logistics real estate developers, brokers, location consultants, logistics service providers, and shippers, are asked for their opinions on proven logistics locations. The jury assesses the locations based on the following criteria:

- Availability of suitable personnel
- Availability of sufficient building land and suitable buildings
- Cooperation from government/municipalities
- Employability and motivation of employees
- Presence of good infrastructure
- Accessibility of logistics hubs (modalities such as motorways, rail, water, and airport)

Last year, the XL Park ranked sixth on this list of 28 logistical hotspots. At the top of this list are some strong logistical hotspots and it will be hard for the XL Park to beat these hotspots in some of these indicators. That is why this park wants to outperform into being more innovative and is looking into fully automating the transport in the park, to be the first logistical hotspot having automated vehicles driving on the public road.

CTT believes that the physical internet will be the future of logistics, and to anticipate these changes, the park needs to be prepared to get connected to this network in the future. To achieve this, transport and data exchange needs to be self-organizing and fully automated and aim for a self-organizing system. This way, the park can operate 24/7 and is not dependent on the working hours of the employees. Nonetheless, automation should create new tasks for employees related to operations, flows, surveillance and logistics planning (ERTRAC, 2019b). With the introduction of highly automated vehicles, other new decisions can be made, for example, how to be more sustainable, choosing electricity or hydrogen as a fuel for the new vehicles and reducing the kilometres driven by trucks.

This business case is about the transport on the XL Park, between CTT and other logistics hubs on the park. We can identify this kind of transport as hub-to-hub transport. In the next paragraph, the current situation is explained together with the challenges that come with automating the hub-to-hub transport on the XL Park.

4.2 CHARACTERISTICS OF THE XL PARK

This section provides an overview of the XL Park's key characteristics, based on the different building blocks of the conceptual model outlined in Section 3.3, presenting the information in the structure of the conceptual model.

4.2.1 Hub-to-hub environment

Figure 4.1: Map of XL Businesspark Almelo

The current layout of the XL Park is shown in Figure 4.1. The only entrance into the park for traffic is at the north side of the park, right next to the highway entrance. This gives more opportunities for implementing CAT since the park can be (temporarily) closed off. Therefore, the roads are only used by traffic with a destination in the park, as there is no passage through the park to external destinations.

CTT is on the left of the map, located next to the Twentekanaal. At this moment, the transport on the XL Park is only between CTT and Timberland, and CTT and Bleckmann. Timberland is on the right side of the map, next to the A35 highway. Bleckmann is in the Heylen Warehouses, shown on the map as "vtech". Most lots on the map are still in development but are future customers of CTT Almelo, e.g., VDL Energy Systems, on the end of the right side of the map and Kees Smit, next to the Heylen Warehouses. There are two modalities in use, a waterway to CTT where barges arrive and public roads where trucks drive for external transportation.

4.2.2 Terminal

At the terminal CTT Almelo, barges arrive at most once a day and the containers switch between modalities. Trucks enter CTT to pick up containers for external transport, or the containers are transported with manned terminal tractors (TTs) to LHs at the business park. Barges arrive from Rotterdam or Hengelo and return to those terminals. The terminal has one quay crane, but room to expand to two. The containers are stored in the space directly under the quay crane and the truck lane is directly next to the storage space. The handling of the crane operator can be split into the following tasks:

1. Unload containers of a barge
    a. Put the container on the stack
    b. Load the container on an empty chassis, so the TT can transport the container into the XL Park
    c. Load the container on an empty truck that is waiting on the truck lane
2. Load containers on the barge
    a. From the stacks
    b. From a truck in the truck lane
    c. From a chassis next to the truck lane
3. Load containers from the stack
    a. To an empty chassis

   b. To a truck waiting in the truck lane
4. Unload containers to the stack
   a. From a chassis
   b. From a truck in the truck lane
5. Move containers between trucks and chassis

In Figure 4.2 the layout of the quay of CTT is shown.

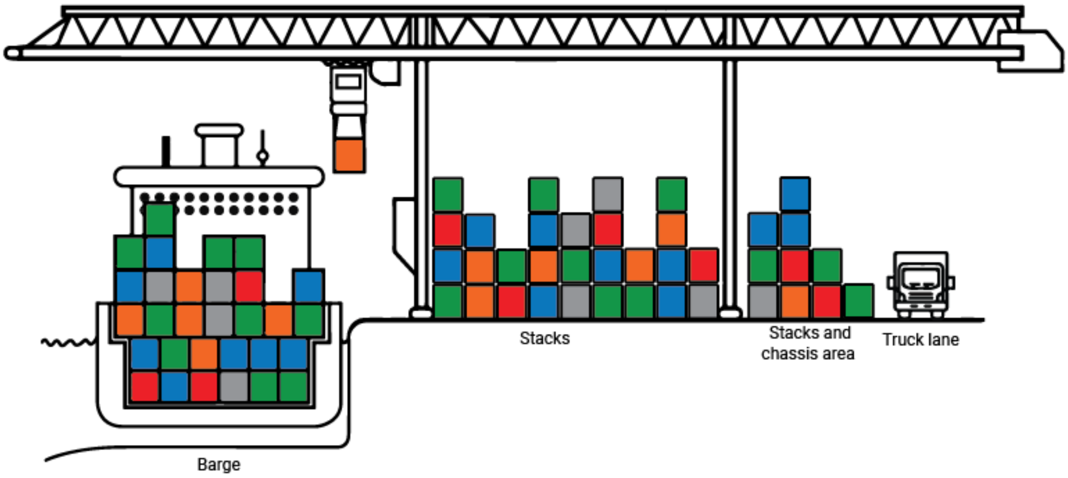

Figure 4.1 Quay layout at CTT Almelo

The handling of one container by the crane takes about five minutes, the containers need to be secured to the crane before they can be lifted. When it is lowered to the quay, truck, or chassis it needs to be detached. This can all be done from the operating room at the top of the crane. For trucks, there are no extra (un)loading times, besides waiting for the crane to be free to catch the correct container.

The opening hours of CTT are generally from 07:00 – 16:00, but when a barge is scheduled to arrive outside those hours, employees will operate the crane in overtime. The barges are traced so arrival times are known, but can be variable because of the long distance, low speed, and obstacles like bridges.

Container arrival and departure data of nine moths are obtained by CTT Almelo for this research, Appendix A contains the analysis of received data. Every line in the data sheets presents the data of a container and contains all the information about the transportation flow, such as the departure location, destination, arrival and departure times, transport times by the TT, transporting barge identification and truck identification. This way, the data can easily be split into internal and external transportation flows.

4.2.3 Logistics Hubs

The LHs at the business park are growing in number, but at the start of this research, only two were operating and are taken into account. Both LHs operate under 'normal' working hours and the TT or AV cannot deliver the containers outside their opening hours. Bleckmann has around 30 docks and Timberland has around 50. However, not all docks are available for internal transport. The companies communicate to CTT which docks can be used by the TT.

4.2.4 External transport flow

Trucks that are delivering or picking up containers are for transport outside the XL Park. This truck transport is managed by Bolk, the truck transportation company of CTT. Trucks are also used to transport containers between CTT Rotterdam, CTT Hengelo, and CTT Almelo when more convenient than barge transport. For example, when a container has a tight delivery date, but there is no barge scheduled to be able to make that date. Another case is when it is not beneficial to stop in Almelo for just a few containers and then continue to Hengelo. Because it takes at least five hours to make this detour, it is more profitable to send the barge directly to Hengelo and transport the containers by truck to Almelo. However, there is no truck transport on the XL Park. Instead, the TT is dedicated to transporting the containers to and from the companies in the XL Park.

The other LHs at the business park have external transportation flows as well, but exact data or estimated numbers are not available for this research. To generate this external transportation flow, data from the highway entrance and exit sensors are used, that distinguish between the size and weight of passing vehicles.

4.2.5 Internal transport flow

The transport of containers by the TT is handled with a chassis. Figure 4.3 shows the chassis used at CTT Almelo. A container can be placed on the chassis by the crane without further human interaction. The operator of the TT can pick up the chassis by manually coupling the chassis to the TT. The tasks the operator must perform are the following:

1. Check if the container number corresponds to the correct container to transport
2. Write down the chassis number
3. Drive the TT backwards until the chassis lays on the TT
4. Couple three cables from the TT to the chassis (this takes about three seconds)
5. Put the delivery papers on the back of the container for the client
6. Transport the container to the client

Arriving at the client, the operator of the TT must do the following things:

1. Get through the gate
    a. At Timberland this works with a camera, or the operator must call the front desk to open the gate
    b. At Bleckmann the operator can open the gate with a card, stored in the door of the TT
2. Park the container at an empty dock
    a. At Timberland the operator can choose a dock to park the container
    b. At Bleckmann the operator receives a dock schedule for parking the containers
3. Decouple the chassis from the TT by
    a. Decoupling the three cables
    b. Slowly drive forward until the chassis stands on itself
4. Check if there is an empty container to take back to the terminal
    a. At Timberland this can be seen by the closed dock door
    b. At Bleckmann this can be seen by the traffic lights next to the docks.
5. If there is an empty container ready, couple the chassis to the TT, drive a little bit forward and check if the container doors are closed
6. Drive back to the terminal and park the chassis with an empty container on an empty spot in the terminal

CTT will own the vehicles, simplifying CS implementation as they already possess most transportation data. However, the LHs at the park are still reluctant to share more information and contribute to the implementation of CAT. This and more challenges are outlined in the next section.

4.3 CHALLENGES FOR AUTOMATED TRANSPORT

Introducing CAT into the XL Park is the first step in aiming for a self-organising system. However, this transition is not without challenges and changes to the system need to be made. In this section, the challenges of implementing automated transport are described.

Transporting the containers

As explained, the containers are transported over the XL Park on chassis. These chassis are fitted to the TT. When the chassis are not coupled to the TT, they can stand on their own, which makes it accessible for the crane operator to load and unload the chassis. When the container is placed on the chassis, it is automatically fixed to the chassis. The TT operator can couple the TT to the chassis by simply driving back and under the chassis. Then, lift it a bit so that the stands come off the ground. The only manual handling the operator must do is the coupling of the cables. One cable is for electricity and two cables connect the air brakes from the chassis to the TT.

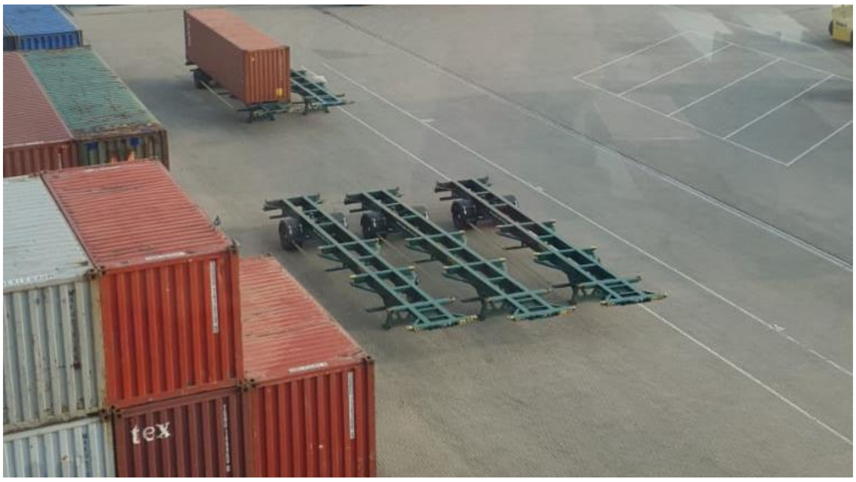

Figure 4.2 Chassis at CTT Almelo

CTT Almelo owns twenty of these chassis, depicted in Figure 4.3, and these chassis are relatively new. It is not a requirement that the new automated/AV can work with these chassis, but it would be an advantage. If the new vehicle cannot work with the chassis, it must be considered to purchase at least twenty new chassis or other systems.

Challenges at the LHs

The transport on XL Park to be automated is from CTT Almelo to the LHs on the XL Park. This means that the automated/AV needs to drive onto the terrain of the LHs. This entails a lot of challenges.

Logistical challenges

From a logistical point of view, first, the TT needs to go through a gate. At this moment, there are only two customers, and they have different systems. With new coming LHs on the XL Park, serving as clients of CTT, also new systems are introduced. The systems of the gates need to be adjusted to the new automated/AV. The yard supervisor of CTT Almelo already encounters problems with the gates when the TT operator is driving onto the terrain of the clients. One client was reluctant to grant CTT an entrance card for the gate, so the operator first had to report at the front desk, which was beyond the docks where the container had to be, turn around to go back to the docks and park the trailer, while the front desk already knew that the operator was there to deliver a container. For a client that receives around forty containers a day, this involves a lot of extra handling, but more importantly, it would more than double the time of the trip to this LH. They came to an agreement that the operator did not need to go to the desk anymore, but the front desk operator still needs to open the gate for the operator. This is not a problem for the TT operator if the front desk watches the camera and opens the gate on the arrival of the TT, but it takes extra handling if the TT operator needs to call the front desk to open the gate. At the other client, an entrance card is stored in the TT, which must be presented at the scanner at the gate to open it. For the TT operator, this is already more convenient. For an automated vehicle, both situations could become a problem. The gate systems of the clients need to cooperate with the automated vehicle so that the vehicle does not experience waiting times at the gate.

At the client, the TT operator checks if there is an empty container to take back to CTT Almelo. At one client this is indicated by a traffic light next to the docks. A new automated vehicle can have the requirement to be able to read these lights. However, at the other client, an empty container is not easily recognizable. When the personnel is finished emptying the container, they close the dock door. This is only visible through the window that is placed above the dock. For an automated vehicle, this is much harder to recognize. Besides, this system fails if the personnel forget to close the door.

A general system is required at all clients to notify whether a container is empty and therefore ready to be taken back to CTT Almelo. This new system can be a digital system, so the AV knows through connectivity that a container is ready to be taken back, or this system can work with a sign the vehicle can notice when it drives past the docks.

Other challenges
Besides logistical challenges, the planning and communication systems of CTT Almelo and its clients need to cooperate. At this moment, three challenges are observed.

First, one client still wants the physical delivery papers attached to the container when the containers are delivered. For this, human interaction needs to be involved in the transport process. For this to work with automated transport, the client needs to be convinced to get rid of paperwork and digitalize the delivery system. The delivery papers are also sent by mail, the papers are only used to check which container arrived and if all the goods are in the container.

Second, the clients can have last-minute changes in the schedule. This is now communicated by telephone. To be able to cope with this with automated transport, a collaborative digital system should be introduced for CTT Almelo and all clients on the XL Park, where last-minute changes can be picked up by the automated vehicle.

Finally, and this may be the most troubling point, at this moment, the clients do not want the containers to be delivered after working hours. The container will be left unguarded on their terrain, which makes it their responsibility. For the clients, this is not beneficial regarding safety, insurance, and e.g., fire hazards. They are now only accepting containers when personnel are present, so containers can be unloaded immediately. One of the biggest benefits of automated/autonomous transport is to be able to drive at night, so to achieve this, the clients need to get on board with this.

All these challenges can easily be solved by collaboration and good communication with the companies in the business park. These challenges cannot all be solved in this research but can be used as input restrictions for the simulation of the XL Park. Some challenges are tackled in this research by the introduction of a CS between CTT and the LHs. All containers that need transportation are added to the system and the AV knows the exact location and destination of the containers. With a CS, the LHs also know when an AV is arriving, so gates can automatically be opened and AVs do not need to have signs when a container is empty and ready for transportation back when jobs are put correctly in the CS.

4.4 CONCLUSIONS

A business case is used to identify the characteristics of hub-to-hub environments in an existing system. The XL Park is a hub-to-hub environment where repetitive internal transportation flow is carried out between a container terminal and multiple warehouses over public roads, and where different modalities are involved in the transport of containers. This describes all the characteristics of a hub-to-hub environment that make the park a perfect business case for this research. The motivation for the XL Park to investigate the automation of their internal transportation flow is to make the park more future-proof. Since the park is still in development and expanding, opportunities arise to anticipate the adaptations needed to implement CAT.

For the inputs of the conceptual model, the characteristics of the park are described following the structure of the building blocks. The environment infrastructure is laid out with the locations of all LHs, the public roads used for internal transportation and the different modalities coming into the environment. The XL Park has two kinds of LHs, the first is a terminal where the modality switch between barge, trucks, and internal transportation is made. The terminal manages the internal transportation flow in the environment, and arrival data of containers to and from the terminal are gathered as input for this research. The other LHs are warehouses with access to internal and external transportation flows, and the variables of these warehouses are gathered.
The external transportation flow is done by trucks and barges and the internal transportation flow is done by manually operated terminal tractors. The aim is to automate the internal transportation flow, so this process is evaluated to understand the challenges of implementing CAT.

Multiple challenges are identified in the XL Park, a new chassis system needs to be purchased with the introduction of AVs, so the AVs can (de)couple the chassis with containers without an operator. The other challenges are mainly at the LHs, where different systems are in place to enter the confined areas, as well as different ways of signalling when a container is ready for transportation back to the terminal. Next to that, one LH wants physical delivery papers attached to the containers and last-minute schedule changes are now communicated by phone. All these challenges could be solved by implementing a CS that connects the terminal with the LHs, the AV and the container flow. Nonetheless, the biggest restriction by the LHs is that the containers need to be delivered during working hours, dismissing TWs at night. However, night TWs would be the ideal time for AVs to operate with the least impact on conventional traffic.

In the next chapter, the defined input variables of this business case are implemented in the conceptual model described in Chapter 3. This results in a simulation model of the XL Park. Finally, experiments are designed to evaluate the impact of CAT in this hub-to-hub environment.

5. SIMULATION MODEL

This chapter describes the simulation model based on the conceptual model in Chapter 3 and with the inputs of the business case introduced in Chapter 4. Section 5.1 explains the software that the simulation is built in and describes what the different building blocks look like for the business case of the XL Park. Section 5.2 describes the process of verification and validation of the simulation and Section 5.3 explains the required experimental settings. In Section 5.4 the results of the experiments are analysed, and Section 5.5 translates the results into practical implementations for the XL Park.

5.1 COMPUTER MODEL

To translate the conceptual model and the business case into a computer model, an existing simulation developed by Brunetti et al. (2020) serves as the foundation. This simulation, designed as a general framework for smart yards is categorized in the dimension of separation by space of the taxonomy. A smart yard represents all the characteristics of a hub-to-hub environment, introducing decoupling points (DPs) to separate conventional traffic from AVs and incorporating a CS as a planning tool. The licensed discrete-event simulation software package, "Tecnomatix Plant Simulation", is used to build the computer model. This software is an object-oriented, 3D simulation environment, facilitating fast and efficient modelling of discrete and continuous processes. Animations play a crucial role in error detection, such as identifying traffic congestion and serving to visualize the simulation for the client. This section describes the computer model structured by the building blocks of the conceptual model, based on the characteristics of the hub-to-hub environment of the XL Park.

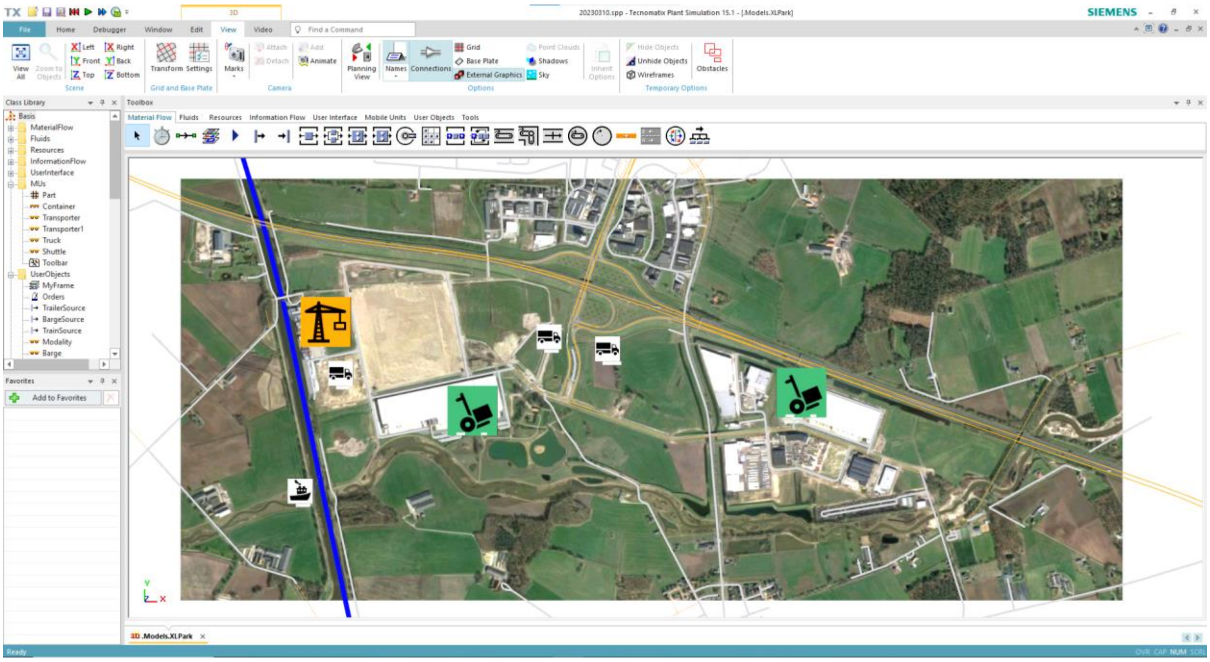

Figure 5.1 Screenshot of the environment in the computer model

5.1.1 Environment

The hub-to-hub environment in the computer model is illustrated in Figure 5.1, utilizing the map of the XL Park. This map is the foundation for the layout and infrastructure of the model, enabling the simulation of travel times and distances to closely resemble reality. The environment includes public roads for both internal and external transport by trucks and AVs, along with conventional traffic. Additionally, a waterway is connected to the terminal CTT where barges arrive. The coloured blocks represent the building blocks of the LHs and traffic and transportation flow generators.

5.1.2 Building Blocks

We distinguish two types of LHs, the terminal CTT Almelo and the warehouses Bleckmann and Timberland. The input variables are described in Section 3.2.4 and the input values for the simulation of the XL Park in Section 4.2. During the container handling process, LHs log various attributes of the containers, storing essential data for later evaluation. Appendix C summarises all input variables and values of the LHs.

5.1.3 Transportation Flows

Three external transportation flows are generated in the simulation model, barge, truck, and traffic. The method of generating barge arrivals is explained in Appendix D. Containers leaving the system by barge are not assigned to a particular barge. After the cargo of a barge is unloaded, all containers waiting in storage for external transport are loaded on the barge, taking its capacity into account.

External Truck transport arrives at the LH to drop off or pick up a container. Containers arriving at the terminal by truck can enter the internal flow and are connected to the CS. Containers intended for external transport leave by barge without interacting with the CS. Arrival distributions for the truck flow can be found in Appendix E, which are obtained from real data of CTT, elaborated in Appendix A.

Conventional traffic in this hub-to-hub environment always has a destination in the environment, so traffic is generated considering arrival in the park and stay time at one of the hubs. There is no passing through traffic on the roads in the environment. Appendix F explains the generation of traffic.

5.1.4 Connected System

The CS consists of two components, the regulation of container transport and the regulation of TWs for the AV.

Internal Container Transportation

In the simulation model, the CS is implemented as a “Job List”. The terminal, warehouses and the AVs are connected to the job list. Figure 5.2 illustrates the connection between the job list and the “methods”, i.e., coded algorithms, that assign jobs based on certain triggers, i.e., simulation events. At the terminal, three processes can put a container in the job list. First, when a barge is unloaded and the container has a destination within the park, the container is put in the job list. The same process applies to an arriving truck at the terminal. Secondly, if an AV is assigned a job at the terminal to pick up a container, but there are no chassis available, the container cannot be transported. When this happens, the AV puts the job back in the job list and checks the warehouses for available jobs. Third, at the LHs, the container is put back into the job list when the process at the warehouse is finished. Additionally, the AV has three triggers to connect to the job list and find a job: At the beginning of the AV TW the “AV Get Job”-method is called to find a job for the AV. Second, when an AV finishes a job, it becomes idle and the “AV on Idle”-method is called to find the next job to do. This is repeated until the job list is empty or the TW for the AVs has passed. Lastly, containers that enter the job list trigger the ‘AV Get Job”-method to call the AV for transportation.

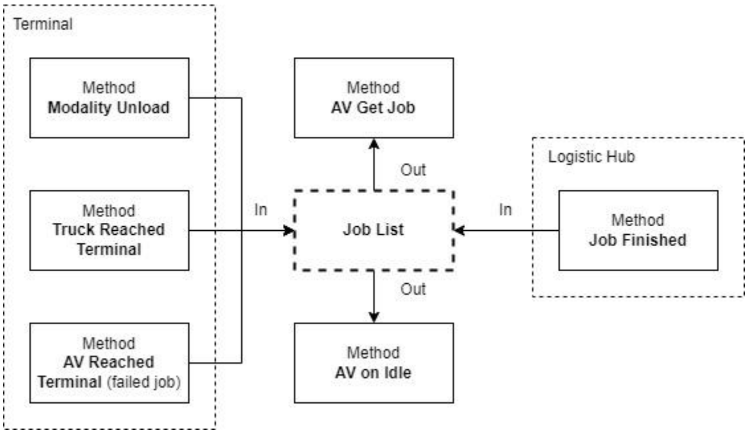

Figure 5.2: The in and outflow of containers to the CS

AV Time Windows

The schedule of the AV TWs is generated based on the experimental input. At the start of every TW, the simulation checks the schedule to determine whether roads are open for AVs or conventional traffic. If the AVs are operational, conventional traffic is directed parking placed in LHs, or at the entrance of the environment. When the TW of the AVs ends, the AV returns to its idle place and the roads open for conventional traffic.

5.1.5 Simulation Output

Different statistics of all objects that move through the simulation are saved to be able to calculate the KPI values of every experiment. Each object is provided with a table in the simulation that stores all statistics and at the end of every run, outputs are calculated for all KPIs. Further details on the statistics of objects and the calculations of KPIs can be found in Appendix B.

5.2 VERIFICATION AND VALIDATION

The computer model is explained, but the credibility and reliability of the simulation should be assessed. This is done by verifying and validating the simulation model. Verification checks if the system is accurately translated into the simulation code. Validation assesses whether the model is scientifically accurate for the purpose of the study. This section will dive into the verification and validation steps that are taken.

5.2.1 Verification Process

To verify the simulation model, Law (2014) provides different techniques that can be used. We describe the techniques used and explain how we apply them in this research.

Write and debug in modules or subprograms

The simulation model contains different building blocks, with each its connected methods, tables, and objects. This is done for simplification, by programming each part individually. This way, errors and bugs can be discovered, so they will not cause bigger problems in the whole system. The complex simulation is built from smaller simpler parts, which are easier to debug. Next to that, the building blocks are generated in a way they can be used for multiple occasions, exploiting the library objects. For example, when adding a new logistics centre, the LH building block can be used, and the input variables will set the characteristics of the LH. Moreover, thanks to the object hierarchy and inheritance, a reused frame does not need to be debugged again.

Structured walk-through of the program

Building a simulation is a complex task, and it is advised to have more than one person review the computer program to enhance the reliability of the verification process. During the process of building this simulation, a supervisor would regularly look at the computer program, to check if it runs correctly and to find overlooked bugs.

Variety of settings of the input parameters

To verify the simulation, the input parameters should be run to a variety of settings, to check what happens to the output. In section 3.2.4 the input variables are described. Three tests are done changing the settings of the input variables:

1. Double freight of barges
2. Double the intensity of conventional traffic (external trucks to LHs and cars)
3. Double the processing time of containers at the LHs

These three variables all test the performance of the simulation in different aspects, workload, traffic intensity, or extend the total time in the system. The tests are done with the same experimental settings of one AV with six TWs during the day of one hour. The warmup runs for fourteen days and the simulation runs for thirty days with ten replications. These settings ensure the reliability of the output. One run is done with normal settings of the three variables to compare with. In Table 5.1, the KPI output of the runs can be found. The fraction of traffic that is delayed does not change over the experiments, which should be the case, since the TWs do not change and they impact this KPI. Doubling the freight of barges results in higher utilization of the AVs and a higher call time for the container to be picked up at the terminal to go to the LH. A doubled process time significantly increases the call time. These conclusions prove that the model reacts correctly to the input variables.

Experiment	FracTrafficWait	TotalTerminalTime	TotalCallTime	Utilization	JobsLeft
Normal settings	0.320562766	02:01:19:22	00:18:31:09	0.671625923	6
Barge Freight	0.316828881	03:02:29:43	01:18:10:31	0.84936331	22
Conventional Traffic	0.319950668	02:04:19:47	00:18:03:25	0.665266774	7
Process Time	0.319298269	01:20:50:08	00:18:31:16	0.637838612	6

Table 5.1 KPI Output Verification Input Variables

Traces

One of the most powerful techniques to debug a discrete-event simulation is a trace, where the state of the simulated system is displayed just after each event occurs. These traces are built into the model for multiple uses. First, to check if the simulation is performing as needed, and second to track the events in the simulation for output and data analysis. Different traces are built into the simulation and saved in tables to track the statistics of all moving objects in the system. Next to that, different counters are built to track the number of generated containers, trucks, cars, and barges. In the terminal, a debug table is built. This table stores failed operations when there are no chassis available to transport a container. This way, failed operations get noticed.

Animation of the simulation

A helpful tool is to observe an animation of the simulation, to see if the simulation runs correctly. A 3D environment of the XL Businesspark is created from the beginning and by running the simulation with 3D animations, bugs can be discovered not detectable in the data. For example, by checking the animation a bug was observed at the LHs, where congestion would arise with traffic and trucks over time. The settings to enter the LHs were not correct, so no vehicle could enter the LH anymore. Next to that, the routes of the AVs were checked, just by following the AV on its way to the different hubs.

Compute sample mean and variance

For each input probability distribution, we compute the sample mean and sample variance and compare them with the desired mean and variance. The input distributions for all vehicle arrivals are compared with the output distributions in Appendix G.

Commercial Simulation Package

By using a commercial simulation package, the amount of programming can be reduced. In the software used for this model, certain tools are available to simplify the building of a simulation. Each building block is built from objects that are linked to each other by methods or even simpler, connectors. This way, only movable objects, i.e., the vehicles and containers, need to be programmed to carry out certain actions.

5.2.2 Validation Process

Robinson (2014) identifies different concepts that can be used to validate a computer model, we use the following to validate the simulation model:

Conceptual Model Validation

The simulation model is based on the conceptual model in Chapter 3 and the business case of Chapter 4. The scope, assumptions, and level of detail are described based on the real system. To determine all details, not only data is analysed, but multiple visits to the hub-to-hub environment were made, to get detailed information about the park. Simplifications and assumptions are made based on the research purpose.

Data Validation

For the most important part of the simulation, the internal transportation flow, real data is gathered, which makes the model valid for the simulation purpose. Data about the external transportation flow into the environment could not be gathered, and distributions are constructed to generate these flows. For the purpose of this simulation, exact numbers are not necessary, but the impact on conventional traffic can still be measured. The intensity of traffic has no impact on the internal transportation flows.

Black-Box Validation

Black-box validation checks if the model provides an accurate representation of the real system and if it meets the objectives of the simulation study. To do this, we examine what happens if the experimental factors change and if the output seems logical. We perform two validations, the number of TWs and the number of AVs. For each validation, three experiments of ten replications are run with a fourteen-day warmup and a thirty-day simulation run.

These settings ensure a reliable output. The TWs are set to 2, 4 and 6 windows of an hour, with one AV. We test the number of AVs with 1, 2, and 3 AVs with three TWs of an hour. The experiments on the number of TWs validate what we expect, the results are shown in Table 5.2. As the number of windows increases, the fraction of delayed conventional traffic increases. The call times of the containers decreased drastically, from more than a day to a couple of hours. The utilization of the AV decreases as expected as well as the average jobs left in the CS at the end of the day. In the simulation, the utilization can be more than one, when the AV is driving on the road transporting a container when the TW is ending. The AV will finish its route, driving in overtime and causing the utilization to be more than 1.

ExpNr	FracCarWait	AvgCarWait	CallTimeOne	CallTimeTwo	Utilization	JobsLeft
1	0.142597	00:20:16	02:06:14:15	01:00:53:44	1.027458	108
2	0.2254	00:20:32	01:15:48:06	00:16:20:04	0.856723	20
3	0.305299	00:20:44	00:13:31:41	00:04:59:28	0.617849	7

Table 5.2 Black-Box Validation on Time Windows

The results of the experiments with the number of AVs are shown in Table 5.3. The number of AVs has no impact on conventional traffic as the TWs stay the same. The call times for the containers decrease again from days to hours. The utilization and jobs left in the CS decrease, which validates the accuracy of the model.

ExpNr	FracCarWait	AvgCarWait	CallTimeOne	CallTimeTwo	Utilization	JobsLeft
1	0.251043741	00:20:11	02:18:00:54	01:05:14:51	0.980306534	34
2	0.255245477	00:20:27	00:17:11:50	00:13:39:16	0.704446372	10
3	0.253804495	00:20:21	00:14:53:31	00:10:41:08	0.594052739	8

Table 5.3 Black-Box Validation on Number of AVs

5.3 EXPERIMENTAL SETTINGS

After the verification and validation of the model, the experiments can be executed. The experimental factors are first described, and then the warm-up period, simulation run length, and the number of replications is calculated. The experimental configuration describes the design of the experiments.

5.3.1 Experimental Factors

To evaluate the impact of the CS in hub-to-hub environments, the input variables of the CS are used as the experimental factors. The two input variables are the number of AVs and the number and duration of the TWs of the AVs.

Number of AVs

In the current situation of the business case, only one vehicle is needed for the internal transportation flow. With the expansion of the park in mind, the future purchase of a second vehicle is under consideration. To see if a second vehicle would benefit the park, the number of AVs is set to 1 and 2 in the experiments.

Time windows

The TWs for the AV can vary in duration, amount, and moment of the day. For the duration of the TWs to experiment with, two settings are chosen: one-hour TWs and half-hour TWs. First, experiments are carried out with the one-hour TWs, with the number of windows ranging from one to twelve. For the half-hour windows, another twelve experiments are carried out, based on the most promising results of the one-hour window experiments. The moment of the day has a great impact on conventional traffic, since less to no traffic drives over the park at night. In the experiments, the TWs will be evenly divided over the day. For the business case, it is a constraint to carry out the internal transportation during the opening hours of the LHs. To get the best results of the impact of the TWs, with the best configurations of the number of windows, the timing of windows is experimented with.

5.3.2 Warm-up period

Determining a warm-up period for a discrete event simulation is essential for ensuring the accuracy and validity of the simulation results. The warm-up period is the initial portion of the simulation run during which the system is allowed to stabilize or reach a steady-state condition before data collection begins. Welch's method is a graphical approach to determine the warm-up period for a steady-state simulation. To collect data for the calculations of the warm-up period, the simulation is run once for 200 days and the average call time of the containers is saved every hour. We divide the collected data into multiple overlapping time intervals, by calculating the weighted average of the time intervals (5 hours, 10 hours, 25 hours and 50 hours). These averages together with the initial call time averages are plotted in a graph, shown in Figure 5.3. With visual inspection, it can be seen that the simulation reached a steady state when the graph crosses 25000 on the y-axis. The first point the graph crosses that threshold is at 310 hours, which is almost 13 days. The simulation distinguishes between the days of the week, so we chose a warm-up period of 14 days. For the simulation length, we use a simple rule of thumb of three times the warm-up period, so 42 days. Therefore, the total simulation length will be 56 days.

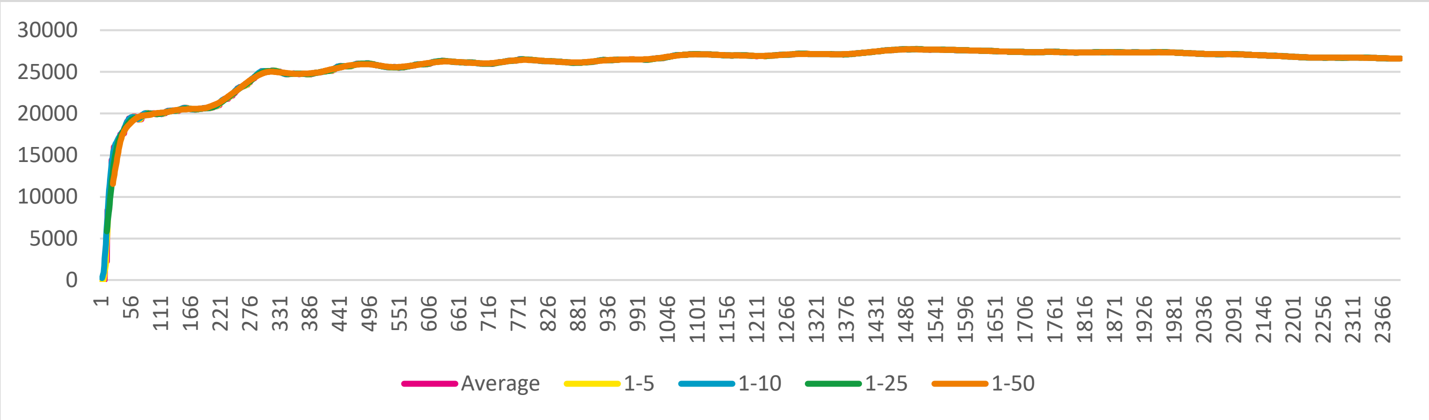

Figure 5.3 Welch's procedure for Warm-up Period

To ensure the reliability of results, it is necessary to conduct multiple replications, to establish a confidence interval with a specific level of relative error. We use a standard significance level of 95% and a relative error of 5%. For the calculations of the number of replications, one experiment is performed with the warm-up period and simulation length stated above and with twenty replications. Again, we use the KPI call time and Appendix H provides the table with detailed computations for the number of replications. As can be seen, after eight replications, the relative error fell below the threshold. The number of replications is set to 10 for the experiments, so we have an even smaller error and a higher confidence level.

5.3.4 Experimental Configurations

The experimental configurations are defined by the TW schedule for the AV. To determine the TWs, a schedule is made of two columns, the first column presenting the TWs for the AV, where a "1" determines the TW of the AV and a "0" means the AV is not allowed to drive. The second column represents open roads for conventional traffic, the rows of the schedule can only contain one "1", which makes the separation of conventional traffic and autonomous traffic on the route. If a row contains a "1" in both columns, both conventional and autonomous traffic are triggered to access the roads. If a row contains a "0" in both columns, no vehicle is allowed to enter the roads. Table 5.4 gives an example of the TW schedule with six One-Hour TWs, evenly distributed over the day. The complete experimental design can be found in Appendix I. The experiments are divided into different topics.

One-hour TWs

The first batch of experiments is done with one-hour TWs for the AV, distributed evenly over the day. These experiments are run twice, first with one AV and next with two AVs. The TWs are distributed evenly over the day. The outputs of these experiments are used to determine the optimal number of TWs of one hour for 1 AV. The outputs of the experiments with 1 AV are compared to the outputs of 2 AVs, to determine if a second AV would benefit the XL Park.

Half-hour TWs

The second batch runs half-hour TWs, ranging from 4 to 15 TWs per day. The TWs are evenly distributed over the day, these experiments are also run twice, with one and two AVs. The outputs of these experiments are compared to the outputs of the first batch, matching the total hours of TWs in a day to establish the difference in impact on the system of the duration of the TWs.

Day and Night

With the best configurations of the first two batches and the number of AVs, experiments are run with varying TWs planning of day and night. The internal transportation in the current system is only done during working hours, so the first experiment is designed with TWs only between 07:00 and 18:00. The second experiment distributes the TWs between 19:00 and 07:00. With the output of the experiments is evaluated what the difference of impact is if AVs can operate at any time of the day.

TW	AV	Conventional
00:00	1	0
01:00	0	1
02:00	0	1
03:00	0	1
04:00	1	0
05:00	0	1
06:00	0	1
07:00	0	1
08:00	1	0
09:00	0	1
10:00	0	1
11:00	0	1
12:00	1	0
13:00	0	1
14:00	0	1
15:00	0	1
16:00	1	0
17:00	0	1
18:00	0	1
19:00	0	1
20:00	1	0
21:00	0	1
22:00	0	1
23:00	0	1

Table 5.4 Input Table for the Experiment with Six One-Hour TWs

5.4 ANALYSIS OF EXPERIMENTAL RESULTS

The experiments described in Section 5.3.4 are performed and the results are analysed in this section. The results are based on the inputs of the business case, but general conclusions can be drawn for the purpose of this research, this will be evaluated in the next chapter.

5.4.1 Number of AVs

Considering the same number of TWs, the impact on the fraction of delayed traffic remains consistent regardless of the number of AVs. A second AV would only be beneficial to the fraction of delayed traffic if the number of TWs can significantly be reduced. In Figure 5.4, the utilization is shown for one-hour TWs ranging from 1 to 12 evenly divided over the day. Assuming one AV can efficiently handle the entire workload in a single TW with 100% utilization, the expectation is that two AVs would perform at 50% utilization with the same workload and TW duration since each AV would share half the workload. To assess the potential benefits of a second AV, we conduct the same experiments with one AV and again with two AVs, comparing the utilization output for the same number of TWs. The average utilization of both AVs is considered for the experiments with two AVs.

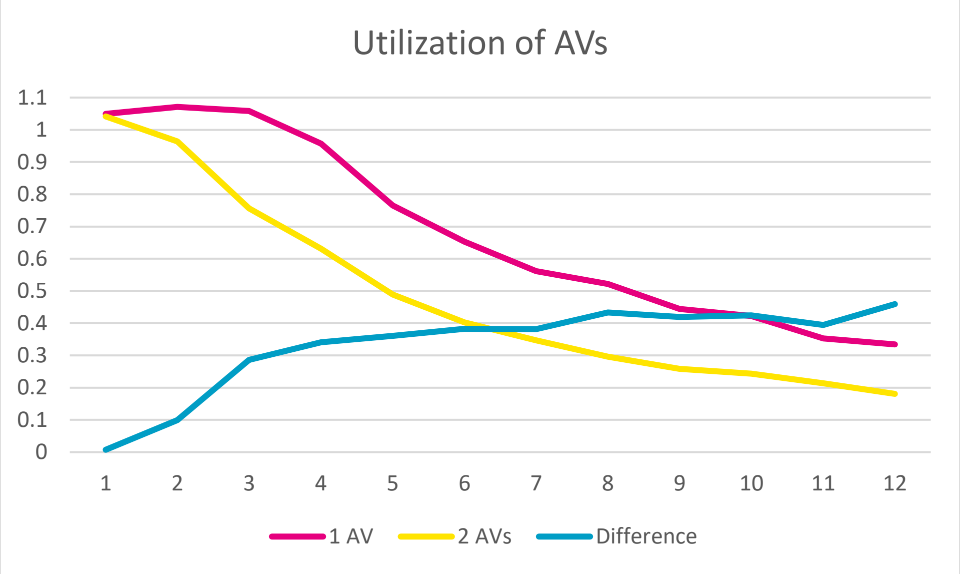

Figure 5.4: AV Utilization Output Comparison for One-Hour TWs

Figure 5.4 visually represents the percentage difference between the utilization of one AV and the average utilization of two AVs performing the same workload within the same number of TWs. The blue line indicates the threshold of 0.5, where a second AV becomes effective. However, the results reveal that, even with six or more TWs, the difference never reaches the 0.5 line. Consequently, we conclude that, for one-hour TWs, the operation of a second AV does not yield substantial benefits. The experiment indicates that with four or more TWs, one AV is capable of managing the given workload.

Comparing the total terminal time and total call time, presented in Table 5.5, results in the same conclusion. The first four experiments show a big difference between one or two AVs, but from 5 TWs or more, the values of these KPIs are not significantly different. This leads to the conclusion that employing two AVs does not reduce the handling time of containers and, therefore, does not significantly benefit the main operation of the system.

When we look at the half-hour TW, we see the same trend in the difference in utilization and likewise, does not reach the 0.5 threshold, but a steady state of 0.4 percentage difference. Figure 5.5 shows the comparison between the utilization of 1 AV and 2 AVs for the same number of TWs per experiment. The x-axis shows the number of half-hour TWs over the day and the y-axis the utilization. The increase in the utilization in the last three experiments is analysed in the next section.

No. TWs	Total Terminal Time		Total Call Time	
	1 AV	*2 AVs*	*1 AV*	*2 AVs*
1	19:00:01:01	06:10:10:19	18:05:03:50	08:19:25:35
2	04:15:57:05	06:02:43:54	04:13:04:22	06:02:19:37
3	07:09:24:04	02:08:09:20	07:08:42:12	01:06:25:04
4	03:00:58:48	01:18:15:16	02:06:25:34	00:20:00:50
5	02:04:43:08	01:19:57:25	01:01:24:38	00:11:51:16
6	02:01:53:17	01:22:44:09	00:17:40:34	00:09:26:19
7	02:02:54:53	02:01:10:29	00:14:03:45	00:07:42:03
8	01:23:30:02	01:21:12:54	00:11:50:47	00:06:13:08
9	01:17:31:28	01:18:16:10	00:09:03:14	00:04:54:38
10	01:20:50:30	01:17:06:17	00:08:04:24	00:04:25:26
11	01:22:56:20	01:17:24:51	00:06:21:17	00:03:45:29
12	01:21:58:22	01:20:28:05	00:06:13:10	00:03:28:12

Table 5.5: TotalTerminalTime and TotalCallTime results for one-hour TWs

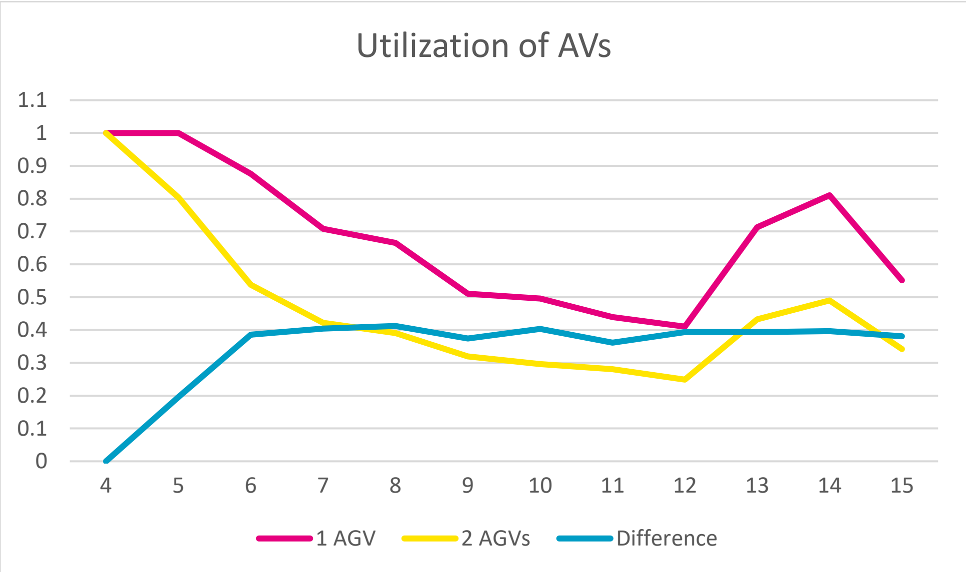

Figure 5.5 AV Utilization Output Comparison for Half-Hour TWs

5.4.2 Duration of TWs

For the analysis of the duration of the TWs, we use the outputs of the experiments with 1 AV and compare the one-hour TWs with the half-hour TWs by total time of TWs per day. We compare the results of four experiments, ranging from 3 to 6 hours of total time of TWs per day. We must keep in mind that the number of TWs for the half-hour TWs is double the amount of the one-hour TWs, and the experimental settings distribute the TWs evenly over the day. For determining the most efficient duration of the TWs, we compare the fraction of delayed traffic with the utilization of the AVs. Figure 5.6 is the graphical visualisation of the fraction of delayed traffic. The x-axis represents the total hours of TWs over the day, which means either 3 to 6 one-hour TWs or 6 to 12 half-hour TWs. The y-axis represents the fraction of delayed traffic. The impact on the delay is about 10% higher with half-hour TWs for the total time of TWs. From the fraction of delayed traffic, we conclude that one-hour TWs are more efficient than half-hour TWs.

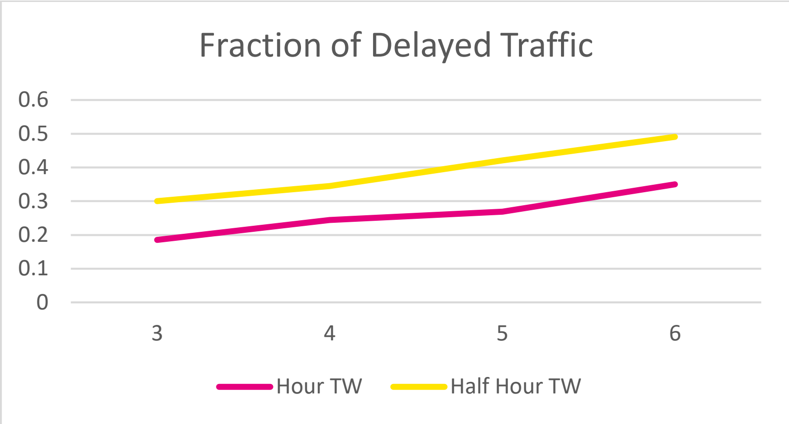

Figure 5.6 Fraction of Delayed Traffic comparison for duration TWs

Figure 5.7 displays the comparison of the utilization of the AV for one-hour TWs and half-hour TWs. For the total time of TWs between three and six hours, we see that the utilization of the half-hour TWs is lower than with one-hour TWs. We want to use the AV efficiently over the TWs, so the utilization should be kept high. If the utilization of the AV is 40%, It means that for 60% of the possible operating time the AV is idle and traffic is delayed for nothing. With one-hour TWs, the use of AVs is more efficient than with half-hour TWs.

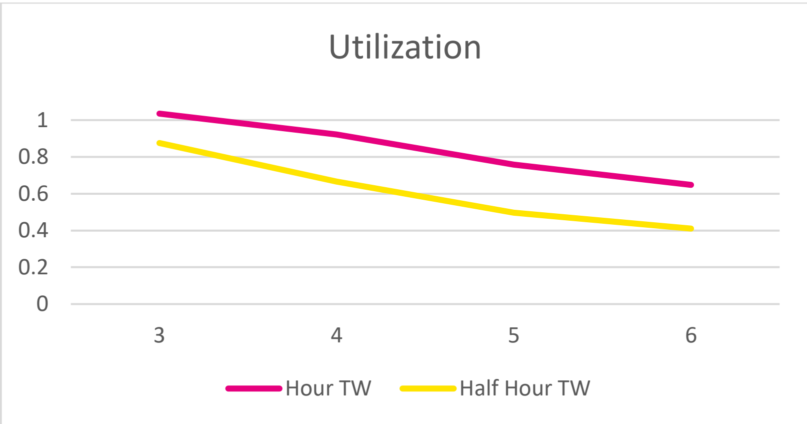

Figure 5.7 AV Utilization comparison for duration TWs

In Appendix J, all outputs for the comparison of the duration of TWs can be found. The call time and terminal time are both lower with half-hour TWs, the cause of this can be the spreading of the TWs over the day. With half-hour TWs, the interval between the TWs is half the time of the interval between one-hour TWs, which means that the call time can be three hours instead of six when a container is put in the CS at the end of the TW, significantly reducing the call time. Due to the significant impact of the spreading of the TWs on the call time and terminal time, the scheduling of the TWs in these experiments may not yield a reliable conclusion. A better approach is to schedule the 3 hours of TWs (so 3 or 6 TWs, depending on the duration) during the working day.

5.4.3 Number of TWs

Table 5.7 provides the output of all KPIs of the experiments with one-hour TWs and 1 AV.

No TW	FracDelayedT	TotalTerminalTime	TotalCallTime	Utilization	JobsLeft
1	0.144553868	19:00:01:01	18:05:03:50	1.041399019	286
2	0.180559686	04:15:57:05	04:13:04:22	1.070915933	173
3	0.18526356	07:09:24:04	07:08:42:12	1.058530089	92
4	0.24466445	03:00:58:48	02:06:25:34	0.957217234	28
5	0.26847089	02:04:43:08	01:01:24:38	0.764686867	11
6	0.350008517	02:01:53:17	00:17:40:34	0.652422872	8

7	0.36661736	02:02:54:53	00:14:03:45	0.561298161	6
8	0.397217487	01:23:30:02	00:11:50:47	0.521963341	5
9	0.435960401	01:17:31:28	00:09:03:14	0.444418285	3
10	0.46311535	01:20:50:30	00:08:04:24	0.42250383	3
11	0.495429035	01:22:56:20	00:06:21:17	0.353190451	2
12	0.548186056	01:21:58:22	00:06:13:10	0.334137803	2

Table 5.6 KPI Output One-Hour TWs

The visualization of all KPIs can be found in Appendix K. The fraction of delayed traffic gradually increases from the number of TWs of six, after a stronger increase between 5 TWs and 6 TWs. The terminal time and call time are with 1 TW extremely high, but from 2 TWs, they decrease slowly and seem to come into a steady state with 5 TWs and more. The utilization of the AV is more than one with 1 to 3 TWs, showing that the workload is too high for the AV. However, we do not want the utilization to become too low, since the AV would be idle during the TWs and traffic is delayed for nothing. After the amount of 4 TWs, the utilization becomes lower than 80%. Utilization between 80% and 90% is usually optimal, but we want to be able to respond to future growth in container transport, so utilization should be between 75% and 80%. The average number of jobs left in de CS at the end of the day decreases rapidly in the first four experiments. After the fifth experiment, it seems to achieve a steady state. Putting these findings together, the optimal number of TWs is 5.

5.4.4 Moment of TWs

After the optimal number of TWs is determined at 5, we want to explore the impact of the timing of the TWs. In these experiments, the TWs are divided evenly over the day, only during working hours and during the night. The output is these experiments can be found in Table 5.8.

Moment	FracDelayedT	TerminalTime	CallTime	Utilization	JobsLeft
Evenly	0.344622807	02:06:33:03	00:20:17:08	0.66531754	9
Day	0.315388994	02:22:06:14	02:08:43:07	0.942478495	28
Night	0.086725379	02:00:21:05	01:06:32:10	0.759129152	12

Table 5.7 Output for Moment of TW

As we can see, only the fraction of delayed traffic changes in these experiments, while the other KPIs stay practically the same. As we look at the fraction of delayed traffic, there is an increase when the TWs are scheduled only during working hours instead of evenly distributed over the whole day. However, compared to the first two experiments, planning the TWs at night has a low impact on the amount of traffic that encounters delays.

5.4.5 Comparison with the Current System

To compare the future scenario of automated transportation with the current system, TTs are introduced to the model to simulate the current system. Conventional traffic does not experience delay, since TTs and conventional traffic can use public roads together. Table 5.9 presents the KPI output of the current system, in which TTs operate between 07:00 and 16:00. Notably, this results in a short call time since TT operators can instantly pick up finished containers at the LHs. The utilization of the TT is slightly more than 10%, which is expected given the total operating time of the TT is nine consecutive hours, compared to the optimal five hours of TWs for AVs divided over the whole day. However, it's important to note that the calculation of utilization is adjusted to the use of TWs, making it unsuitable for TT utilization and comparison with AV utilization. Additionally, the comparison with the real system is challenging based on the KPIs determined in this research. The impact on conventional traffic is measured by delay, while in the current system, conventional traffic might be impacted by travel time, given that the speed of the TT is lower than normal vehicles. The main operation of the system, internal transportation, can be executed throughout the entire working day, making the current system more efficient based on these KPIs. However, it's emphasized that the decision to automate internal transportation is driven by other goals, as explained in Section 4.1.1, and these objectives cannot be adequately measured by the KPIs used in this research.

TotalTerminalTime	TotalCallTime	Utilization	JobsLeft
01:17:44:16	07:40:21	0.10881953	3

Table 5.8 KPI Output of Current System

5.5 IMPLEMENTATION OF CAT IN THE XL PARK

With the analysis of results, the practical implementations of CAT are described for the XL Park. We will describe the implementations by the characteristics of the hub-to-hub environment and the corresponding experiment results are used to evaluate the impact on the system.

5.5.1 Environment

The environment requires certain adaptations to facilitate the implementation of CAT in the XL Park. During the investigation into different TWs for AVs and conventional traffic, considerations for road closures within the park were examined. Given the park's infrastructure, a single entrance and exit, implementing road closures can be achieved using traffic lights or barriers. A designated carpool space has been established at the park's entrance, which can serve as a buffer for conventional traffic to wait until the roads reopen. These adjustments have a relatively minor impact on the park's infrastructure. However, addressing the human factor in this implementation is crucial. Clear and accurate information regarding the park's accessibility must be communicated effectively. This is particularly important for conventional traffic operators and visitors, as their schedules may be impacted. To address this concern, establishing fixed TWs during the day or shorter TW durations to minimize delays is recommended. Additionally, exploring flexible TW schedules for conventional traffic, supported by digital signals or mobile applications, could enhance adaptability. Such measures aim to not only optimize operational efficiency but also mitigate disruptions to conventional traffic.

5.5.2 Terminal

At the XL Park, CTT currently manages internal transportation using manually operated TTs. As the initiator of the automation of internal transport, CTT will take ownership of the AVs, which consequently gives CTT the responsibility for managing the implementation of the CS. The CS will require integration with CTT's existing systems, translating the overview of all containers that need transportation into a CS. This adaptation represents a significant change for CTT in achieving the implementation of CAT. In addition to the CS, significant changes are needed in the physical systems. To maximize the efficiency of AVs, they must be capable of (de)coupling containers without operator assistance. Implementing such a system is expected to be the most expensive part of the investment. This involves purchasing AVs equipped with charging stations and renewing chassis. For effective operation, trackers need to be installed in containers. This requirement extends not only to CTT's containers but also to those used by LHs. It's important to note that if the crane remains a manually operated system, AVs can only operate during the working hours of CTT, which as we have seen, results in a bigger impact on conventional traffic.

5.5.3 LHs

In Chapter 4, most challenges of implementing CAT were found at the LHs. The different handling systems of the LH need to be adjusted to the AVs. The gates of the LHs, but also the different docks need to be connected to the CS, so the AV can operate without the interference of humans. Furthermore, the LHs need to change their communication system to the CS, which impacts the use of delivery papers, communication of last-minute priority jobs and dock allocation for the containers. However, a CS can improve these factors since all information is updated every moment of the day and accessible for all LHs connected to the system. This includes details on when a container is scheduled to arrive at a specific dock throughout the day. This real-time traceability has the potential to optimize internal LH operations, enhancing efficiency and resource utilization. It is essential, however, for LHs to embrace a collaborative approach and be willing to participate in a system where information sharing is crucial to its success.

5.5.4 Connected System

Connectivity is currently represented in the model through the CS, which maintains a list of containers requiring transportation to different locations within the system. However, implementing connectivity in the actual system poses more complexity. In addition to managing internal transportation, it involves integrating all physical barriers the AV encounters during internal transportation. This includes the crane that loads the containers on the chassis, a system that determines the TW and triggers the AV to operate, the road system to open and close the roads, the gates of the LH, all incoming and outgoing containers, and monitoring conventional traffic on the roads. More importantly, real-time availability of all this information is essential. An advanced system could utilize connectivity to enhance efficiency. For instance, if the park's infrastructure is interconnected, it could detect road congestion, enabling AVs to avoid congested routes or delay jobs when LHs are inaccessible. While this vision holds great potential, further research is required to design and implement such a connected-to-everything system.

At this moment, container transportation relies on manually operated TTs. This system can still be in place with the introduction of CAT. For instance, if TWs are all scheduled during the night, but an LH needs a container with urgency during the day, employees of CTT could manually operate TTs for priority container transport. This solution could facilitate the gradual implementation of CAT in the XL Park. The CS should also allow manual adjustments for operators when intervention becomes necessary in the system. This adaptability ensures a smooth transition and accommodates scenarios where human intervention is essential.

6. CONCLUSIONS AND RECOMMENDATIONS

In this chapter, this research is concluded by answering the research questions in Section 6.1. Section 6.2 discusses the challenges and limitations of this research and Section 6.3 presents the general recommendations obtained from this research.

6.1 CONCLUSIONS

To formulate the conclusions of this research, we will answer the research questions stated in Section 1.3.

6.1.1 Characteristics of Hub-to-Hub Environments

Hub-to-hub logistics is defined as the transportation flow between LHs. LHs are defined as hubs that have a logistics operation as the distribution, transport, or storage of freight. A hub-to-hub environment is a designated area containing multiple LHs that are connected by a repetitive internal transportation flow. The hub-to-hub environment is connected to different modalities that provide an external transportation flow into the environment. Transportation is done over public roads which complicates the implementation of CAT.

6.1.2 Logistic Concepts of Mixed Traffic

The logistics concepts of mixed traffic, particularly in the context of CAT, are investigated by examining two key components: connectivity and automation. Connectivity identifies four different dimensions, vehicle to vehicle, vehicle to infrastructure, infrastructure to vehicle, and vehicle to anything. These dimensions play a crucial role in the implementation of CAT and the adjustments that need to be made to the environment. Automation of vehicles increases in degree, from no automation to driver assistance, partial automation, conditional automation, high automation, to full automation. This research focuses on full automation, where the vehicle can operate without any human interference.

Considering these levels of connectivity and automation, a taxonomy for the implementation of CAT in mixed-traffic situations is made. The taxonomy for traffic separation categorizes four dimensions of operation. The first dimension, full separation, aligns with the current situation on public roads where AVs are permitted. CAT systems are allowed in confined areas where full monitoring is possible. The dimension of separation by space is characterized by static spatial separation, enabling AVs to operate independently on dedicated roads, distinct from public roads used by conventional traffic. Decoupling points facilitate transitions between these transportation flows. The dimension of separation by time, whether static or dynamic, allows both conventional and autonomous traffic to use the same roads alternately, achieved by periodically closing off roads or specific sections, resulting in Time Windows (TWs) for each traffic type. The final dimension categorizes logistic concepts with no separation, achieving fully mixed traffic on public roads. With the exploration of the logistic concepts in the dimensions of the taxonomy for traffic separation, it becomes evident that addressing the challenges posed by each dimension is crucial for the successful implementation of logistic concepts, particularly in achieving a smooth integration of CAT systems into mixed-traffic environments.

The most crucial challenge involves a smooth integration of AVs into the existing road infrastructure, where human drivers coexist. This challenge encompasses aspects such as providing accurate information to human drivers about the presence of AVs on shared roads available roads or designated TWs for specific routes or areas. Addressing these challenges is crucial for achieving a smooth and effective integration of CAT systems into mixed-traffic environments.

6.1.3 General Conceptual Model of Hub-to-Hub Environments

Simulation is a tool to understand, manage, and improve complex systems. It enables the evaluation of future scenarios without impacting the current physical system. This research employs a discrete-event simulation, which is used for modelling queueing systems. A hub-to-hub environment is characterized as a queueing system. The model is designed to solve the problem of how CAT can be implemented in hub-to-hub environments when it is separated by time from conventional traffic.

To test the impact on conventional traffic and the day-to-day operations in the hub-to-hub environment, five KPIs are formulated. The fraction of delayed traffic evaluates the impact on conventional traffic when CAT is implemented by scheduling dedicated TWs for AVs to operate on public roads. Terminal time measures the duration containers spend in the system from their arrival with external transport at a Logistics Hub (LH) in the environment until they arrive at the next destination in the environment. This includes the container waiting time, for example, at a terminal waiting to be processed. Call time represents the duration a container spends in the CS before it gets processed, serving as an indicator of CS efficiency. AV utilization assesses the efficiency of TW duration and frequency and the containers left in the CS at the end of the day to evaluate the workload of the CS per day.

The model is composed of multiple building blocks, each representing the different characteristics of the hub-to-hub environment. These general blocks can be tailored to any hub-to-hub environment by adjusting the input variables. The building blocks can be used multiple times within a model and the variables can be modified for each block separately. This design ensures the conceptual model's generality for various hub-to-hub environments. For the implementation of CAT systems in hub-to-hub environments, the conceptual model introduces a CS for managing the internal transportation flow, to which all actors in the environment are connected.

6.1.4 Computer Model of XL Park

The XL Park is a designated area connected to two modalities, water and road. The park is accessible by one main road, which is useful for temporarily closing off the roads for conventional traffic. The XL Park contains two types of LHs, one terminal and multiple warehouses. External transport of containers enters the system by trucks going directly to the terminal or to the warehouses where the containers are processed. Additionally, containers arrive at the terminal via barges. The internal transportation within the park to LHs is currently managed by a manually operated TT. This transport flow involves the handling and interactions with the infrastructure of the environment and LHs, presenting challenges for the implementation of CAT in this environment.

The characteristics of the XL Park are used as input for the conceptual model and a simulation model of the park is designed in an object-oriented 3D modelling software. From the XL Park, container data is gathered to determine arrival distributions for the external transportation flow, subsequently generating the internal transportation flow. The CS designed in the simulation model embodies a job list containing all containers in the system waiting for internal transportation. The AVs prioritize the containers based on their arrival times, in the absence of due dates in the gathered data. The schedule of the AV with corresponding TWs is used as an experimental factor, to systematically test its impact on the system. Various experiments are conducted to evaluate the impact of the duration of TWs, the number of TWs and the scheduling of TWs. The simulation model is verified and validated by multiple techniques and the simulation is an accurate representation of the real system for the purpose of this research.

6.1.5 Impact of CAT Implementation in Hub-To-Hub Environments

Multiple experiments are performed with the simulation model, to determine the optimal scheduling of TWs and assess their impact on the system's operations. The efficiency of the number of AVs is evaluated, leading to the conclusion that introducing a second AV is not advantageous for the current intensity of container transportation in the XL Park and is not worth the investment for the current intensity of container transportation.

Regarding TW durations, a comparative analysis between one-hour and half-hour TWs reveals that the duration significantly affects the fraction of delayed traffic and the utilization of AVs. The impact of delayed traffic should be minimized, while the utilization should be maximized to efficiently make use of the TWs. The experiments conclude that one-hour TWs are more efficient than half-hour TWs.

Focusing on one-hour TWs, analysing the results of the experiments considering all KPIs identifies that the optimal number of TWs with one AV is five TWs of one hour each. Further experimentation involves testing the scheduling of these TWs, revealing that scheduling them during the night, despite the LHs' restricted opening hours, significantly reduces the impact on conventional traffic.

To facilitate and communicate the separate use of the roads by AVs and conventional traffic, adaptions need to be made to the environment, such as traffic signs or gates. The implementation of a CS requires collaborative efforts from LHs to share essential data and adapt physical barriers, enabling AVs to transport containers without human interference. Implementing CAT systems in the hub-to-hub environment entails the investment in an AV, charging station, (de)couple systems for the containers, digital trackers, and designing and managing the CS. This will require further research into the CS and its impact on the environment.

6.2 DISCUSSION

This research evaluates the transportation flow in hub-to-hub environments, using the XL Park as a business case. However, it's crucial to note that the external transportation flow to and from the different LHs is unknown, and only the container flow to and from CTT is based on real data. The external transportation flow is derived from data obtained by highway sensors and Google Analytics, introducing potential reliability issues. For a comprehensive analysis, all real logistical flows of an environment must be taken into consideration to determine the real impact of implementing CAT in the system. Furthermore, it's essential to acknowledge that the inputs for the simulation of the XL Park are based on outdated information, as the park undergoes rapid development with the addition of more LHs. This expansion leads to increased logistical flows to, from, and within the XL Park. Consequently, the potential impact of implementing CAT within the current system might be significantly more substantial than portrayed in this study. Continued monitoring of the development of the XL Park and the corresponding adjustment of model inputs are necessary to ensure the accuracy of simulation outcomes.

Within the taxonomy of mixed traffic, this research only focuses on the dimension of separation by time. Considering the layout of the XL Park, there is potential to investigate other dimensions, such as separation by space. For example, exploring the possibility of making the XL Park fully autonomous and establishing a decoupling point at the entrance could be considered. Nevertheless, this introduces practical implementation challenges, particularly regarding the transportation of employees and visitors of LHs within the park. Allocating and realising dedicated lanes for AVs could be possible in the XL Park, given its spacious infrastructure, which supports potential adaptations like this.

Expanding on the implementation of separation by time, there is potential in dynamically close roads where the AV needs to drive. The CS has real-time information on the whereabouts of the AV, making it possible to dynamically close the next road on the route of the AV. This has some practical complications for conventional traffic, lacking information about available roads to take. Solutions to connect conventional traffic to the system should be investigated. The routing of traffic can also be turned around and let the AV choose the roads that are empty or have the least amount of traffic at that moment. Implementing this approach adds complexity to the CS, as it needs to monitor all aspects of the environment to facilitate dynamic route adjustments. The feasibility and practicality of such solutions should be thoroughly explored to ensure seamless integration of CAT within the hub-to-hub environment.

Operational hours of the LHs are not included in the simulation, therefore, containers can be processed upon arrival at an LH at any time, which does not reflect the real system. This is mainly reflected in the experiment for planning the TWs, the result of optimal scheduling at night does not fully align with the practical scenario where LHs operate with constraint. While the impact on conventional traffic remains low, the logistics of internal transport differ significantly. Containers will pile up at the LHs during the night and remain there all day to be transported back to the terminal the subsequent night. This scenario requires more chassis, particularly if there is no workforce available at night to operate cranes. Addressing this challenge may involve introducing new systems where chassis are eliminated, allowing AVs to autonomously manage the entire process of loading, transporting, and unloading containers.

In terms of the experiments, there is room for improvement in the simulation to enhance the analysis of system performance and ensure the collection of validated results. An unexpected trend is observed in the utilization results with half-hour TWs. As the number of TWs increases, there is an unexpected increase in utilization, while a stabilization or gradual decrease is expected. Several potential causes for these results are identified. Firstly, the spreading of TWs throughout the day and the stochastic nature of container arrival could contribute to this outcome. Another potential factor is related to the calculation of utilization and the presence of programming errors. The current utilization calculation considers the total time of TWs, and if an AV is in the process of transporting a container while a TW is ending, it will finish the job before checking road availability when idle. If the AV is at an LH at the end of a TW, it will return to its home base outside the TW, possibly resulting in a utilization exceeding 100%. Additionally, the way of calculating utilization is adapted to the use of TWs, which gives a distorted picture when comparing it with the current system.

The calculations and results for call time and terminal time are nearly identical, as terminal time represents the waiting time of the container at the terminal before transportation, added to the call time. To provide more insightful findings, it would have been beneficial to utilize a KPI that measures the impact on the system from a different perspective. For instance, the impact on conventional traffic is currently assessed solely based on the fraction of traffic affected by the TWs. Although the total waiting time of delays is stored in the simulation, the average waiting time resulted in half the length of the TW for all experiments. While this is a logical outcome, more consideration could be given to the use of available data to evaluate the impact on conventional traffic. Additionally, the KPI for delayed traffic is tailored to the specific logistic concept examined in the simulation. However, with other logistic concepts, conventional traffic may face disruptions from the operation of AVs in different ways. Further research should involve better reasoning and the development of KPIs to accurately measure the impact of various logistic concepts.

6.3 RECOMMENDATIONS

The implementation of CAT in the logistics concept of separating autonomous and conventional traffic by time requires adjustments to the hub-to-hub environment. The LHs within the environment must collaborate to establish an effective CS. This can be achieved by overarching management (as CTT in the business case that takes ownership of the vehicles), or a decentralized CS where LHs independently regulate internal transportation but use a common CS as a communication tool. A significant challenge lies in designing and implementing a CS where all LHs are willing to share the necessary information. Additionally, a crucial decision must be made regarding vehicle ownership and investment responsibilities. Determining the location for storing AVs is essential for optimizing their routes in each environment. All physical barriers the AVs encounter must be adjusted to a new system, which can be a costly investment for both the infrastructure of the environment and the LHs integrated into the internal transportation flow. Thorough planning and cooperation are essential to address these challenges effectively.

Determining the schedule of TWs presents the next challenge, with the objective of minimizing the impact on conventional traffic in the environment, including the visitors, drivers passing through the environment, and the external transportation flow into the environment. Each LH will have its demands and restrictions, which impact the schedule of the TWs. The experiments conducted provide a clear result: TWs are most efficient when scheduled at night, minimizing disruption to the day-to-day operations of a hub-to-hub environment. While the intensity of the internal transportation flow varies across environments, its impact on the number of TWs and the required number of AVs can be investigated using the simulation developed for this research. Adjusting the TW schedule based on the unique characteristics of each environment is essential for optimal implementation.

Implementing logistics concepts of the dimension separation by time requires adjustments to the environment. This involves the regulation of allocated traffic on the roads and the impact is related to the infrastructure of the roads leading into the environment and to the LHs. The creation of parking spaces may be necessary to accommodate conventional traffic during the active TWs of the AVs. Additionally, clear communication about road closures is essential to avoid confusion for conventional traffic. This implementation requires a transition period for external traffic to adapt, making transportation planning more complex. This impact extends beyond the LHs in the environment to all connected external LHs. Coordination and communication are vital during this transition to ensure a smooth and effective integration of CAT systems.

In the simulation, additional attributes are stored to calculate various KPIs beyond those utilized in this research. These additional statistics can be utilized in hub-to-hub environments with different goals or problem statements. For instance, the duration of waiting time for conventional traffic is stored and calculated, which could be valuable if experimenting with dynamic TW. In environments where mixed traffic is possible, travel times may offer more insights into the impact on conventional traffic. Unlike waiting times, which are relevant when AVs are not on the roads, travel times reflect the speed reduction experienced by conventional traffic when sharing the road with AVs.

APPENDICES

A. REAL SYSTEM DATA ANALYSIS

For an accurate simulation of the real system, real data is needed on the transportation flows in the system. This data is obtained from the business case of the XL Park. CTT gathered the departure and arrival data of containers in an Excel sheet for January to October of the year 2021. With ten months of data, arrival and departure distributions are analysed and this is used as input for the simulation model.

First, the data is cleaned. The data for January is observed to be incomplete because the incoming containers were booked in prior months, which was not saved in the data. The data for January is not accurate to measure arrival distributions, so this month's data was cut from the sheet. The sheet contains 19492 data lines, and each represents a transportation movement of a container. If a container has multiple transportations in the system, it can appear multiple times in the sheet. From the data is assumed that not all truck arrival times are logged correctly, in the data most trucks arrive at 00:00 at night but looking at the arrivals the hours before and after the arrivals are low, which results in incorrect outliers in the distribution. Concluded is that trucks with missing arrival stamps are logged with an arrival at 00:00 that day, so the data is cleaned by distributing these arrivals over the day by the distribution of arrivals of the other hours in the day to correct these errors.

In Table A.1 the information in the data-sheet is explained. Each column is made into a filter, to sort the data into different categories.

Table A.1 Obtained System Data Explanation

Name	Explanation
CALCSEQ	Vehicle identification
INSDATE	Date of booking
BOOKING	Batch number of total booking
CNTR	Container identification
UNITTYPE	Container size, 20ft, 40ft, or 45ft
MODALITYOPER (C/T)	Modality of transportation, C = barge, T = Truck (or terminal tractor)
SPLIT (C/D/N)	Type of transportation flow, C = internal arrival, D = internal departure, N = external transportation flow (no modality split)
VOYTERM FROM	Departure terminal of the barge
VOYTERM TO	Arrival terminal of the barge
TRIPID	Departure and destination of transport, for the data analysis, split into 'from' and 'to'.
FROMLAT – FROMLONG	Geographic coordinates of the departure location
TOLAT - TOLONG	Geographic coordinates of the destination
ETA FROM	Estimated time of departure
ETA TO	Estimated time of arrival

To analyse the different transportation flows, the data is split into three categories.

1. With "MODALITYOPER" the barge transports are filtered and split between "BargeArrivals" and "BargeDepatures". For each barge transport the number of containers broken down, so a cargo distribution for the barge arrivals can be determined.
2. With "SPLIT" and the "TRIPID" the internal transportation flow is determined and labelled as "TerminalTractorArrivals" and "TerminalTractorDepartures". Transports between CTT and the LHs Bleckmann and Timberland are filtered from the data.
3. The "MODALITYOPER" is split into barge and truck or terminal tractor. So, the truck data is derived with modality "T" and "TRIPID" from or to CTT and from or to any destination that is not Bleckmann or Timberland.

All categories are analysed separately. With "ETA FROM" and "ETA TO" the transportation day (weekday) and time window (per hour) are derived, and transports are counted resulting in a schedule of total arrivals of every weekday per hour of nine months of data.

Data Distributions

For the input distributions, the data is analysed in two categories, the arrivals per day of the week and for every day the arrival distribution per hour. Based on the dates of the data, the specific day of the week is determined. For every day the number of arrivals is counted. The days without arrivals are also counted for the arrival frequency. In the input table for the arrival frequency, the columns represent the days of the week and the contents in the cell of row *i* is the frequency *i* arrivals occur for that day of the week. For example, if three Mondays in the data had six arrivals, the sixth row in the column Monday contains a three. The same is done for every hour of the day, separately for each weekday. The input table for the arrivals per hour contains the weekdays in the columns and the rows contain the hours of the day.

At the start of each simulation day, the arrivals for that day are generated with the frequency table of number of arrivals per day. When the number of arrivals is determined, for each arrival the arrival hour is generated with the frequency table of the number of arrivals per hour. After that, the time of the arrival is set randomly over the hour. This results in an arrival time for that day and the arrival times are saved in a table, sorted from earliest arrival to latest, and these times trigger the arrival of the next vehicle.

B. KPI CALCULATION FOR SIMULATION MODEL

To calculate the values of the KPIs, the attributes of all moving objects are saved at certain events. Each object has a separate table in the simulation to save the statistics. Next to that, the number of generated objects is saved in counters in the simulation, as well as the number of cars and trucks that had to wait to enter the roads when the roads were closed off for the AV timeslots. Table B.1 summarises all the attributes that are saved for each object entering the system, with the variable's data type.

Table B.1 Attributes of Moveable Objects Saved in the Simulation

Containers	Trucks	AVs	Barges	Cars
Container (object)	Truck (object)	Vehicle (object)	Barge (object)	Car (object)
ContainerID (integer)	TruckID (integer)	Loaded (time)	BargeID (integer)	CarID (integer)
ArrivalTime (time)	Operation (string)	Unloaded (time)	ArrivalDay (string)	ArrivalTime (time)
ArrivalLocation (string)	Destination (string)	NoJob (time)	ArrivalHour (integer)	Destination (string)
TerminalArrival (time)	TravelTime (time)		ContArr (integer)	ArrivalDestination (time)
TerminalLeft (time)	Container (integer)		ArrivalTime (time)	StayTime (time)
CallTime (time)	WaitingTime1 (time)		ContDep (integer)	WaitingTime1 (time)
Destination (string)	WaitingTime2 (time)		SystemLeft (time)	WaitingTime2 (time)
DestinationArrival (time)				LeavingDestination (time)
DestinationLeft (time)				SystemLeft (time)
TerminalDestination (time)				
TerminalDestLeft (time)				
SystemLeft (time)				

At the end of each replication, the values of the KPIs are calculated and at the end of each experiment, the average of all replications is calculated for the experiment KPI output. Each KPI is calculated with different statistics.

Fraction of Delayed Traffic

The fraction of delayed traffic is calculated with the attributes of trucks and cars. When the roads are closed, the vehicles are put in a buffer, and the start time of the wait is saved. When the roads are open for conventional traffic, the vehicles exit the buffer, and the total waiting time is calculated under WaitingTime1 (this is the waiting time for when the vehicle enters the park) and WaitingTime2 (when a vehicle leaves the LH). When calculating the fraction of delayed traffic, all vehicles with a waiting time are counted and divided by the total number of conventional vehicles that entered the system during the simulation.

Fraction of Delayed Traffic = Number of delayed vehicles / Total amount of vehicles generated in the system

Terminal Time and Call Time

These two KPIs are described together since these KPIs are calculated by the container data. The data of the container is first sorted and stored in a temporary table so that only containers that are transported by AVs are used to calculate the KPI times. This is done by subtracting the containers from the table that had the destination BargeSource or TruckSource when they entered the system. That meant that these containers were for external transport (TruckSource destination) or were empty and needed to be transported away by barge (BargeSource destination). With the data of containers that were transported within the business park, the following times are calculated:

TerminalTime1 = DestinationArrival – TerminalArrival
The time between the first arrival in the system and the arrival of the first destination (being an LH).

TerminalTime2 = TerminalDestLeft – DestinationLeft
The time between leaving the LC and the time of leaving the terminal.

CallTimeOne = TerminalLeft – TerminalArrival
The time between the arrival at the terminal and leaving the terminal for its destination.
CallTimeTwo = DestinationLeft – CallTime
The time between being ready for pick up at the LC and leaving the LC to go back to the terminal.

Utilization

The Utilization is first calculated per vehicle, if there is more than one AV in the simulation, whereafter the average utilization is calculated. Since the AVs have a timeslot to transport the containers, the total time of these timeslots during the simulation is saved. Two different types of utilizations are distinguished: the time an AV travels with a container, so being loaded, and the time an AV has a job assigned, so the time being loaded plus the time being unloaded but travelling to pick up a container. The utilization is not a time value, but a fraction:

Utilization1 = Total "Loaded" time / Total AV TW time
The time an AV is transporting a container divided by the total time of all AV TWs.

Utilization2 = (Total "Loaded" time + Total "Unloaded" time) / Total AV TW time
The time an AV is travelling while having a job assigned divided by the total time of all AV TWs.

Jobs Left

At the end of each day, the number of jobs left in the CS is saved in a table, Then, at the end of each replication, the average of all the days is calculated and saved for this KPI output.

C. INPUT VARIABLES OF BUILDING BLOCKS

Table C.1 displays the input variables of the building blocks for the simulation model of the XL Park.

Table C.1 Input Variables for Simulation Model XL Park

Building Block	Input Variable	Data Type	Value
CTT Almelo	Type of Modality	Label	Barge and Truck
	Number of cranes	Integer	1
	Number of chassis	Integer	20
	Storage Space	Integer	Infinite
	Truck (un)load time	Time	10 min (including waiting time)
	Barge (un)load time	Time	3 min per container
	Destination frequency	Real	0.35/0.35/0.30
	Parking Capacity	Integer	-1 (infinite)
	Opening Hours	Time	24/7
Bleckmann	Number of docks	Integer	30
	Container process time	Time	30 minutes
	Truck (un)load time	Time	10 minutes
	Parking Capacity	Integer	Infinite
Timberland	Number of docks	Integer	50
	Container process time	Time	30 minutes
	Truck (un)load time	Time	10 minutes
	Parking Capacity	Integer	Infinite
Barge Source	Arrival intensity	Distribution	*See Appendix D*
	Number of containers (cargo)	Integer	*See Appendix D*
	Destination frequency	Real	0.24/0.29/0.47
Truck/Traffic Source	Arrival intensity	Distribution	*See Appendix E & F*
	Destination frequency	Real	0.54/0.46
	Truck operation frequency	Real	0.3/0.5/0.2
	Working/visiting duration	Distribution	*See Appendix F*
Internal Transportation Flow “AV Source”	Connected System	Table	Dynamic Job List
	Number of vehicles	Integer	1
	Schedule	Table	*Experimental factor*
	Location of AV	Object	CTT Almelo

D. BARGE SOURCE ARRIVAL DISTRIBUTIONS

Barges arrive once a day or not, so the barge arrival probability is calculated by all barge arrivals on a specific weekday, divided by the number of that weekday in the data. The arrival of a barge is determined at the beginning of the day by a uniform probability between 0 and 1. If the chance of a barge arrival that day is higher than the uniform probability, a barge arrival is scheduled for that day. The barge arrival probabilities per weekday are stated in Table D.1.

Table D.1 Barge Arrival Chance per Weekday

Day	Arrival Chance
Monday	0.480769
Tuesday	0.673077
Wednesday	0.596154
Thursday	0.346154
Friday	0.622642
Saturday	0.538462
Sunday	0.403846

The distribution for barge arrivals per hour is the same for all weekdays since barge arrivals are uncertain because of the long travel distance. To determine the arrival hour of the barge, an empirical distribution is used over the arrival frequency of the barges obtained from the data of CTT. Table D.2 shows the arrival frequencies per hour.

Table D.2 Barge Arrival Frequency per Hour

Hour	Frequency
00:00	0
01:00	0
02:00	0
03:00	0
04:00	0
05:00	4
06:00	30
07:00	10
08:00	8
09:00	9
10:00	10
11:00	13
12:00	9
13:00	12
14:00	7
15:00	8
16:00	6
17:00	15
18:00	15
19:00	7
20:00	12
21:00	4
22:00	0
23:00	11

E. CTT TRUCK FLOW ARRIVAL GENERATION

At the beginning of a simulation day, the number of truck arrivals for that day is determined. In the data of CTT, at most 55 trucks arrive in a day at the terminal. Table E.1 shows the frequency of number of arrivals per weekday. The first column represents the number of arrivals and the number in the columns of the day represents the frequency of the number of arrivals for that specific day.

After the number of arrivals for the day is determined, the arrivals are distributed over the day with an empirical distribution of the frequency of truck arrivals per hour, which is different for each weekday. Table E.2 shows the frequency of truck arrivals per hour. As explained in Appendix A, the data is cleaned up by errors in the saved arrival times of the trucks.

Table E.1 Truck Arrival Frequency per Weekday

Number of arrivals	Mon	Tues	Wed	Thurs	Fri	Sat	Sun
1	2	0	0	4	1	13	17
2	5	3	1	3	2	6	5
3	1	3	6	4	4	4	1
4	2	5	4	1	5	5	3
5	3	4	4	5	3	6	2
6	3	4	3	0	2	0	2
7	2	2	4	4	1	0	3
8	3	2	1	2	3	1	2
9	3	3	1	1	1	0	0
10	1	2	0	1	3	1	0
11	3	0	4	1	2	1	0
12	1	2	2	4	2	0	2
13	1	1	1	3	1	0	0
14	1	1	1	1	0	1	1
15	0	0	1	1	1	0	0
16	2	0	3	0	1	0	0
17	2	0	1	0	2	1	0
18	0	1	1	1	0	0	0
19	0	1	0	0	0	0	0
20	1	2	0	0	0	0	0
21	0	0	0	0	1	0	0
22	1	1	0	0	0	0	0
23	0	0	0	0	0	0	0
24	1	0	1	0	1	0	0
25	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0
27	0	0	0	1	0	0	0
28	0	0	0	0	1	0	0
29	0	0	0	0	0	0	0
30	0	1	0	0	0	0	0
31	0	0	0	1	0	0	0
32	1	0	0	0	0	0	0
33	0	0	0	0	1	0	0
34	0	0	0	0	0	0	0

35	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0
37	0	0	0	1	0	0	0
38	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0
41	0	0	0	0	0	0	1
42	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0
55	0	1	0	0	0	0	0

Table E.2 Truck Arrival Frequency per Hour

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00	0	14	6	0	11	0	0
01:00	5	0	0	0	1	0	1
02:00	0	0	1	0	0	2	0
03:00	0	4	0	0	2	0	4
04:00	0	0	0	0	0	3	0
05:00	1	0	0	1	3	0	3
06:00	6	1	11	41	14	1	0
07:00	22	25	29	25	20	12	0
08:00	46	39	43	38	32	11	5
09:00	44	47	35	46	69	14	8
10:00	23	43	29	24	42	1	11
11:00	34	45	44	22	39	3	2
12:00	83	41	25	27	46	27	22
13:00	34	27	17	29	23	13	12
14:00	9	3	8	19	5	0	34
15:00	3	37	11	19	14	0	5
16:00	4	0	2	6	1	8	8
17:00	0	3	2	0	1	0	16
18:00	7	5	2	3	1	0	0
19:00	2	0	12	0	0	0	0
20:00	1	2	4	0	1	5	4
21:00	1	0	0	0	6	0	0
22:00	0	1	0	1	18	0	0
23:00	3	15	16	14	20	8	6

F. TRAFFIC FLOW INPUT GENERATION

Traffic plays an important role in the simulation, but gathering real data is hard since traffic at the business park is not being monitored. To get a close-to-reality distribution for traffic data, Google Analytics is used. Google uses aggregated and anonymized data from users to determine popular times, waiting times, and visit duration for businesses that get enough visits from users. The carpool parking at the entrance of the Business Park is a location for which this data is shown in Google Maps. The traffic flow is determined by these graphs on Google Maps, together with the sensor data of the highway next to the Business Park.

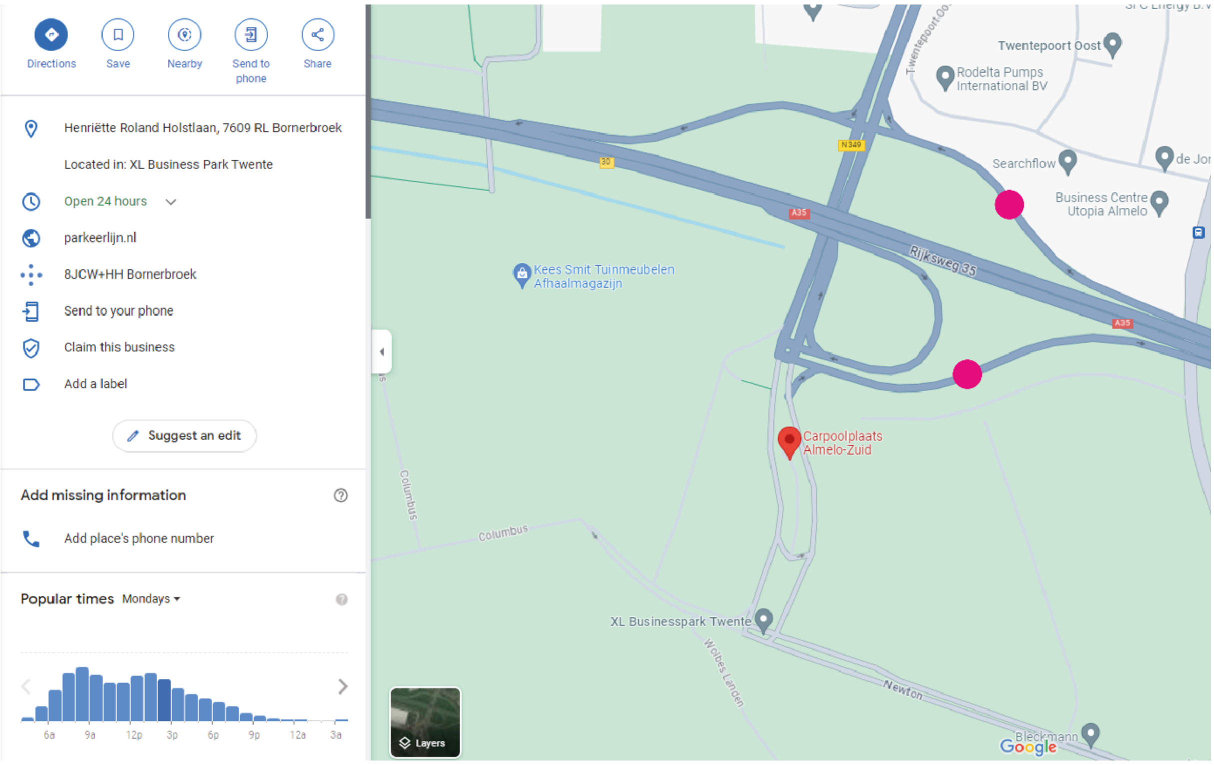

Figure F.0.1 XL Park Location of Carpool and Highway Sensors

Figure F.1 shows the entrance of the XL Park with the carpool. The pink dots on the highway represent the location of the highway sensors, from which data is gathered about passing traffic. In the window on the left, the distribution data of the carpool is visible. This distribution shows how many phones are passing that location in that hour, so arriving and leaving traffic. This distribution does not show numbers, which is why the intensity of traffic is estimated based on the highway sensor data. Figure F.2 displays the Google Analytics data for all weekdays and how the distribution is determined.

Table F.1 shows the distribution derived from Google in percentages. With these percentages incoming traffic is generated, by taking into account leaving and arriving traffic in the distribution, based on a fraction of the highway sensors. Arriving traffic enters from the upper sensor, so the number of cars is taken per hour, subtracting a big fraction that leaves the highway to enter Almelo, which is the road to the north. Leaving traffic passes the lower highway sensor. Table F.2 shows the input of traffic arrivals for the simulation, after all calculations.

The highway sensors are monitored by Rijkswaterstaat and this data can be requested per sensor and per weekday for a specific period, resulting in the data already being sorted over the days, which is the same structure as the input table for the simulation. The sensors count the intensity of traffic in the number of vehicles and distinguish the vehicles between vehicles smaller in length than 5.6m, vehicles between 5.6 m and 12.2m, and vehicles longer than 12.2m. For these vehicles, the fraction of the intensity is given per hour. Table F.3 shows an example of the gathered highway sensor data.

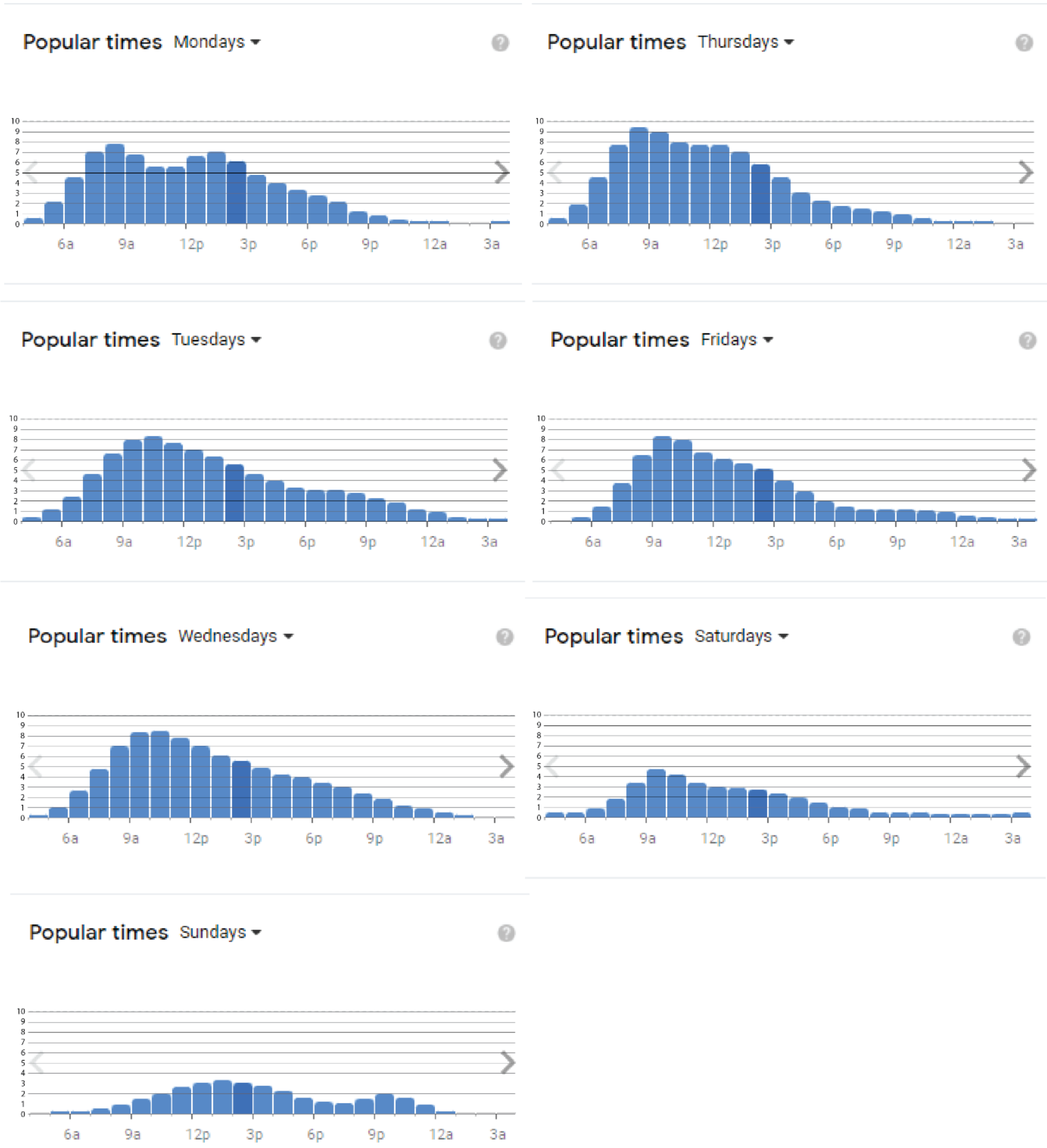

Figure F.0.2 Google Analytics Traffic Distribution of XL Park Carpool

Table F.1 Google Analytics Traffic Arrivals Converted to Percentages

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0	0.02	0.09	0.05	0.02	0.05	0.03	0.02
1	0	0.03	0.02	0.02	0.03	0.03	0
2	0	0.02	0	0	0.02	0.03	0
3	0.02	0.02	0	0	0.02	0.05	0
4	0.05	0.04	0.02	0.05	0	0.05	0
5	0.2	0.12	0.11	0.08	0.03	0.05	0.02
6	0.45	0.23	0.26	0.45	0.15	0.09	0.02
7	0.7	0.47	0.48	0.77	0.37	0.18	0.05
8	0.78	0.66	0.7	0.94	0.65	0.34	0.1
9	0.68	0.8	0.84	0.9	0.83	0.48	0.15
10	0.55	0.84	0.85	0.8	0.8	0.42	0.2
11	0.55	0.78	0.78	0.77	0.68	0.34	0.17
12	0.65	0.7	0.7	0.77	0.61	0.3	0.3
13	0.7	0.64	0.61	0.7	0.57	0.29	0.33
14	0.61	0.55	0.55	0.58	0.52	0.28	0.3
15	0.48	0.45	0.49	0.45	0.4	0.24	0.28
16	0.4	0.4	0.42	0.3	0.29	0.2	0.22
17	0.33	0.33	0.4	0.22	0.2	0.25	0.16
18	0.28	0.3	0.35	0.18	0.15	0.1	0.12
19	0.21	0.3	0.3	0.15	0.12	0.09	0.11
20	0.12	0.28	0.24	0.12	0.12	0.05	0.15
21	0.08	0.22	0.19	0.09	0.12	0.05	0.2
22	0.03	0.19	0.12	0.05	0.1	0.05	0.16
23	0.02	0.12	0.09	0.02	0.09	0.03	0.1

Table F.2 Traffic Arrival Input after Calculations

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0	0.4	1.8	1	0.4	1	0.6	0.4
1	0	0.6	0.4	0.4	0.6	0.6	0
2	0	0.4	0	0	0.4	0.6	0
3	0.4	0.4	0	0	0.4	1	0
4	1	0.8	0.4	1	0	1	0
5	4	2.4	2.2	1.6	0.6	1	0.4
6	9	4.6	5.2	9	3	1.8	0.4
7	14	9.4	9.6	15.4	7.4	3.6	1
8	15.6	13.2	14	18.8	13	6.8	2
9	13.6	16	16.8	18	16.6	9.6	3
10	11	16.8	17	16	16	8.4	4
11	11	15.6	15.6	15.4	13.6	6.8	3.4
12	13	14	14	15.4	12.2	6	6
13	14	12.8	12.2	14	11.4	5.8	6.6
14	12.2	11	11	11.6	10.4	5.6	6
15	9.6	9	9.8	9	8	4.8	5.6
16	8	8	8.4	6	5.8	4	4.4
17	6.6	6.6	8	4.4	4	5	3.2
18	5.6	6	7	3.6	3	2	2.4
19	4.2	6	6	3	2.4	1.8	2.2
20	2.4	5.6	4.8	2.4	2.4	1	3
21	1.6	4.4	3.8	1.8	2.4	1	4
22	0.6	3.8	2.4	1	2	1	3.2
23	0.4	2.4	1.8	0.4	1.8	0.6	2

Table F.3 Example of Highway Sensor Data Notation

Hour of the day	Intensity	Smaller or equal to 5,60m (%)	between 5,60m and 12,20m (%)	Larger than 12,20m (%)
00:00 - 00:59	20.6	93.4	2.5	4.1
01:00 - 01:59	12.1	89.4	7.5	3.1
02:00 - 02:59	7.9	84.9	5.2	10
03:00 - 03:59	6.8	85.7	6.5	7.8
04:00 - 04:59	7.7	72.7	13.5	13.8
05:00 - 05:59	33.4	86.3	7.2	6.5
06:00 - 06:59	131.6	88.9	7.6	3.5
07:00 - 07:59	302.4	89.2	8.3	2.5
08:00 - 08:59	343.2	91.2	6	2.9
09:00 - 09:59	210.9	81.6	12.3	6
10:00 - 10:59	160.6	81.6	12.4	5.9
11:00 - 11:59	168.1	83.2	11.7	5.1
12:00 - 12:59	198.8	86.9	8.3	4.8
13:00 - 13:59	212.4	86.1	8.8	5.1
14:00 - 14:59	247.8	87.5	9.3	3.3
15:00 - 15:59	219.2	88.3	8.7	3
16:00 - 16:59	264.6	90.2	8	1.8
17:00 - 17:59	299.4	94.3	4.3	1.4
18:00 - 18:59	178.3	94.1	4.2	1.7
19:00 - 19:59	118.9	94.3	4.6	1.1
20:00 - 20:59	85.3	95.2	4	0.8
21:00 - 21:59	69.5	95.6	3.5	0.9
22:00 - 22:59	71.1	96.8	2.5	0.7
23:00 - 23:59	42.7	97.8	1.6	0.5
Total	**3413.2**	**89.2**	**7.6**	**3.2**

G. VERIFICATION SAMPLE MEAN

To verify if the simulation reacts correctly to the input distributions, we compare the input arrival distributions with the arrivals in the simulation. Every arrival of a vehicle is saved in a table and per vehicle, the simulated arrival distribution is determined. We use the paired samples t-test to see if there is any significant difference between the distributions or not. For the computations, we use the average arrival of a vehicle on a specific weekday. For the t-test, the degrees of freedom are 6 and we use a confidence interval of 95%. The value of $t_{0,05;6}$ is 2,4469. To prove there is no significant difference between the distributions, the t-value of the observations should be lower than the $t_{0,05;6}$. The observed T-values for the Barge, CTT Truck flow, and Cars are respectively 0,5851, 0,6383, and 0,9045, verifying that there is no significant difference between the input distributions and the simulation arrivals. Tables G.1, G.2, and G.3 contain the comparison between the real data input and the simulation arrival output of the barges, trucks and cars.

Table G.1 Barge Arrival Distribution Verification

	Real Data	Simulation Data	Absolute Difference
Monday	0.480769231	0.476190476	0.004578755
Tuesday	0.673076923	0.714285714	0.041208791
Wednesday	0.596153846	0.642857143	0.046703297
Thursday	0.346153846	0.285714286	0.06043956
Friday	0.622641509	0.666666667	0.044025157
Saturday	0.538461538	0.571428571	0.032967033
Sunday	0.403846154	0.428571429	0.024725275

Table G.2 CTT Trucks Arrival Distribution Verification

	Real Data	Simulation Data	Absolute Difference
Monday	8.410256	8.166667	0.24359
Tuesday	9.025641	9.904762	0.879121
Wednesday	7.615385	9.357143	1.741758
Thursday	8.076923	8.5	0.423077
Friday	9.461538	9.404762	0.056777
Saturday	2.769231	3.047619	0.278388
Sunday	3.615385	4.785714	1.17033

Table G.3 Traffic Arrival Distribution Verification

	Real Data	Simulation Data	Absolute Difference
Monday	9.416667	7.952381	1.464286
Tuesday	10.21429	11.52381	1.309524
Wednesday	10.20238	11.80952	1.607143
Thursday	10.03571	9.190476	0.845238
Friday	8.238095	6.547619	1.690476
Saturday	4.785714	3.333333	1.452381
Sunday	3.761905	2.809524	0.952381

H. CALCULATIONS NUMBER OF REPLICATIONS

In Table H1 the calculations for the number of replications are shown. The first column represents the experiment number. The KPI Call Time is used for the calculations and the values in the KPI column are the average values of each whole experiment. With these values, the significance level of 95% is calculated, so we look for an error below 0.05. As can be seen in the last column, this threshold is reached after eight replications.

Table H.1 Calculation Number of Replications

n	KPI	Mean	Var	T-Value	Error	Test
1	24605.27					
2	28379.01	26492.14	7120563	12.7062	0.904984	N
3	27400.56	26794.95	3835358	4.302653	0.181562	N
4	25799.26	26546.03	2804751	3.182446	0.100387	N
5	27987.97	26834.41	2519406	2.776445	0.073445	N
6	25715.06	26647.86	2224351	2.570582	0.058735	N
7	24593.17	26354.33	2456730	2.446912	0.055004	N
8	26750.71	26403.88	2125409	2.364624	0.046161	Y
9	25166.21	26266.36	2029934	2.306004	0.041695	Y
10	26509.17	26290.64	1810282	2.262157	0.03661	Y
11	25266.07	26197.5	1724685	2.228139	0.033678	Y
12	28382.95	26379.62	1965913	2.200985	0.033771	Y
13	25751.63	26331.31	1832423	2.178813	0.031066	Y
14	28095.94	26457.36	1913888	2.160369	0.030191	Y
15	24993.18	26359.74	1920103	2.144787	0.029111	Y
16	27074.3	26404.4	1824008	2.13145	0.027255	Y
17	25919.11	26375.86	1723862	2.119905	0.025594	Y
18	27284.56	26426.34	1668332	2.109816	0.024306	Y
19	27592.54	26487.72	1647227	2.100922	0.023354	Y
20	28045.87	26565.63	1681922	2.093024	0.022848	Y

I. EXPERIMENTAL DESIGN

The input tables for the experiments will be shown by the different topics. The tables in this Appendix are not the direct input tables for the simulation. The tables will show a “1” when the TW for the AV is active and a “0” when it is not. If a row contains a “0”, the input table will have a “1” for the conventional traffic TW. If the AV TW is active, the conventional traffic TW will have a “0” in that row.

Table I.1 One-Hour TW Experiment Design

Hour	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12
00:00	0	1	0	1	0	1	0	1	0	1	1	1
01:00	0	0	0	0	0	0	0	0	0	0	0	0
02:00	0	0	0	0	1	0	0	0	1	1	1	1
03:00	0	0	0	0	0	0	1	1	0	0	0	0
04:00	0	0	1	0	0	1	0	0	1	0	0	1
05:00	0	0	0	0	0	0	0	0	0	1	1	0
06:00	0	0	0	1	0	0	1	1	0	0	0	1
07:00	0	0	0	0	1	0	0	0	1	1	1	0
08:00	0	0	0	0	0	1	0	0	0	0	0	1
09:00	0	0	0	0	0	0	1	1	0	0	0	0
10:00	0	0	0	0	0	0	0	0	1	1	1	1
11:00	0	0	0	0	0	0	0	0	0	0	0	0
12:00	1	1	1	1	1	1	1	1	1	1	1	1
13:00	0	0	0	0	0	0	0	0	0	0	0	0
14:00	0	0	0	0	0	0	0	0	1	0	1	1
15:00	0	0	0	0	0	0	1	1	0	1	0	0
16:00	0	0	0	0	0	1	0	0	0	0	1	1
17:00	0	0	0	0	1	0	0	0	1	1	0	0
18:00	0	0	0	1	0	0	1	1	0	0	1	1
19:00	0	0	0	0	0	0	0	0	0	0	0	0
20:00	0	0	1	0	0	1	0	0	1	1	1	1
21:00	0	0	0	0	0	0	1	1	0	0	0	0
22:00	0	0	0	0	1	0	0	0	1	1	1	1
23:00	0	0	0	0	0	0	0	0	0	0	0	0

The one-hour experiments have a range from 1 AV TW to 12 AV TWs, as shown in Table I.1. The TWs are evenly divided over the day. These experiments are executed with both 1 and 2 AV.

Table I.2 Half-Hour TW Experiment Design

Hour	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12
00:00	1	0	1	0	1	0	1	1	1	1	0	0
00:30	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0	0	0	1	1
01:30	0	0	0	0	0	0	0	0	0	0	0	0
02:00	0	1	0	0	0	1	1	1	1	1	0	0
02:30	0	0	0	0	0	0	0	0	0	0	0	0
03:00	0	0	0	1	1	0	0	0	0	0	1	1
03:30	0	0	0	0	0	0	0	0	0	0	0	0
04:00	0	0	1	0	0	1	0	0	1	1	0	0
04:30	0	0	0	0	0	0	0	0	0	0	1	1
05:00	0	0	0	0	0	0	1	1	0	0	0	0
05:30	0	0	0	0	0	0	0	0	0	0	0	0
06:00	1	0	0	1	1	0	0	0	1	1	1	1
06:30	0	0	0	0	0	0	0	0	0	0	0	0
07:00	0	1	0	0	0	1	1	1	0	0	0	0
07:30	0	0	0	0	0	0	0	0	0	0	1	1
08:00	0	0	1	0	0	0	0	0	1	1	0	0
08:30	0	0	0	0	0	0	0	0	0	0	0	0
09:00	0	0	0	1	1	0	0	0	0	0	1	1
09:30	0	0	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	0	1	1	1	1	1	0	0
10:30	0	0	0	0	0	0	0	0	0	0	1	1
11:00	0	0	0	0	0	0	0	0	0	0	0	0
11:30	0	0	0	0	0	0	0	0	0	0	0	0
12:00	1	1	1	1	1	1	1	1	1	1	1	1
12:30	0	0	0	0	0	0	0	0	0	0	0	0
13:00	0	0	0	0	0	0	0	0	0	0	0	0
13:30	0	0	0	0	0	0	0	0	0	1	1	1
14:00	0	0	0	0	0	1	0	1	1	0	0	0
14:30	0	0	0	0	0	0	0	0	0	0	0	0
15:00	0	0	0	1	1	0	1	0	0	0	1	1
15:30	0	0	0	0	0	0	0	0	0	1	0	0
16:00	0	0	1	0	0	0	0	1	1	0	0	0
16:30	0	0	0	0	0	0	0	0	0	0	1	1
17:00	0	0	0	0	0	1	1	0	0	0	0	0
17:30	0	1	0	0	0	0	0	0	0	1	0	0
18:00	1	0	0	1	1	0	0	1	1	0	0	1
18:30	0	0	0	0	0	0	0	0	0	0	1	0
19:00	0	0	0	0	0	0	0	0	0	1	0	0
19:30	0	0	0	0	0	0	0	0	0	0	0	1
20:00	0	0	1	0	0	1	1	1	1	0	0	0
20:30	0	0	0	0	0	0	0	0	0	1	1	0
21:00	0	0	0	1	1	0	0	0	0	0	0	1
21:30	0	0	0	0	0	0	0	0	0	0	0	0

22:00	0	1	0	0	0	1	1	1	1	0	0	0
22:30	0	0	0	0	0	0	0	0	0	1	1	1
23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:30	0	0	0	0	0	0	0	0	0	0	0	0

Table I.2 shows the experiment design for the half-hour TWs for twelve experiments. The number of TWs ranges from 4 to 15. The number of TWs is chosen based on the output of the one-hour TW experiments, which is elaborated in Section 6.1.

Table I.3 Scheduling of TW Experiment Design

Hour	Exp0	Exp1	Exp2
00:00	0	0	0
01:00	0	0	1
02:00	1	0	0
03:00	0	0	1
04:00	0	0	0
05:00	0	0	1
06:00	0	0	0
07:00	1	1	0
08:00	0	0	0
09:00	0	1	0
10:00	0	0	0
11:00	0	0	0
12:00	1	1	0
13:00	0	0	0
14:00	0	0	0
15:00	0	1	0
16:00	0	0	0
17:00	1	0	0
18:00	0	1	0
19:00	0	0	0
20:00	0	0	0
21:00	0	0	1
22:00	1	0	0
23:00	0	0	1

Table I.3 shows the experiment design for the scheduling of the TWs. Experiment 0 is already performed with the one-hour TW experiments. In this experiment, the TWs are evenly distributed over the day. Experiment 1 only schedules the AV TWs during operating hours of the XL Park. The operating hours differ per LH, so the operating hours determined for this experiment, are between 07:00 and 18:00. Experiment 2 schedules the TWs only during the night, so outside the 07:00 – 18:00 operating hours.

J. OUTPUT EXPERIMENTS FOR THE DURATION OF TWS

Section 6.1.2. analyses the duration of TWs based on the fraction of delayed traffic and the utilization of the AVs. The half-hour TWs are double in number and therefore more spread over the day. This has an impact on the Total Terminal Time and Total Call Time. Appendix B explains the calculation of the KPIs, and Terminal Time 1, Terminal Time 2, Call Time 1, and Call Time 2 are explained. The output tables show the Total Terminal Time of the container, Terminal Time 1 and Terminal Time 2 added up, the same applies to the Call Time. Table J.1 shows the KPI output for the one-hour TWs and Table J.2 the output of the half-hour TWs. The number of TWs for the one-hour TWs ranges from 3 to 6. The number of TWs for the half-hour TWs ranges from 6 to 12. This way, the total operating hours of the AV per day are the same. The difference in Total Terminal Time and Call Time between the one-hour TWs and half-hour TWs can be explained by the scheduling of the TWs over the day. With half-hour TWs, the interval between the TWs is half the time of the interval between one-hour TWs, which means that the call time can be three hours instead of six when a container is put in the CS at the end of the TW, reducing the call time drastically. However, the difference is not significantly large with the total time of TWs ranging from four to six hours per day. To consider these KPIs, more experiments with the scheduling of the TWs should be performed, to investigate the impact of scheduling on the Total Terminal Time and the Total Call Time.

Table J.1 Output One-Hour TWs for Duration of TWs

Hours	FracTrafficWait	TotalTerminalTime	TotalCallTime	Utilization	JobsLeft
3	0.18526356	07:09:24:04	07:08:42:12	1.035150499	92
4	0.24466445	03:00:58:48	02:06:25:34	0.921788275	28
5	0.26847089	02:04:43:08	01:01:24:38	0.757556546	11
6	0.350008517	02:01:53:17	00:17:40:34	0.647831942	8

Table J.2 Output Half-Hour TWs for Duration of TWs

Hours	FracTrafficWait	TotalTerminalTime	TotalCallTime	Utilization	JobsLeft
3	0.300161917	02:14:10:55	01:13:48:09	0.875312753	17
4	0.344622807	02:06:33:03	00:20:17:08	0.66531754	9
5	0.420833729	01:20:31:26	00:10:17:14	0.495964903	3
6	0.490716266	01:22:35:02	00:11:06:46	0.410253003	2

K. GRAPHICAL VISUALIZATION OF KPIS FOR THE NUMBER OF TWS

Figures K.1 to K.5 display the graphical visualization of the KPI output to analyse the optimal number of one-hour TWs. The x-axis represents the number of TWs in the day. The y-axis shows the value of the KPIs.

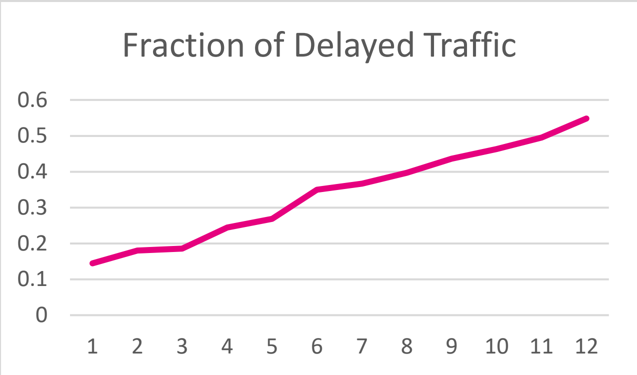

Figure K.1 Output Visualization for Fraction of Delayed Traffic

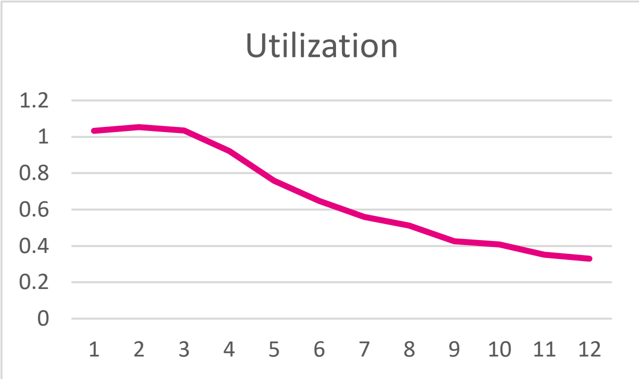

Figure K.2 Output Visualization for AV Utilization

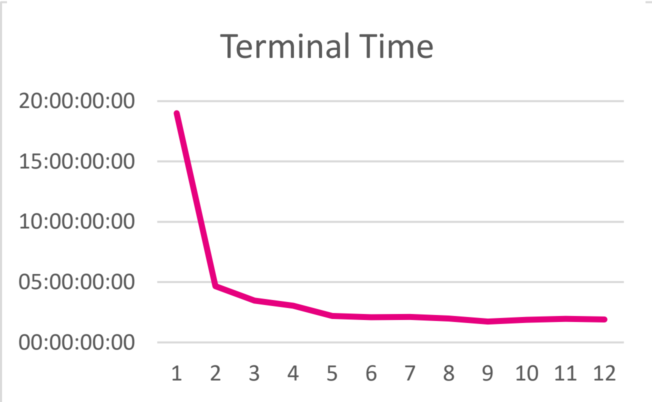

Figure K.3 Output Visualization for Total Terminal Time

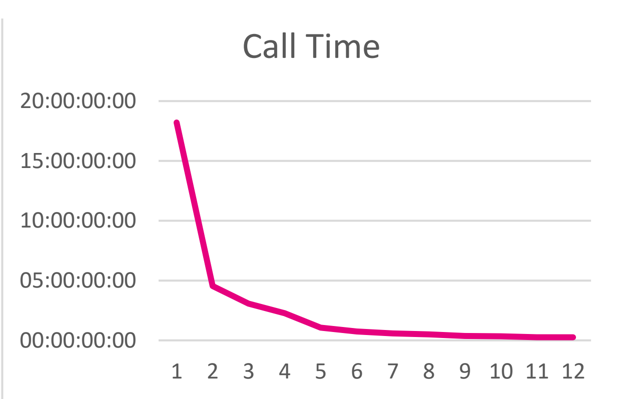

Figure K.4 Output Visualization for Total Call Time

Figure K.5 Output Visualization for Number of Jobs Left in the CS

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