Master Thesis, Industrial Engineering and Management

Improving the cargo transport flow within the yard of Amsterdam Airport Schiphol by using improved connectivity

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Management summary

The motivation behind this research is the heavy congestion within the Amsterdam Airport Schiphol area. The infrastructure around Schiphol consists of public roads, thus the traffic is not directly controlled by the airport authority. There is a mix of passenger transport together with freight transport. The congestion in the Schiphol area is caused by (i) limited space at the ground handlers (GHs) and (ii) cargo deliveries that are not regulated. Regarding the first, the limited space at the GHs results in the lack of space at the GH waiting area for trucks that need to drop off or pick up cargo. Therefore, trucks will park alongside the public road and will wait there until they can proceed to the GH parking places. This can sometimes take a long time and results in unsafe traffic situations and congestion.

Regarding the second, unregulated cargo deliveries, the GHs do not have full information about the incoming cargo or the expected arrival time since most trucks arrive unannounced. In practice, the cargo from all forwarders arrives around the same time just before the deadline. When multiple trucks arrive at the same time, the GHs do not have enough available docks and personnel, which results in waiting times and the above-mentioned situation. To improve this situation, this research studies the impact improved connectivity has on the yard of Schiphol, by making use of a central parking (CP), which can be used both as a buffer and a (de)coupling point and of Automated Vehicles (AVs).

The concepts from the literature used for improved connectivity are geofencing and information-sharing platforms. Geofencing is used for monitoring mobile objects within a virtual boundary around a geographical area. This can be used at Schiphol to provide an accurate ETA of trucks. Furthermore, an information-sharing platform can be used by freight carriers to make a reservation at the ground handler (GH). This is a more advanced way of sharing data, allowing for peak-shaving to occur, but also for data-driven decision making, based on knowing the ETA of trucks in advance.

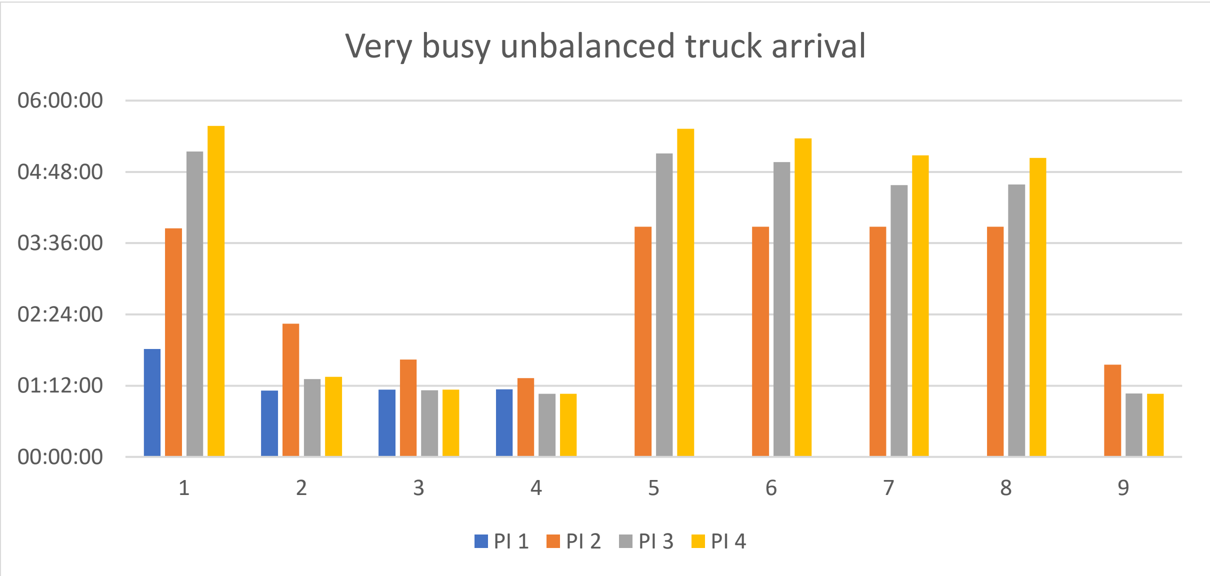
Based on the two improved connectivity concepts and the potential use of the CP, we define four information interventions and four physical interventions, for a total of 9 experiments as shown in the table below. The information interventions used for experimenting in a simulation model are in line with the improved connectivity concepts. The four physical interventions show the routing options that the trucks and trailers can take in said simulation.

Nr	Information interventions
1	No use of connectivity
2	A given percentage of trucks have a reservation at the GH
3	Knowing the ETA of trucks, a certain time in advance
4	Using both reservations and ETA

Nr	Physical interventions
1	The current situation, trucks can only drive directly to the GH
2	Trucks can drive directly to the GH, or to the CP which can be used as a waiting area, till called by the GH
3	Trucks can drive directly to the GH or the CP. The CP can be used both as a buffer and (de)coupling point. Last-mile transport by traditional trucks
4	Trucks can drive directly to the GH, or to the CP. The CP can be used both as buffer and (de)coupling point. Last-mile transport by AVs

The results of the experiments in the simulation model show that improved connectivity can significantly help in lowering the average throughput time (TPT) and waiting time (WT) of trucks and trailers, as well as lowering the occupation rate at peak moments in the yard of Schiphol. To further explain some of the more interesting results with some examples, the use the settings in the table below. To explain further on these settings, the operation rate is the percentage of all trucks that come to the yard to drop off, pick up, or drop off & pick up cargo. Specifically, the unbalanced rate is 25%/25%/50% respectively. The information intervention column explains which information intervention we use, and the last two columns explains the setting we use if we use an information intervention. The figure below shows the results on average TPT for each of the nine experiments on all four physical interventions. Experiment 5 to 9 do not make a difference for physical intervention 1, since trucks can only drive to and from the GH. Therefore, the figure shows a total of 31 experiment results. It should be kept in mind that the first experiment is always the base scenario, and therefore the other 8 are best compared to this scenario. When looking at using reservations (experiment 2 to 4), it shows that in all scenarios using reservation improves the flow at the yard of Schiphol. The idea behind making reservations is that it leads to peak-shaving. The trucks arriving to the yard on a certain day are more evenly spread over the day and therefore the GHs can better handle the arrivals. The difference in decrease of the average TPT with the very busy arrivals per physical intervention can be found in the figure below. The percentage used for reservations in the model does not always produce very large differences, however for practice it would be beneficial to have a larger percentage, since more of the arrivals are known ahead, which can give more control. However, it could also be a choice to only give trucks or trailers with certain characteristics the option of making a reservation.

Experiment	Operation rate	Information intervention	ETA time known in advance	Reservation %
1	Unbalanced	None	-	-
2	Unbalanced	Reservation	-	25%
3	Unbalanced	Reservation	-	50%
4	Unbalanced	Reservation	-	75%
5	Unbalanced	ETA	30 min	-
6	Unbalanced	ETA	2 h	-
7	Unbalanced	ETA	5 h	-
8	Unbalanced	ETA	12 h	-
9	Unbalanced	Both	5 h	75%



The use of ETA (experiment 5 to 8) does not provide an improvement for physical intervention 2, however with physical intervention 3 and 4 the effect of using ETA is slightly positive. Using ETA slightly lowers the average TPT. However, the effect is not as impressive as the use of reservations. The problems that occurred are that GHs sometimes were idle, waiting on a priority truck or trailer to arrive soon. This waiting time is ineffective and could be improved. Another problem is that ETA is also used for preparing trailers to bring to the CP (de)coupling point to prepare for future peak hours. This helps trucks that arrive during peak hours to only pick up a trailer by making it available to only drive to the CP to pick up a trailer, and not wait in line at the GH. However, a balance needs to be found in preparing for more busy moments, and still having enough space and capacity of (de)coupling at the CP to prevent a long queue. When these two problems are improved, ETA might give a decrease in average TPT. Within the model, there is currently no reason to use both reservations and ETA, since the use of only reservations always works better. However, in practice the use of both can give benefits like both having a peak-shaving effect, but also to make it possible to make data-driven decisions, like calling trucks to the GH from the CP, based on knowing the ETA of trucks in advance.

Preface

The thesis before you is written to fulfil the graduation requirements for the Master's degree in Industrial Engineering and Management at the University of Twente. I learned a lot during this assignment, both on the topic as well as about myself. I have to say that finishing this assignment was one of the biggest challenges of my studies, especially because of the coronavirus, but I am very happy to present this thesis. I hope you enjoy reading it too.

I would like to thank Martijn Mes for your guidance during this project and the valuable feedback you gave. Our meetings were very constructive, and you helped me find the right direction to finish the assignment. Also, I would like to thank Matteo Brunetti for all the fun meetings we had, the discussions about the model and the answers to errors on the strangest times of the day. Thank you very much, it helped a lot.

Furthermore, I would like to thank all the people of TNO involved in my assignment, but especially Elisah van Kempen. Although we had some planning and data issues, you were very kind to take the time for me when needed.

Lastly, I want to thank my friends and family for all the support I got to get me through this time. And of course, to my boyfriend Huub for the help of discussing issues and reading everything to correct my dyslexia mistakes.

Jade van Laar
Enschede, April 2022

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1. Introduction

This thesis is the result of the research performed for the living lab Connected Automated Transport And Logistics Yielding Sustainability (CATALYST). First, we introduce CATALYST in Section 1.1. Section 1.2 covers the problem description, followed by the research setting in Section 1.3. With this information, we determine the objective of the research including the research questions and framework, which is given in Section 1.4.

1.1 Context

This research builds further on the research performed by van Heuveln (2020), who looked into the characteristics of Connected Automated Transport (CAT) and smart yard processes, and how to analyse their potential impact and effectiveness. His research was conducted as part of the CATALYST living lab. The CATALYST living lab focuses on the safety, efficiency, and sustainability of the logistics sector (Janssen et al., 2020). This is done by developing Connected Automated Transport innovations for heavy-duty road transport, testing these innovations, and improving them by making simulations and doing practical experiments. CAT is a collective term that includes technologies associated with connectivity and/or automated transport, and innovations include, for example, truck platooning or intelligent traffic lights (Janssen et al., 2020; Voege, 2017). The scope of CAT innovations in CATALYST is provided in Figure 1. The CATALYST living lab is led by TNO and is carried out by a large consortium of companies. TNO is the Netherlands Organization for applied scientific research and is mainly focused on innovative research. Under CATALYST, logistics partners are aided in measuring the impact of implementing CAT in end-to-end supply chains and to help accelerate innovation. This ultimately contributes to safer, more efficient, and more sustainable transport and logistics. CATALYST is divided into twelve related subprojects divided over three main topics: Smart Yards, Connected Corridors, and Users. This research contributes to the main topic of Smart Yards. In the following subsection, Section 1.1.1, the smart yards concept is explained, together with the difference between regular yards and smart yards. In Section 1.1.2, the use case for this research is introduced.

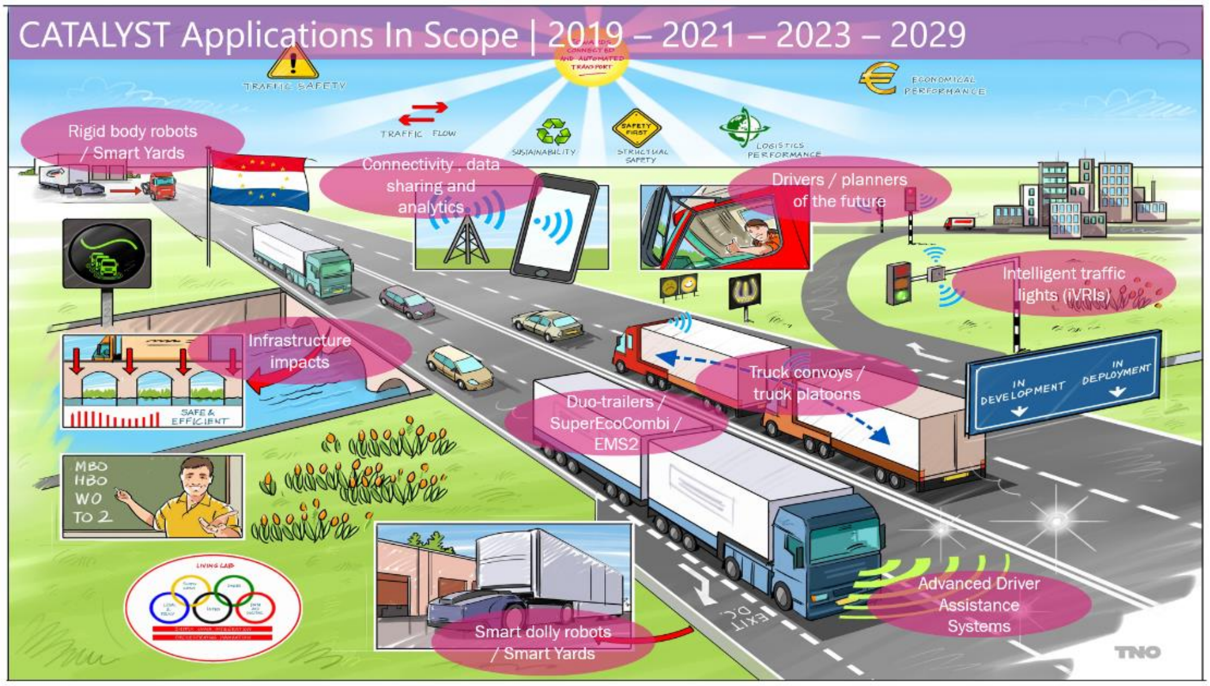

Figure 1: CAT applications in scope

1.1.1 Smart yards

For the concepts introduced in this section, we follow the terminology of Brunetti et al. (2020), who state that a *yard* refers to any logistics hub that is comprised of various stakeholders, transport modalities, terminals, and warehouses for transhipment operations and value-adding services. *Transport modalities* are vehicles that carry cargo, such as trucks, barges, trains, airplanes, or drones. The cargo they carry are loads of products that are usually stored in trailers or containers. A *logistics hub* refers to a seaport, airport, or hinterland distribution centre. Within this hub, there are multiple *logistics centres* (LCs), which refer to any terminal, warehouse, or area for the consolidation of goods. Within one yard, there are usually several terminals, dozens to hundreds of logistics companies, and there can be various parties, such as a port authority, a customs authority, and manufacturing and chemical companies. When Automated Vehicles (AVs) are being used in such a yard, they are typically used in confined areas, are guided, and are not able to handle uncontrollable factors or uncertain events. CAT applications can be introduced within this yard to make the transition to a so-called smart yard. These CAT applications should be able to handle uncontrollable factors such as other transportation means, like passenger vehicles and road traffic, or other obstacles. A *smart yard* includes all entities that influence the flow of goods, also called the physical smart yard, and these entities are aligned through IT platforms, the digital smart yard. The term smart indicates that the logistics process is planned, managed, or controlled more intelligently by, for example, making use of data (McFarlane et al., 2016).

The physical smart yard consists of all physical parties within the yard and the cargo movements between them. These areas can be open or (semi-)closed, which means that entities can either enter the system easily or have more difficulty, respectively. A closed area would make it easier to separate traditional and automated traffic, but this separation is often hard to achieve and therefore not realistic. A smart yard can also feature a central parking (CP) to better control the internal flow within the yard, and this CP can be used by inbound modalities to stop, park, and possibly decouple their cargo. Additional services might be present like a rest area for drivers, showers, a cleaning and washing location for containers, a repair shop, etc. This CP could also work as a pick-up area where trucks can pick up cargo and leave. A possibility is to make use of AVs for the internal handling of cargo. AVs in smart yards are vehicles that do not act completely independently, due to the direct connection and collaboration with other vehicles and resources through an IT system, which may include a central fleet planner. These forms of automated transport can reduce congestion at the yard since they take over some of the transport of human-driven trucks and can drive at less busy times, which can also increase safety. Furthermore, it can allow for higher utilization of resources by continuous operations if the AVs are supported by data, and internal and external flows are separated. The CP enables the separation of the incoming road modalities to reduce the number of human-driven vehicles in the smart yard area, which could be a more realistic solution to this problem. The focus of this research is on the movement of freight between the LCs and between the CP and the LCs.

The transformation to a smart yard requires proper use of the available data and that data is shared among all stakeholders in the yard and to a certain extent within the supply chain. This data can be used for the planning of operations, online rescheduling, and efficient use of resources, and is stored and shared in the digital smart yard. The digital smart yard platform can include all incoming modalities, upstream locations in the supply chain and freight destinations. This digital smart yard is a seamlessly integrated network system in which data is exchanged, stored, and used as input to make decisions. This data can for example be used to perform real-time optimization for the scheduling and routing of vehicles. Figure 2 provides a visualization of the generic smart yard concept. Various external modalities arrive at the physical smart yard where the cargo is consolidated in a LC. Then, the cargo is transported within the physical smart yard from and between the CP and warehouses, which can be done with internal trucks or AVs. At the CP, the cargo is (de)coupled from external trucks to internal trucks or AVs.

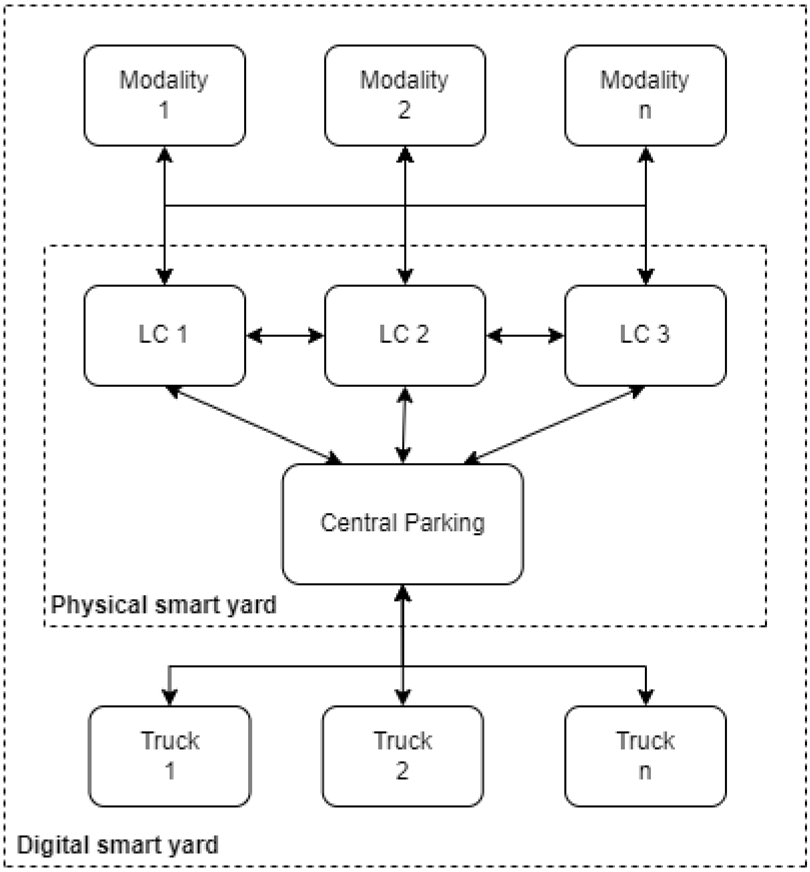

Figure 2: Generic smart yard concept

The smart yard research of CATALYST focuses on four use cases. These are the Port of Moerdijk, Amsterdam Airport Schiphol, the North Sea Port and a distribution centre of DPD. For this research, the focus will be on the use case Amsterdam Airport Schiphol, hereinafter referred to as Schiphol.

1.1.2 Schiphol use case

Schiphol is the main airport in the Netherlands and besides passenger flights, it also facilitates the transport of air cargo. In 2019, Schiphol transported roughly 1.57 million tons of cargo, in around 14.000 full cargo trips (Schiphol Royal Group, 2020). Schiphol has 159 cargo destinations in 83 countries, of which 23 destinations only receive cargo, and no passengers (Royal Schiphol Group, 2019). To make the cargo airport smarter, the Smart Cargo Mainport Program (SCMP) has been established in 2016. The goal of this program is to develop and implement (innovative) solutions, to improve the sustainable, reliable, and safe flow of cargo on Schiphol for the (end) customers, supported by relevant information exchange between the market parties. In collaboration with CATALYST, research has been started to improve the cargo handling process at the landside of Schiphol by using a smart yard. The current situation of the yard at Schiphol will be further explained in Chapter 2.

The motivation behind this use case to transform into a smart yard is mostly because there is great congestion within the Schiphol area. The area of Schiphol consists of an open road, so it is public, and the traffic is not controlled. There is a mix of passenger transport together with freight transport. The congestion in the Schiphol area is caused by (i) limited space at the ground handlers (GHs) and (ii) cargo deliveries that are not regulated. Regarding the first, the limited space at the GHs results in the lack of space at the GH waiting area for trucks that need to drop off or pick up cargo. Therefore, trucks will park alongside the public road and will wait there until they can proceed to the GH parking places. This can sometimes take a long time and results in unsafe traffic situations and congestion.

Regarding the second, unregulated cargo deliveries, the GHs do not have full information about the incoming cargo or the expected arrival time since most trucks arrive unannounced. However, each GH receives a loading list of cargo for the airplane and therefore knows which export cargo should arrive soon. In general, the cargo should be at a GH at least 8-12 hours before flight departure. However, in practice, the cargo from all forwarders arrives at the same time just before the deadline. When multiple trucks arrive at the same time, the GHs do not have enough available docks and personnel, which results in waiting times and the above-mentioned situation. Furthermore, the driver costs are the most expensive for transport companies, and therefore these unpredictable waiting times for truck drivers should preferably be minimized. Being able to control the logistics flow can result in peak shaving. This research takes all these problems of different stakeholders into account by optimizing the overall logistics flow at Schiphol.

1.2 Problem description

As stated by Brunetti et al. (2020), multiple challenges occur for the LCs regarding shorter delivery times, driver shortage, traffic congestion, safety, and environmental concerns. To be able to follow the trends of digitalization and changes in transportation systems, adjustments must be made to transform the traditional yard into a smart yard and thus improve the operational efficiency and environmental footprint. In the use case of Schiphol, there is one big yard that includes multiple logistics companies, which are the GHs. This is called the yard of Schiphol. Within this yard, the main problem is traffic congestion, both in- and outside of the airport area. Furthermore, there is an unpredictable and uncontrollable arrival and departure process of trucks, which leads to flow disruption, more congestion and inefficiency of the process. For this use case, we want to analyse the possibility to become a smart yard using CAT innovations. Previous research by van Heuveln (2020) has been done on automated transport, but limited research has been done on the effects of improved connectivity within the Schiphol yard and how this influences the flow within the yard**.** We define improved connectivity as all actors within a process communicating with each other in real-time, to improve flow and allow decisions to be made on this data. This can include anticipatory arrival time information, real-time data on congestion and waiting times, etc. Since improved connectivity received limited attention, this research will build upon previous research and focus on improved connectivity.

1.3 Research setting

According to Law (2014), and as also mentioned by van Heuveln (2020), there are several methods to study a system, which can be seen in Figure 3. For the Schiphol use case, the actual system exists. However, it is not realistic to experiment with this system directly without knowing the consequences. Therefore, we will experiment with a model of the system. Because of disproportionally high investment costs, a physical model of the system is not realistic, and therefore we will work with a mathematical model. Furthermore, since a smart yard is a very complex system with a lot of different aspects, an analytical solution is not sufficient. Therefore, the preferred option to analyse smart yards is by means of a simulation model, as done in van Heuveln (2020). For this, we make use of discrete-event simulation. With this simulation model, we simulate the flow of cargo in the Schiphol area. The flow consists of the arrival of cargo at Schiphol until the cargo is delivered at the GH for export and the other way around for the import of cargo. With this model, we can test different connectivity options and check the results to decide if one of these options would be beneficial for the yard of Schiphol.

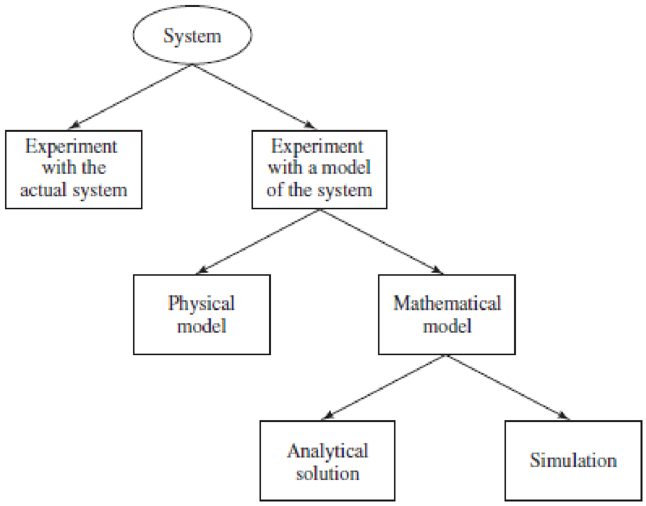

Figure 3: Ways to study a system (Law, 2014)

1.4 Research Design

As mentioned before, our research focuses on the impact of improved connectivity on the cargo transport flow within a smart yard implementation for Schiphol. Therefore, this research will focus on the following research question:

"How can improved connectivity be achieved within the yard of Amsterdam Airport Schiphol, and what will be the impact of this improved connectivity on the cargo transport flow within the yard, by making use of a Central Parking and preferably automated vehicles?"

In order to answer this main research question, several supportive sub-questions are formulated. These questions guide the research and eventually lead to answering the main research question. This research answers the following sub-questions:

1. *What are the characteristics of the yard of Schiphol and what does the* cargo *transport flow look like?*
   First, we conduct research on the use case of the yard of Schiphol. We look at all stakeholders involved in the flow and where the GHs are located at this yard to understand where trucks drop off and pick up cargo. We define all important characteristics of this yard and explain the flows relevant to this research to be able to design a simulation model of the yard of Schiphol.

2. *What is connectivity and what different concepts of improved connectivity are defined within literature?*
   We study relevant literature related to this research. We further elaborate on improved connectivity, what it is and what it is useful for. Then, we look at different concepts in the literature to achieve improved connectivity that might be useful for our use case.

3. *Which concepts from the literature are the most suitable for the use case of Schiphol?*
   We select different concepts for improved connectivity found in the literature that may be useful for the case of Schiphol. Then, we define how to use these concepts in practice. A simulation model later tests these concepts to determine which ones are most beneficial for the yard of Schiphol.

4. *How to design a simulation model to study the impact of the improved connectivity concepts on the cargo transport flow within the yard of Schiphol?*

To test the impact of the different concepts of improved connectivity on the Schiphol yard, a simulation model needs to be made. Using this simulation model, it is possible to experiment with different situations and visualize the impact of different improved connectivity concepts based on different Key Performance Indicators (KPIs). We develop a conceptual model for this simulation model. We keep the building blocks for the simulation as generic as possible, to support the reusability of these building blocks in future use cases.

5. *What is the potential impact of the chosen improved connectivity concepts on the cargo transport flow at the yard of Schiphol?*
   The different concepts for improved connectivity are tested in the simulation model using different interventions and scenarios. We evaluate the outcomes of this based on different KPIs from RQ4. We determine the added value that improved connectivity can deliver to the cargo transport flow of the yard of Schiphol based on these KPIs.

The outline of this report is given in Figure 4. This overview links the research question to the specific chapters and clarifies the steps taken in this research.

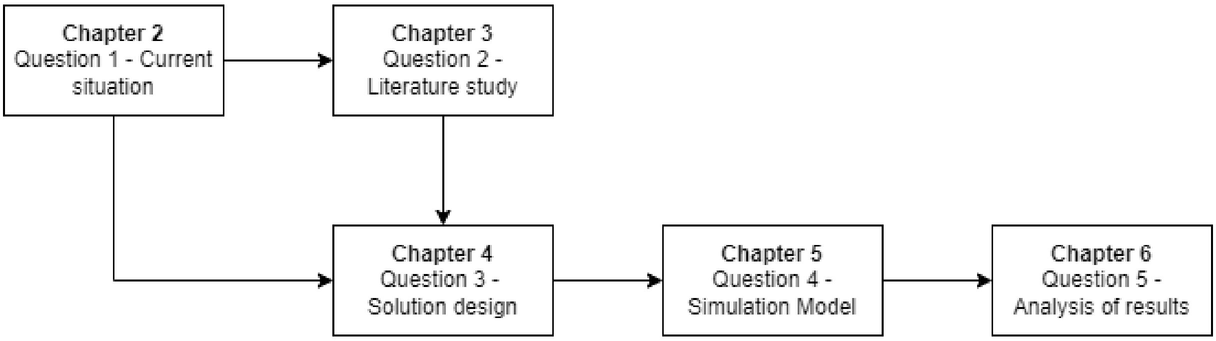

Figure 4: Research outline

2. Amsterdam Airport Schiphol

This chapter describes the yard of Schiphol. We first introduce the stakeholders in Section 2.1 and describe the logistics processes at Schiphol in Section 2.2. In Section 2.3, we provide the characteristics and specifications of Schiphol using the conceptual framework of van Heuveln (2020). Lastly, we describe the Schiphol area in Section 2.4.

2.1 Stakeholders

There are several stakeholders involved in the process of import and export of air cargo at Schiphol. We describe the following stakeholders for this research:

- **Shippers**: suppliers of cargo to be transported.
- **Carriers**: trucking companies that transport the cargo, commissioned by forwarders.
- **Forwarders**: on the instruction of the shipper, the forwarder organizes the door-to-door transportation of the cargo through carriers. More specifically, the forwarder books the shipment with an airline, possibly consolidated with other shipments (Burghouwt et al., 2014).
- **Ground handlers**: collect cargo for export from the forwarders and distribute import cargo among the forwarders. They also build up and break down special flight pallets to do this. Furthermore, they transport and load the cargo into the airplane and vice versa (Burghouwt et al., 2014).
- **Airlines**: transport the cargo by air and instruct a specific GH to handle its cargo for flights (Burghouwt et al., 2014).

For this research, we only take carriers and GH into account. Both the shipper, forwarders and airlines are out of the scope of this research. More specifically, we only consider the transport at the yard of Schiphol performed by the carrier to and from the GH.

2.2 Logistics process

The logistics cargo process flow can go both ways for the import and export of cargo, of which Figure 5 provides a visualization. For the export, the cargo is transported by the carrier from the shipper to the forwarder (flow 1), this forwarder can be close to the Schiphol area, but also further away. This forwarder books the shipment with an airline, or multiple shipments if the cargo consists of multiple packages that need to go to different locations or destinations. Each airline works with one GH to prepare cargo for air shipment, this GH also loads and unloads the plane (flow 4). Since multiple shippers make use of the services of the forwarder, the forwarder can also consolidate shipments from different shippers that need to go to the same GH. Then, the cargo is transported to the right GH (flow 2). The GH consolidates cargo from different forwarders for the same airplane and prepares this cargo on special pallets for the airplane. Another option is that cargo does not arrive from a forwarder, but by direct transportation from another ground handler at another airport (flow 3). Since this transport is mostly international transport, this method is designated as an international road feeder. All cargo should be delivered at the GH before a fixed predetermined time, so the GH can load the airplane on time and the airplane can depart on schedule with all cargo on board. The GH works with very tight time schedules to load and unload the plane. If the shipment of a carrier is late, the plane will not wait. To make sure the GH can fully load planes, they prefer to have cargo early, so they have backup cargo when a shipment is late. It is important to have fully loaded planes, both for profit and for good weight distribution in the plane.

The import process starts by taking out the cargo from the airplane, which is then transported to the GH. This cargo needs to be distributed to multiple forwarders and some of this cargo might be transported by an international road feeder to another GH at a different airport. Forwarders will pick up the cargo, and the cargo will be transported to their warehouse. The carriers pick up the cargo at the forwarder and transport the cargo to the right address, which sometimes happens through distribution centres.

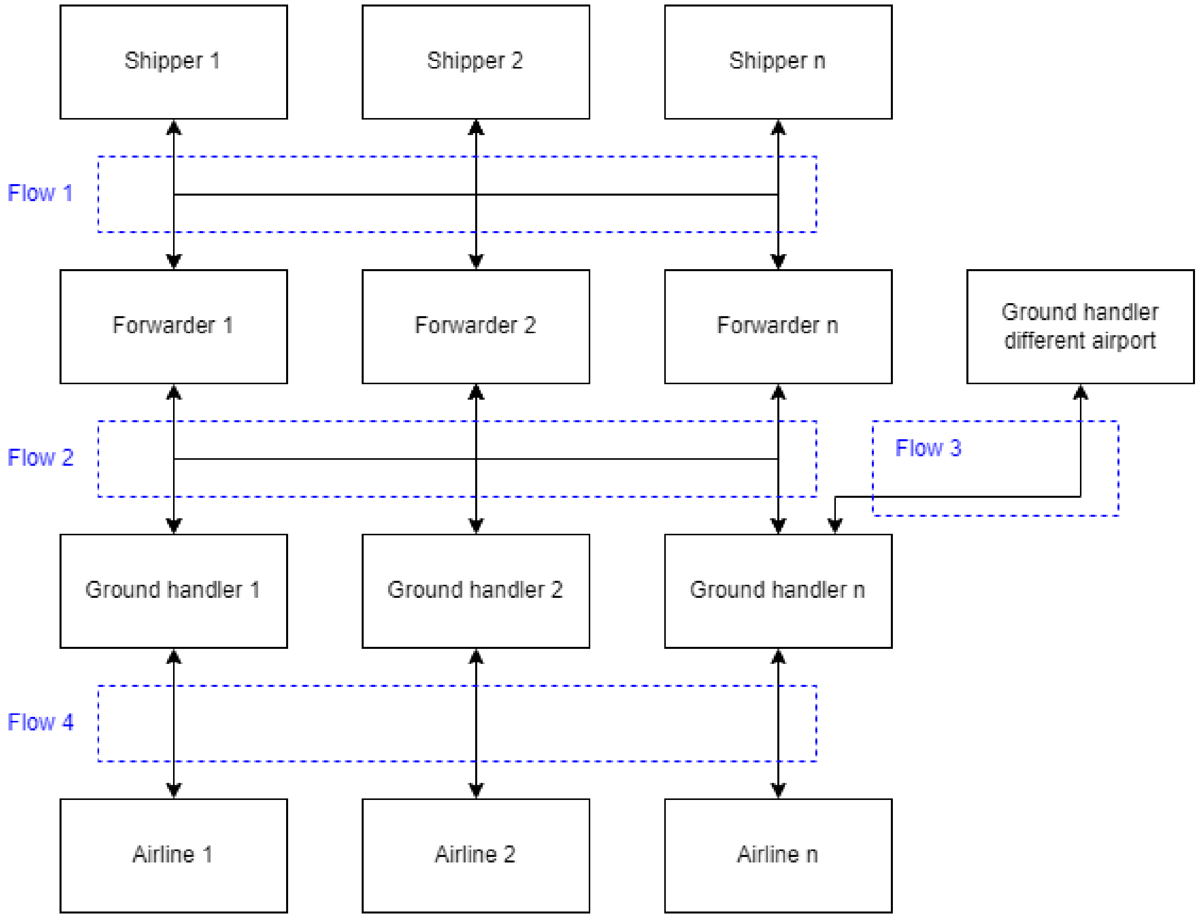

Figure 5: Logistics process Schiphol

2.3 Schiphol characteristics and specifications

According to van Heuveln (2020), the conceptual framework for smart yards can be used to determine the characteristics of the smart yard. Following his framework, Table 1 shows the characteristics of the yard of Schiphol. These characteristics can be used as the input for the smart yard concept.

Table 1: Characteristics of Schiphol

Type	Characteristics
Modalities	Airplane, truck
Distance	Medium
Cargo type	Trailer
Product type	General, dangerous, perishable
Environment	Hub-to-hub
Flow scale	Average shipments at forwarder: 30 at normal days, 110 at busy days
Flow timing	Peak during weekdays, weekend is less busy
Handling	Manual
Job type	Pick up, drop off, routing

2.4 Schiphol area

Now we go into more details on the Schiphol cargo area and the stakeholders in this yard including some specifications that will be used as input for the simulation model. We first describe the ground handlers, then the multiple truck parking areas, followed by the truck arrivals.

Ground handlers
There are five GHs located at Schiphol. These are Dnata, KLM cargo, Menzies (MZ), Swissport (SP), and World Flight Services (WFS). Figure 6 shows the cargo area of Schiphol and where these five GHs are located in orange. As can be seen, two of the forwarders are on the north side of a landing strip and three are located below the same landing strip. These GHs are supplied by around 300 forwarders located near the Schiphol area (van Heuveln, 2020). Table 2 provides the distribution of cargo among the five GHs, including the number of docks used for loading and unloading and the number of parking spaces at the GH that can be used as a buffer for trucks to wait till a dock is free. This information was gathered by van Heuveln (2020) and complemented by information from Google Maps and Versleijen (2021). Van Heuveln (2020) gathered this information from experts that are working at various companies at Schiphol and using the paper of Romero-Silva & Mujica Mota (2021). The resulting data is validate by Versleijen (2021), who mentioned that MZ, SP and WFS together process more than 50% of this arrivals at Schiphol. No further information was available about the time windows of orders, or the number of orders for import or export.

Figure 6: Locations ground handlers (orange), Location's truck parking's (blue), Locations entrances (yellow)

Table 2: Specification of ground handlers at Schiphol

Specifications	Dnata	KLM cargo	MZ	SP	WFS
Probability of arrival at GH	8%	37%	23%	19%	13%
Number of docks	11	24	20	17	9
Parking places	19	20	17	12	5

Truck parking's
According to Air Cargo Netherlands (2018), there are three parking areas that can be used by trucks within the Schiphol area, these are so-called truck parking's (TPs). In Figure 6 the location of these TPs

can be found in blue. Two of these truck parking areas can be used by members paying a monthly rate, while the third parking can be used by paying an hourly rate. In Table 3, more information about the TPs can be found, which was gathered from Air Cargo Netherlands (2018) and we complemented with information from Google Maps. These three TP areas are in use since 2018 and offer a fully-fledged and safe parking solution. The idea was that these parking's would improve the flow and traffic safety within the Schiphol area. However, at this moment there is no obligation to use these TPs and the benefits of using these areas does not outweigh the costs, according to an expert from Air Cargo Netherlands. For our research, we use TP 3 to serve as a CP, since this is the most central TP considering the whole area of Schiphol. At this CP, the trucks can wait until they are called when a dock at the GH is available. Of course, this CP can also be used as a pick up or drop off point where cargo can be coupled or decoupled by trucks. Furthermore, this CP could also serve as an idle positioning place for AVs that are used for the internal handling of the yard.

Table 3: Specification truck parking's

Truck parking	Fee	Capacity
1	Monthly	160
2	Monthly	70
3	Hourly	70

Truck arrivals

Currently, there is no complete information about the incoming cargo or the arrival time, because most trucks arrive unannounced. For the export process, the GH receives a loading list for the airplane, and therefore knows which cargo should arrive at the GHs, but more information, for example on the expected arrival time, is not available. In general, the cargo should be at the GH 8-12 hours before flight departure, but in practice all cargo from different forwarders arrives just before this deadline. This leads to high peaks, and the GH is unable to handle these high peaks. For the import process, the trucks need to pick up cargo, but it is also unknown when these trucks will pick up the cargo.

To arrive at the Schiphol cargo area by road, two entrances can be used. There is an entrance on the South-side of the landing strip, which is an exit of the N201 road, and an entrance on the North-side of the landing strip, which is an exit of the E19 road. Both entrances can be found in Figure 6 in yellow. NDW, which is the national road traffic data portal, placed sensors in those roads and collects data about the flow of traffic. We used NDW OPEN DATA to collect data from the sensors around the Schiphol yard. Unfortunately, not all sensors were functioning in 2019 and 2020, but we used the sensors at the south side of the yard, on the N201 road, to provide information about the arriving trucks at the yard of Schiphol. The data shows the average number of trucks passing the sensors per hour and can be found in Table 4. It should be kept in mind that these numbers do not tell us how many trucks actually entered the yard of Schiphol, but how many trucks pass the specific sensor on the road next to the entrance.

As can be seen in Table 4, there are more arrivals during the weekdays than the weekends. When looking at the distribution of the arrivals over the weekdays, we can conclude that no large differences exist between the different weekdays. Also, no big differences occur in the total number of arrivals, as well as in the distribution of arrivals through the day. The only exception is Friday evening, where there are less arrivals than at the same time on the other weekdays. In general, Saturday and Sunday are far less busy than the weekdays. However, while Saturday follows almost the same distribution of arrivals over the day as the other weekdays, Sunday does not. On Sunday the arrival intensity grows as the day progresses.

Table 4: Average number of trucks passing the N201 road sensor

Hour	Mon	Tue	Wed	Thu	Fri	Sat	Sun
00:00-00:59	27	37	34	29	34	18	8
01:00-01:59	22	30	25	23	30	16	8
02:00-02:59	27	29	27	27	28	19	7
03:00-03:59	42	46	40	42	43	22	12
04:00-04:59	84	80	74	76	83	29	13
05:00-05:59	109	111	104	105	116	47	15
06:00-06:59	119	122	115	121	133	56	18
07:00-07:59	141	141	128	135	149	55	21
08:00-08:59	152	149	131	147	155	58	26
09:00-09:59	159	154	143	141	161	51	25
10:00-10:59	152	145	142	125	154	46	24
11:00-11:59	168	148	133	129	153	44	26
12:00-12:59	157	145	133	131	148	40	23
13:00-13:59	151	134	113	118	132	33	23
14:00-14:59	125	113	94	100	115	26	23
15:00-15:59	98	92	85	83	96	26	22
16:00-16:59	85	84	71	66	75	20	27
17:00-17:59	76	70	61	63	64	16	32
18:00-18:59	74	70	62	64	54	16	36
19:00-19:59	63	61	56	56	43	14	33
20:00-20:59	55	53	46	47	34	13	32
21:00-21:59	47	48	42	43	29	11	31
22:00-22:59	45	41	38	44	24	11	29
23:00-23:59	39	35	31	38	19	10	28
Total	**2190**	**2101**	**1894**	**1924**	**2038**	**679**	**534**

3. Connectivity in logistics

In this chapter, we first describe connectivity in Section 3.1, we then go into more detail on the preconditions, barriers, and opportunities of connectivity in Section 3.2. Then, we explain some connected applications in Section 3.3 and lastly, in Section 3.4, we explain the applicability of these applications on the use case of Schiphol.

3.1 Connectivity

A vast amount of literature can be found on connected vehicles and their applications, or the physical connectivity of cities or ports with each other (e.g., Jadaan et al. (2017), Krasniqi & Hajrizi (2016), Wang et al. (2016) and Bodhani (2012)). However, the literature on connected logistics or connected transport is more scarce. In the literature, both the terms network connectivity and digital connectivity are used. In this research, we deem those to be equal and generalize both under the term of connectivity. As explained in the introduction, connectivity is the digital communication between all actors in a process, which preferably happens in real-time. This can be seen as an information flow between stakeholders. This allows decisions to be made based on the data, and to optimize the freight flows. The idea behind connectivity is to allow stakeholders to exchange information and data, to be able to have a fast reaction to different situations and thus reach shared goals (Da Silva Serapião Leal et al., 2019). Using connectivity enables logistics companies to update and monitor current locations and the status of moving persons, trucks and cargo (Yeun et al., 2015). Furthermore, sharing this data solves the creation of "information islands" and promotes integration between members of the supply chain (N. Zhang & Zheng, 2020). The above-described connectivity is vital for the structure of digital supply chains, which in turn are essential to achieve efficient processes and to gain a sustainable competitive advantage (Büyüközkan & Göçer, 2018). Thus, the role of connectivity in optimizing supply chain processes is vital.

Horizontal and vertical integration partly enables the cooperation of actors within the supply chain and allows data to flow freely and transparently to make data-driven decisions. It helps to respond appropriately and quickly to changes and new opportunities (Schuldenfrei, 2019). Achieving real-time data sharing unlocks the considerable potential of increasing effectiveness and responsiveness, increased resilience towards changes and unplanned events, and can help improve aligned decision-making among different stakeholders (Zafarzadeh et al., 2019). According to Brahim-Djelloul et al. (2012), real-time information is defined as "information that constantly allows action on the system in order to react rapidly and in suitable ways with respect to environment dynamics". In considering which information is real-time, and which information is no longer usable, Brahim-Djelloul et al. (2012) argue that when information is still relevant and valid after collection and processing, it can be considered real-time.

According to Queiroz & Fosso Wamba (2020), there are six dimensions related to connectivity in supply chains and logistics. These dimensions should enable all actors involved in the process to interact in a streamlined and appropriate manner, to enable maximal value generation in the network. These dimensions are:

- *Smart*: this dimension represents smart applications that are used internally, as well as in the entire supply chain.
- *Innovative*: this dimension refers to a significant opportunity for making improvements to the process.
- *Measurable*: this dimension relates to the level of interoperability and indicates the efficiency generated by connectivity and the results achieved.
- *Profitable*: this dimension relates to value created through connectivity and the resulting profit for the organization.
- *Lean*: connectivity should create a Lean relationship with stakeholders and use technologies that support the Lean operations.

- *Excellence*: this dimension refers to an implementation of technology that supports real-time interactions and enables all actors to be connected in different layers, with the final goal of maximizing value. It is about optimizing the level of services, *interconnection*, and *interoperability* in the supply chain.

In these dimensions, the term *Interconnection* refers to the connection between supply chain partners that is enabled by technology. The goal of interconnection is to obtain and share real-time information to maximize value and take personalization requirements into account (Min et al., 2019). The term *Interoperability* refers to the interaction between supply chain partners that is supported by suitable technologies, which in turn foster information sharing and the utilization of exchanged information (Da Silva Serapião Leal et al., 2019).

3.2 Connectivity preconditions, barriers, and opportunities

To implement connectivity in a process or organization, it is important that technologies are available to support it. Connecting technologies enable different stakeholders within the supply chain to communicate wirelessly and to share data with each other. Da Silva Serapião Leal et al. (2019) mention that connectivity should be continuously improved and verified in order to ensure the information exchange and related decision-making processes remain valid. Shladover (2018) gives an overview of different wireless communication technologies in the transportation sector:

- *Dedicated Short Range Communications* (*DSRC*) are specifically designed for road transportation applications. DSRC is a Wi-Fi-like technology that relies on licenses and a protected spectrum. It supports time-critical and safety-critical messages over a limited range.
- *Wi-Fi* has a relatively long connection latency. When the channel is congested, Wi-Fi is vulnerable to delays and packet losses. So, dependent on the information that has to be transferred, Wi-Fi can be a solution. For critical information, Wi-Fi is not the best technology to use.
- *Cellular communications* span the technologies of 4G LTE, WiMAX and 5G. The existing cellular systems can be used in a very cost-efficient manner. The infrastructure in built-up areas provides full coverage and therefore there is no reliance on other public agencies. However, all involved stakeholders need to pay the network operator for data usage. Furthermore, according to Coronado M. et al. (2009), this communication technology does have some reliability and connectivity problems and has difficulties associated with limited range, scalability and security.
- *Satellite communication systems* can be used in remote areas that lack cellular services. However, this communication technology faces significant costs, bandwidth, and latency limitations, and is therefore not suitable for all applications.
- *Bluetooth* is a very short range and low bandwidth service to support some applications. However, due to its short range, this technology is not suitable for connectivity in logistics.

Depending on several factors, such as the kind of data, the speed at which data has to be transferred, and if the data is 'mission-critical', a different mode of communication should be chosen.

In essence, Information and Communication Technology (ICT) plays a key role in facilitating the exchange of information amongst the stakeholders in a supply chain. Without it, the stakeholders are not able to contribute to the efficiency and responsiveness of the supply chain (Coronado Mondragon et al., 2009). Mobile ICT has a substantial role in road transport logistics because of more accessibility to detailed information that is being shared. Mobile ICT enhances visibility in multimodal logistic operations and provides further levels of detail and information exchange capabilities (Coronado Mondragon et al., 2009). Visibility within the supply chain can be defined as the awareness and control over the end-to-end supply chain information. It includes the knowledge and insight on sources of data and whereabouts of operating assets and goods (W. Hofman et al., 2016; Pettit et al., 2010). Hofman

(2019) also states that visibility enables a supply chain that is agile, resilient, sustainable, compliant and trusted.

Of course, there are barriers related to data-sharing within the supply chain. Eckartz et al. (2014) define five main categories of barriers to data-sharing: (i) technical, (ii) data quality, (iii) ownership, (iv) privacy and (v) economic. Arshinder et al. (2008) translate categories into problems such as (i) incompatibility of software solutions, (ii) a lack of skills and knowledge during implementation, (iii) the unwillingness of members of the supply chain to share information, and (iv) possible misalignments of motives. In the transition to data-sharing, it is not unusual that companies have different technologies they use within logistics systems, which can result in problems of software incompatibility, lack of interoperability leading to low information visibility, a long response time and low efficiency (Khurana et al., 2010). Furthermore, a really important aspect of data-sharing is that collaborations are based on mutual trust (Daudi et al., 2017). However, according to Eckartz et al. (2014), most barriers concerning data-sharing are in the field of privacy or competition regarding economically sensitive data.

An opportunity for improved connectivity in combination with automation is that, in addition to autonomous driving, the system and the vehicles in it are capable of automated decision-making. This is done by connecting the vehicles with their environment, thus granting automated vehicles access to real-time data. The information that is exchanged and obtained by the vehicle can be used to make decisions and automate actions (Shladover, 2018).

By sharing information and increasing visibility, the opportunity arises to improve decision-making based on the increased situational awareness. Caridi et al. (2014) provide a detailed elaboration on the many advantages of process visibility, such as time and costs reductions. However, the primary purpose of the process visibility is to improve the performance of the company or the supply chain (Caridi et al., 2014). By synchronisation of processes, for example, inventories can be reduced, and service-levels can be improved. This process synchronisation, according to Hofman et al. (2016), requires three things. First, it requires the sharing of knowledge of the location of physical objects. In case these physical objects are transportation means, it also requires their speed and direction. Second, it requires any relations between physical objects, like object A transporting object B. An example of this is a container that is being transported by a truck. And lastly a prediction of the time for completing a particular logistics operation is needed. This prediction of time can be various, like:

- For transport operations, the following relevant times can be predicted:
  - Estimated Time of Arrival (ETA) of the object at a location, e.g., a vessel in a port.
  - Estimated Time of Departure (ETD) of the object, which can be calculated by the Actual Time of Arrival (ATA) and the predicted duration of the process at the location, e.g., the loading time at a terminal.
- For transshipment operations, the following times are relevant:
  - Estimated discharge time of cargo, which provides information on when cargo can be picked up for the next step in the supply chain.
  - Estimated (un)loading time of cargo objects on transport means.

Sharing knowledge and data about the process, including the sharing of information when disturbances occur or times change, will help to optimize the flow in the supply chain and help improve data-driven decision-making.

3.3 Connected applications

A more in-depth explanation of connected applications, paired with examples from the literature, can be found in this section. Nowadays, there are many applications that use wireless communication technologies. These applications can connect domains like homes, wearables, and e-commerce platforms. All these applications in the domains are connected via the internet, also known as 'the cloud'. By using smart instruments like a smartphone or tablet, the applications can be controlled, perform tasks, or provide information. This information allows data-driven decision-making. For the transport sector, there are also applications that can be used to allow similar connections. In the following paragraphs, some of these will be explained.

3.3.1 Track and trace

Track and trace is a widely known concept that is mostly used in the business of transporting parcels. Using track and trace means that each parcel has a barcode or Radio Frequency Identification (RFID) tag. Scanning the code/tag provides information on the current and previous locations of the parcel. This information is updated during each step in the transportation process and is saved in a database. The benefits for consumers are twofold. First, they can receive information on where the parcel currently is and second, they can also see the estimated arrival time of the parcel at the delivery address. Due to the application nature of track and trace technology, no relevant literature was found that applies track and trace to use cases similar to Schiphol. Therefore, track and trace will be disregarded for the use case we are considering.

3.3.2 Geofencing

According to Reclus & Drouard (2009), the concept of geofencing is used to monitor mobile objects, which can be vehicles, persons, containers, etc., within a virtual boundary around a geographic area. The concept makes use of a GPS connection and determines whether a tracked object is inside or outside the geofenced area. If an object exits or enters the geofenced area, it generates an alert allowing operators to intervene. Geofencing can be used to track and monitor freight that enters a specific geofenced area. This allows companies that are located within the area, or enter the area to pick up objects, to exchange information like ETA. There are different techniques of geofencing to meet different pragmatic needs:

- *Geofenced area*: this technique works with a geofenced area making use of automatic monitoring of mobile objects within this area. When these monitored objects enter or exit the boundary, an alert is generated. The size and shape of the geofenced area can be small or large, and simple or complex.
- Figure 7 provides a visualization of a geofenced area.

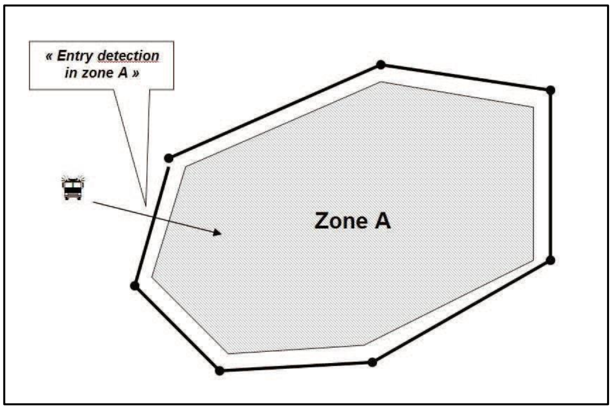

Figure 7: Geofenced area (Reclus & Drouard, 2009)

- *Proximity with a point of interest*: This technique makes use of a circular area with a point of interest at the center. This technique is intended to detect the distance between an object or vehicle in relation to the point of interest. Figure 8 provides a visualization of proximity with a point of interest.

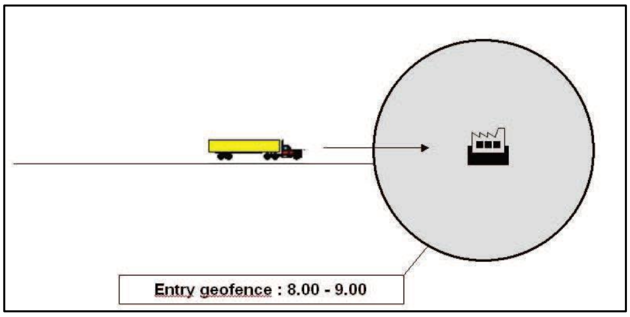

Figure 8: Proximity with a point of interest (Reclus & Drouard, 2009)

- *Route adherence*: this technique is used to monitor a mobile object from a departure point to a destination. Geofencing gives an alert if the vehicle deviates from its allocated route. Figure 9 provides a visualization of route adherence.

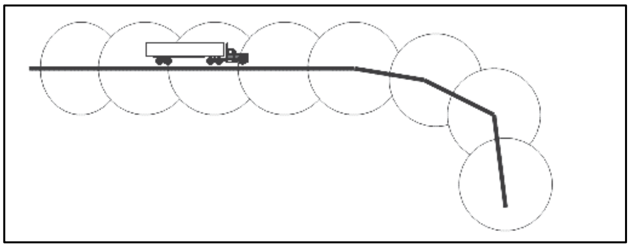

Figure 9: Route adherence (Reclus & Drouard, 2009)

- *Route and schedule adherence*: this technique is similar to the previous technique but includes the relation to a schedule. It monitors the object on the allocated route in relation to an allocated schedule. These can be compared to checkpoints. Figure 10 provides a visualization of route and schedule adherence.

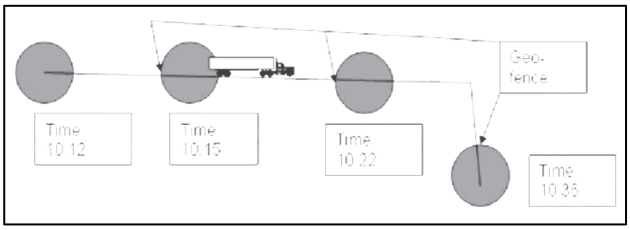

Figure 10: Route and schedule adherence (Reclus & Drouard, 2009)

Even though geofencing is a well-established and not necessarily novel technique, little literature can be found on applications that match the Schiphol use case. One such study is the UK's FMCG industry, as described by Wang & Potter (2007). Through the use of a geofence, specifically the proximity with a point of interest type, for real-time tracking in cargo transportation, many benefits regarding delivery management and overall efficiency are found. By having a geofence system in place that sends an alert with ETA to a destination location when a truck departs from its origin location, a much-improved operational planning can be made.

3.3.3 Platforms

Another concept that can help with connectivity is a digital platform, which we will simply refer to as platform. A platform is an online reachable application where information can be shared, and different actors can communicate with each other in a simplified manner. A platform can satisfy the increasing need of stakeholders to be better connected with other stakeholders, being more time- and cost-efficient, and combining information from various stakeholders. By implementing a connectivity platform, data exchange between different stakeholders can be simplified and visibility can be increased (Fanti et al., 2019). A platform can also deal with more complex supply chains and a lot of stakeholders. Fanti et al. (2019) state that with the use of ICT, a platform creates an information-sharing eco-system that results in better responsiveness and efficiency of the supply chain. All stakeholders can make use of an internal interface called dashboard that allows quick access to different information on the platform. Also, it is possible to manage data access permissions for all stakeholders. To make the platform successful, it is important that all stakeholders trust the platform and each other, that the platform is updated in a timely and accurate manner, and that actors think outside of their own system. This last dimension is especially important, as information that is crucial to an actor, can also be of value to other actors in the system (Gustafsson, 2007).

In the world of logistics, freight mobility is key. In current literature a multitude of examples can be found of platforms that aid the freight transportation process. All of these platforms are aimed at improving or altering one or more links in the supply chain, varying from the matching of freight to carriers (Zhou et al., 2021) to ways last-mile delivery in urban areas can be improved (Martins et al., 2019; Y. Zhang et al., 2019).

Connectedness in these platforms can go into several directions, all adding value in distinct ways. Introducing manners to improve the last-mile delivery is a first example of this. By utilizing an information sharing platform, smaller loads (i.e., consumer packages or less than full truckloads) can be aggregated to achieve a reduction of the number of truck trips required to fulfil all deliveries (Martins et al., 2019). Examples of such platforms are described by de Souza et al. (2014), who describe the opportunities of an 'e-market' for logistics service providers in Singapore, to allow for the generation of efficient routing options, and by Zhang et al. (2019) who demonstrate the superiority of consolidating orders in the last-mile through integer programming. In each case, the truck trip reduction associated with last-mile delivery consolidation leads to a reduction of costs and environmental impact, as well as an improvement in efficiency.

An expansion of the last-mile delivery consolidation are freight matching platforms. By better connecting the supply of freight carriers and the demand of freight shippers, the efficiency of both parties is increased (Zhou et al., 2021). In essence, such a platform performs the same as the above-described platform, but its capabilities are expanded to short-haul and long-haul trips. By being a more open platform compared to the traditional broker structure, smaller freight carriers are better able to provide services to customers, allowing for an increased free market function (Zhou et al., 2021). This is demonstrated through the example of Uber Freight, which since its launch has grown to connect 400,000 drivers, 36,000 carriers and 1,000 shippers in 2018 (Uber Technologies Inc., 2019). A variation on such a freight matching platform is a multi-modal online exchange platform, which expands the ways it connects shippers and carriers to a multitude of transportation forms. Instead of the sole focus on truck transport, rail, air, or ocean transport can also be considered and implemented in the platform (Jain et al., 2020).

Oftentimes these forms of logistics are referred to as collaborative logistics, a form of logistics where shippers and carriers communicate with each other, and coordinate their efforts, to achieve improved performance and profitability (Lin et al., 2012). Collaborative logistics can span from solely the sharing of information to the creation of a joint planning or even a joint execution of the logistics operations. Whereas the connected platform examples above are more focused on the joint execution of logistics operations, a more common connected platform occurrence is that of collaboration through the sharing of information. This sharing of information allows actors in the process to adapt their own processes to that of the other actors, increasing overall flow and efficiency in the process (Coronado Mondragon et al., 2009; Fanti et al., 2019; Gustafsson, 2007; Irannezhad et al., 2017).

An example of information that can be shared on a platform is from Douma (2009). Douma (2009) presents a so-called *service-time-profile*. The service-time-profile shows the guaranteed maximum waiting time per hour of the day till served. An example of a service-time-profile can be found in Figure 11. In their use case, the service-time-profile is provided by a terminal to show the guaranteed maximum service time for an inland vessel. Of course, this is dependent on the time of arrival of the vessel. The service time of the vessel is the total waiting time together with the handling time at the terminal. In the example, this service-time-profile is provided by each terminal to each vessel. A benefit of this method is that vessels can optimize their route along several terminals and know their maximum waiting times in advance. But they can do this without the need for terminals to share sensitive information. The shared service-time-profiles only provide an upper bound on the sum of the service and waiting time, without revealing the source of, e.g., a long waiting time that could be caused by many barges that need to be handled at that time or having only a limited number of staff and/or cranes working at

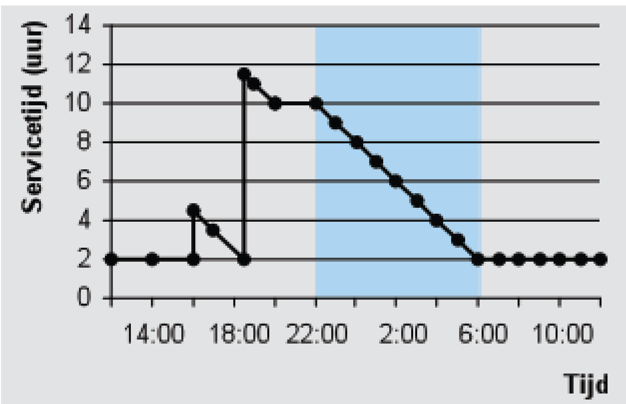

Figure 11: Example of service-time-profile (Douma, 2009)

that time. This method can decrease waiting times a lot when a vessel needs to visit multiple terminals. However, a disadvantage of this method is that the service-time-profile changes every time a vessel chooses to go to a certain terminal, and therefore is different for each vessel. The waiting time is dependent on the loading times of the vessel and other activities at the terminal for other vessels, which has an effect on the service-time profile.

Another example of an information sharing system, aimed at connecting actors that transport freight around a central hub, is the Port Community System (PCS). A PCS is aimed at encouraging all connected actors to share information, with the overall goal of improving the logistics process for all those involved (Irannezhad et al., 2017). A PCS can also be defined as an inter-organisational system that integrates private and public actors, technologies, systems, and processes. By doing so, a PCS enables communication between all connected organisations that operate in the port area (Heilig & Voß, 2017). For example, by having incoming actors sharing information like ETA through the PCS, actors further on in the process can adapt their schedule to allow for a better overall flow. A relevant example of a PCS is the Portbase platform of the Port of Rotterdam. This third-party platform connects the harbour, all freight processing partners and any freight transport companies, and allows for easy and secure information sharing (Portbase, 2021).

Another example is the use case of the Trieste port, as described by Fanti et al. (2019). Here, a platform is designed to share information in real-time among different stakeholders and users, by aggregating and creating data from multiple sources in the logistics sector. The access to the port of Trieste is often blocked by queues at its gates, caused by extensive administrative and customs procedures due to the nature of Trieste being a free port. The Trieste port also wishes to use the platform to optimize the customs procedures by pre-clearing trucks before arrival at the port. The proposed platform gathers real-time, actionable information from both the sides of the port and from the trucks, to allow for the sharing of said data. Due to sharing the data, both sides possess more data, allowing for data-driven decision making. The use case of the Trieste port shows similarities with the use case of the Port of Gothenburg, as described by Gustafsson (2007). This port is also troubled by efficiency issues, resulting from of the lack of information on the port side. Those tasked with operational coordination can only work reactively, leading to inefficiencies. By incoming vessels sharing ETA and ETD on a central platform, the platform can function as a broker and provide vital information to different stakeholders. How such a platform should function is described by, amongst others, Coronado Mondragon et al. (2009), whom detail the connecting of inbound transport to the port and the shipping companies, through a central port network. An impression of such a platform can be found in Figure 12.

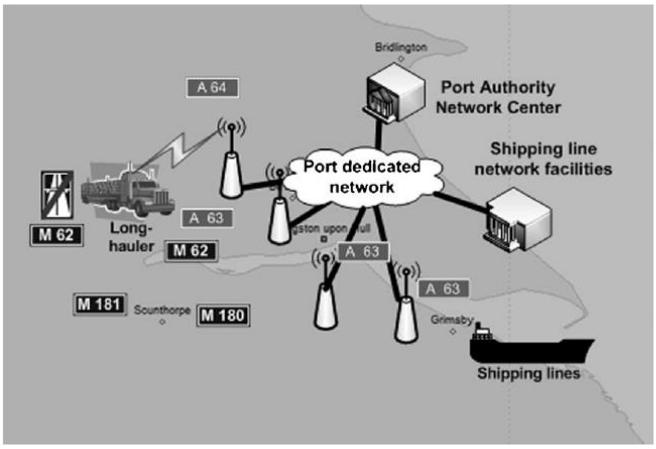

Figure 12: Example central port network (Coronado Mondragon et al., 2009)

3.4 Applicability of existing literature

We reviewed a large selection of existing literature in the search of studies that apply the concept of connectivity of information flows to a yard, with the goal of transforming the yard into a smart yard. A variety of connectivity techniques were gathered, which in themselves do not fully satisfy the transformation to a smart yard. Based on this selection of literature, there are different ways to implement connectivity with the main goal of allowing stakeholders to exchange information and data.

These implementations all have the objective to enable a faster reaction to unplanned situations and to better reach shared goals (Da Silva Serapião Leal et al., 2019).

This means that if a yard has to deal with incoming cargo streams with an arrival uncertainty, and that cargo has certain due dates by which it has to be processed, we can propose several connected applications that might be of added value. For a yard with these characteristics, like Schiphol, this could mean that GHs can exchange information with the carriers on, for example, peak hours, best arrival times with low waiting times, or the number of free docks. On the other hand, carriers can exchange information with the GHs about their ETA or communicate which GHs they will visit. This way the arrival and departure process of trucks becomes more predictable, which will benefit the flow of goods and traffic within the yard. In addition, by controlling the flow within the yard better, less trucks will be waiting on the side of the road, which is beneficial for safety as well. By adding connectivity between the different stakeholders, both the carriers and GHs will be able to react faster to sudden changes and make the overall process more efficient. The addition of a central parking, where trucks can (de)couple, helps this process by allowing to already decouple cargo during long waiting times at the GHs. By knowing this earlier, it is possible to bring cargo that needs to be picked up by decoupled trucks to the same CP. This way the trucks only need to visit the CP and do not need to wait in line till a dock is free at the GHs.

In essence, by combining existing literature and applying it to our use case, we hope to provide a meaningful contribution to existing literature. We propose the combination of, amongst others, different connectivity aspects from a PCS, the sharing of ETA information, and the inclusion of a (de)coupling point, as a new way to transform a yard to a smart yard through the connectivity of information flows.

4. Solution design

In the previous chapter, we presented some concepts of connectivity to be added to a yard. In this chapter we evaluate these options for the yard of Schiphol in Section 4.1. Next, we describe more about the information flow intervention in Section 4.2, and the physical flow interventions in Section 4.3. Lastly, the decisions that have to be made with regard to these flows are described in Section 4.4.

4.1 Evaluation of improved connectivity concepts

As described in Section 3.4, different connectivity applications could be used at Schiphol. We already mentioned that, since no relevant literature was found on the matter, the track and trace application is disregarded for our research. The application of geofencing has four different ways of implementation. The *Route adherence* option is mostly used to give an alert if a vehicle deviates from its allocated route. Since we do not focus on route checking, this option is disregarded, as well as the more advanced option of *Route and schedule adherence*. However, if in the future more research is performed on AV application, this could be an interesting option. For example, when one container contains products for more than one GH, and a schedule to deliver those products is applied. The other two options of a *geofenced area* and *proximity with a point of interest* could work for the yard of Schiphol. Both options work with a virtual fence that gives an alert and detects the distance from a certain place to an object. In our use case, we can use this to make an ETA for incoming trucks. When trucks are at a certain distance from the GH and cross the virtual boundary, we can generate an alert. This alert informs the GH that the truck is a certain distance away, which can be translated to an ETA. Of course, the further away the boundary is, the more deviation should be allowed for this given ETA. However, multiple fences could mean that the ETA is updated every time the truck is closer to the GH, which makes the given ETA more accurate. Something to keep in mind is that it should be known to which GH the truck is headed to make sure a virtual geofence has added value.

Another application that could work for the yard of Schiphol is a platform. Using a platform allows stakeholders to share information more easily, which could be implemented in the Schiphol yard in several ways. The example of Martins et al. (2019), about a platform to facilitate the aggregation of smaller transportation loads to achieve a reduction of the number of truck trips on the last-mile transport, is a good example to reduce the number of trucks necessary at the yard of Schiphol. However, a lot of last-mile transport in our use case is between forwarders and GHs. Forwarders already consolidate packages from different depots and deliver them to the GHs, therefore the number of trucks is already reduced. Since we are assuming full truck loads, and we currently have no further information about the realistic truck load at the yard of Schiphol, this example will not be used for our research, but can be looked into in further research. This also includes the research of de Souza et al. (2014) and Zhang et al. (2019), since these are similar to the example of Martins et al. (2019).

The example of freight matching platforms to connect the supply and demand of freight carriers is also an example we do not take into account in this research. Our research focuses on improving the flow at the yard of Schiphol, and freight matching platforms do not contribute to this problem directly. Therefore, freight matching platforms are out of scope for this research.

The different examples given in Section 3.3.3 of a platform to facilitate the sharing of information among different parties involved can be useful for the yard of Schiphol. The amount of information that is shared can differ, depending on whether stakeholders want to share sensitive data or not. A service-time-profile is mostly useful when trucks have to visit multiple GHs, like in the example of Douma (2009) where vessels had to visit multiple terminals. However, the idea of a service-time-profile can be used in a different way. It is possible for GHs to give information on the expected maximum waiting time to carriers, based on historic data, to inform them on the peak moments. Carriers can decide for themselves if they want to wait the time given or come at another time with less waiting time. This could result in peak shaving for the GHs, and the carriers have the advantage of having less waiting time. A disadvantage of this method is that GHs do not know in advance how many trucks will come at different times, and the service-time-profile can therefore give a wrong impression of the waiting time. Moreover, the platform still gives uncertainty to the GHs, since they do not get a confirmation by the carriers. Therefore, the GHs cannot make a data-driven decision, which makes the platform less effective.

Another option of an information-sharing platform is the example of a PCS. This system encourages all stakeholders to share information with the goal of improving the logistics process for all involved. This platform allows the GHs and carriers to communicate with each other, for example by allowing carriers to reserve a time slot at the GH at a time it also suits the GH. This way the carrier will not incur any waiting time, but the GH also knows when the truck will arrive. This prevents long waiting times and has a peak-shaving effect for GHs. Less waiting time for the carrier will also result in less congestion in the system, as a truck spends less time at the yard of Schiphol. Furthermore, it is possible to share the ETA of trucks through this platform, which makes it possible to also make data-driven decision based on this. Overall, this method seems very suitable for the yard of Schiphol and offers a lot of possibilities.

To conclude, there are several interesting concepts that could work for the yard of Schiphol now, or in the future. We decided to further study the concepts of (i) geofencing to create a more accurate ETA and of (ii) an information-sharing platform with the option for carriers to make a reservation at the GH to drop off or/and pick up cargo. Of course, we also study the combination of the two concepts. We explain in more detail how we use these concepts in Section 4.2.1 and Section 4.2.2, respectively.

4.2 Information flow interventions

From the literature, we found different methods of adding connectivity to the yard of Schiphol. From these methods, the most promising ones for the yard of Schiphol are geofencing and an information-sharing platform, as described in the previous section. In Section 4.2.1 we explain more about how we use the concept of geofencing, as well as how we use the concept as intervention in our study. In Section 4.2.2 we do the same for the use of an information-sharing platform.

4.2.1 Geofencing

The first promising method we found in the literature is geofencing. Geofencing is a method that provides an alert when a truck crosses a virtual boundary. As one of the problems in the Schiphol use case is the unknown arrival time of trucks, we use this method to provide us with an accurate ETA. The only difference with the literature, is that we use this concept in our study not as a physical virtual boundary, but in a time perspective. This means that instead of knowing the distance to a vehicle passing the physical boundary, we assume we receive a reliable ETA a given time x before arrival. This means that it does not matter what the distance from the vehicle to the GH is at that time. This ETA is communicated to the GH where the truck needs to go. The higher this x, the less accurate this ETA will be. However, this ETA can be constantly updated in practice, which makes the ETA more accurate as time progresses. By knowing this ETA and making use of the different options of a smart yard, it is possible to prioritize trucks over others and make an active and data-driven decision on which truck should be next in line. We assume that it is also known what the due date of the load of the trucks is, what the trucks destination is, and if they want to pick up, drop off, or drop off and pick up a container. This method enables to make a data-driven decision on which truck is helped next at the GH.

4.2.2 Information-sharing platform

The second promising method that we found in the literature, is to use an information-sharing platform. An example of such a platform is Portbase, which is the PCS of the port of Rotterdam. This makes it possible for different stakeholders to communicate with each other. Within such a platform there are two options for the yard of Schiphol. The first option is to make it possible for truck drivers to make an appointment at a GH for timeslots that are dictated by the GHs. This method allows peak-shaving for the GHs, since the options for making an appointment can be at less busy hours. Furthermore, the truck drivers do incur less waiting time, mostly not even any waiting time. They can go directly to the GH and drop off or pick up their cargo. However, unexpected delays can occur in reality which can give some waiting time. A second option is using this reservation system, but also share the ETA of trucks on this platform. This is a more advanced way of sharing data, allowing for both peak-shaving to occur, but also to make it possible to make data-driven decisions based on knowing the ETA of trucks in advance.

There are many ways of making reservations on a platform, however, we decided to only model the outcome of using such a platform and not modelling the reservation itself. For these reservations in the real-world, trucks can make an appointment at the GH. For this we use time slots of one hour in which the trucks should arrive. Of course, in future research or in practice, the timeslots can be made smaller. For our model, we use a fixed parameter that represents the percentage of all arriving trucks that made a reservation on such a platform. More details on how we model this can be found in Section 5.1.7. We do experiment with the parameter of percentage of trucks that make a reservation and study its impact. Ideally, this parameter might not be fixed but more dynamic. For example, a dynamic parameter would enable trucks with certain characteristics to make a reservation, or reservation options based on certain groups of incoming trucks, e.g., road feeders. By implementing a dynamic parameter, a more efficient situation can be achieved. However, the choice for a fixed parameter regarding this application was made to allow for us to study if the direction of our solution could work for the Schiphol use case. Further improvement on this aspect is left for further research.

Information flow interventions

For this research, we make use of four different information flow interventions. The information interventions are:

1. **No connectivity –** In this case there is no connectivity used. Nothing changes in comparison how the yard is currently functioning on the information flow.
2. **Reservations –** A given percentage of trucks use the option to have a reservation at the GH for a certain time, earlier than their due date.
3. **ETA –** The use of ETA is knowing x time ahead which trucks will arrive and what their ETA is.
4. **Both reservations and ETA –** In this case we use the information intervention of both having reservations as well as knowing the ETA of trucks x time ahead.

4.3 Physical flow interventions

To evaluate the impact of the information flow interventions described in Section 4.2, we propose four interventions of last-mile vehicle control for the yard of Schiphol building on the work of van Heuveln (2020). These interventions start with the current situation and get more complex and smarter with each following intervention. However, the more complex the situation, the harder to implement it is in the current yard of Schiphol. The physical flow interventions we propose are the following:

1. **Current situation** – This physical flow intervention is the benchmark to compare with other physical flow interventions.
2. **Central parking as a buffer with a calling system** – The CP is used as a buffer. Trucks can park at the CP until they are called to their destination. If trucks are needed immediately, they can drive to the GH without going to the CP. The calling system will work based on the information flows described in Section 4.2. Data-driven decision making is dependent on the information flows available and the prioritization.
3. **Central parking, both as buffer and decoupling point. Last-mile transport by terminal tractors** – The CP is used both as a buffer and a Decoupling Point (DP). When used as a buffer, trucks can wait until they are called to their destination. When used as decoupling point, then the cargo is decoupled from the trucks, and the cargo is transported between the CP and GH by a shuttle fleet made up of terminal tractors which are traditional trucks. Based on the available

information flows, which are explained in Section 4.2, and the priority of trucks, different decisions on the route and calling of trucks and trailers are made. This is explained in more detail in Section 4.4. Also, truck drivers will only drive during opening times. Furthermore, if the cargo is needed immediately at the GH, truck drivers can go to the forwarder without going to the CP.

4. **Central parking, both as buffer and decoupling point. Last-mile transport by Automated Vehicles (AVs)** – This intervention is the same as intervention three, except the cargo is transported between the CP and GH by a shuttle fleet made up of AVs. Furthermore, AVs can drive outside of opening times of the GHs.

These interventions may, amongst others, resolve traffic issues around the Schiphol area, capacity problems at the GHs, and decrease the waiting times for truck drivers significantly. The four interventions are visualized in Figure 13.

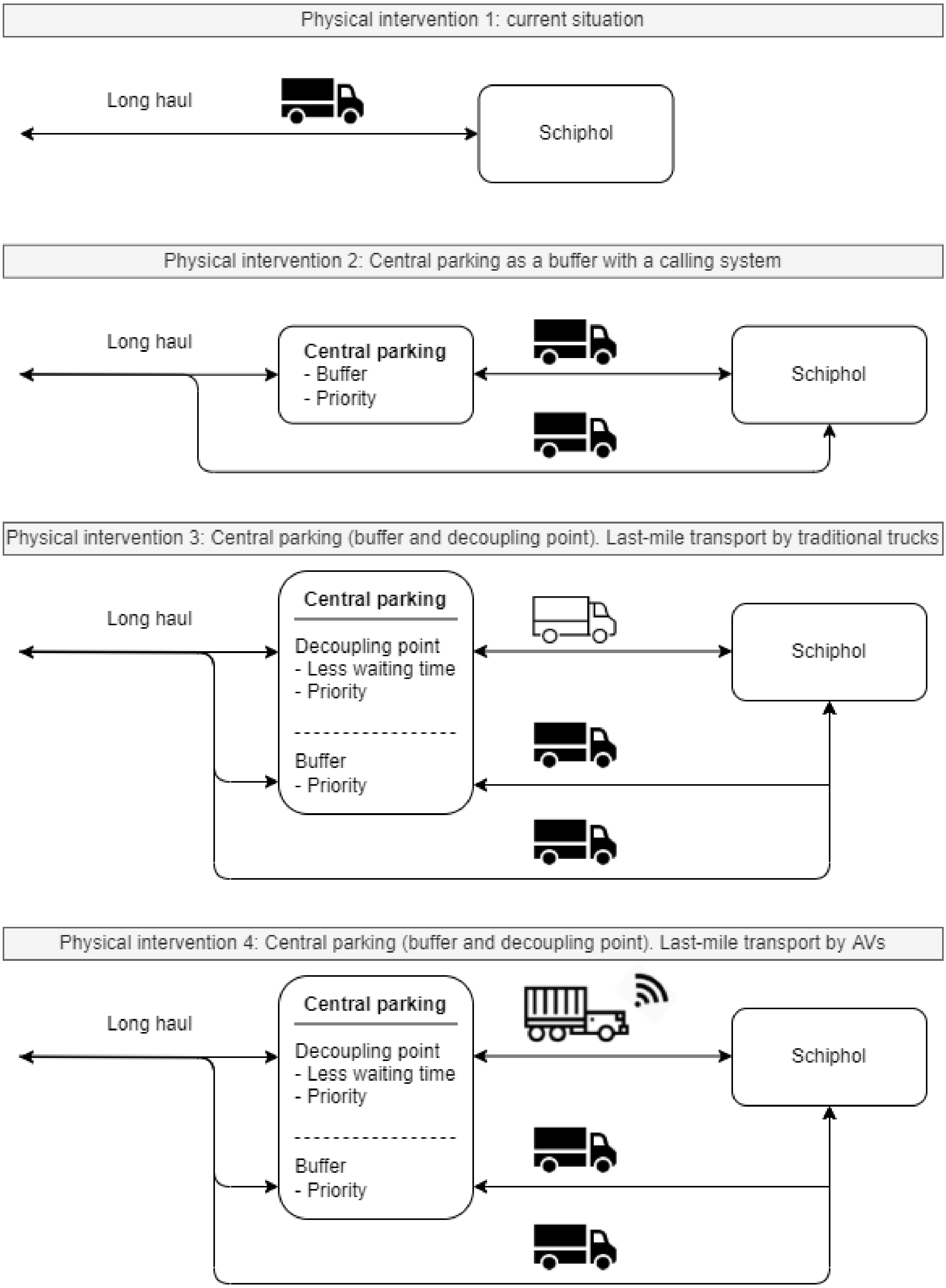

Figure 13: Visualised physical interventions

4.4 Prioritization decision rule

By using different physical flow interventions, the number of different paths a truck can follow after arriving at the yard increases. Having a number of information flow interventions adds complexity to this, by having to account for more options in the path decision making. Furthermore, when the GH has an empty dock, they need to call a truck to be handled next. Therefore, we need a prioritization decision rule that will choose the paths of the trucks, as well as which truck will be handled first by the GH. First, we need to decide what trucks have prioritization over other trucks in the reservations list. For this, the due date of the load is very important. Airplanes have very tight schedules and delays result in huge costs. It is therefore important that trucks deliver their freight on time at the GH, so delays do not occur. Therefore, we decide that trucks that are close to their due date are preferred over other trucks, and thus have a higher prioritization. Furthermore, when a truck driver has made a reservation at the GH for a certain time, it is known that this truck will arrive around this time. The GH tries to handle the truck around this time, since the truck reserved this time to be handled and therefore not has to wait as long as other trucks arriving at the GH without a reservation. To implement this, we decide that these trucks are handled as if they have prioritization over other trucks arriving at the GH without reservation. So, in the case of physical intervention 1, where trucks can only drive to the GH directly, trucks with a reservation are handled with preference over trucks without a reservation. More specifics on reservations and how we handle trucks with reservations can be found in Section 5.1.7. More details on the use of ETA can be found in Section 5.1.7. Furthermore, the different thresholds like a 'soon due date' and 'the number of trucks waiting at the CP buffer' are experimented with in the simulation model and are therefore not quantified here. The experimental ranges are described in Section 6.2. Below, the prioritization rule for the truck paths and the GH handling order are given.

Arrival of a truck

When a truck arrives at the yard of Schiphol, there are several physical paths the truck can take. Of course, this is based on what the physical flow interventions are for the last-mile transport, but also based on the available information flows. The first thing that is checked when a truck arrives is if it has a reservation. If so, it can drive immediately to the GH and does not take place at the end of the queue at the GH but moves up to first in line. Thus, meaning the truck is prioritized over other trucks without a priority. This is also the case when the arriving truck has a container with a due date that is coming up soon or has already passed. If the arriving truck does not have at least one of these, we decide that the path of the truck is decided based on the number of trucks already at different locations of the yard and the capacity of the GHs. First, we check if there are trucks with a higher priority arriving soon, based on the known ETAs of the other trucks. When no other higher priority trucks are arriving soon, and a dock at the GH is free, the truck can drive to the GH directly. If no dock is free at the moment, or there are higher priority trucks coming, the truck needs to drive to the CP. If there are not a lot of trucks already waiting at the CP buffer, the truck can go to the truck parking. If it is very busy at the CP buffer at moment of arriving, the truck will go to the central parking DP and decouple if needed. If the truck also needs to pick up a trailer, the internal vehicle will be assigned to picking up the trailer that is needed. In Figure 14 the flowchart of the route

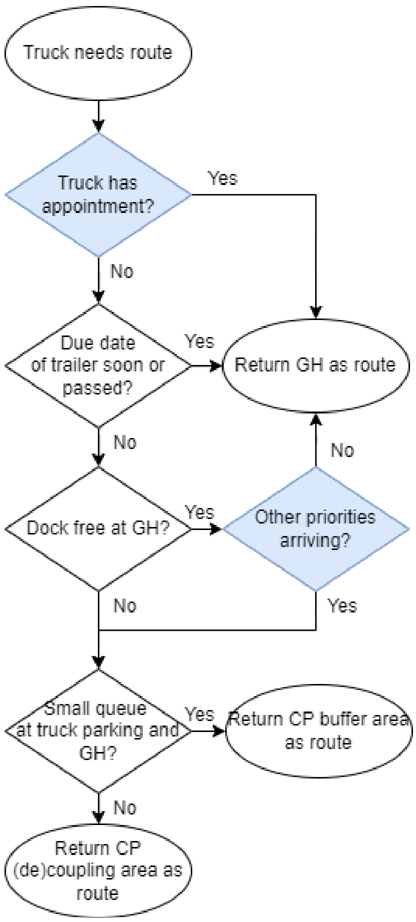

Figure 14: Flowchart determine route of trucks

determination at a truck arrival is visualized. The blue decisions only apply when the information flow of improved connectivity with reservations and ETA is enabled, if not, these decisions will be skipped.

GHs dock free

When a GH is done loading or unloading a trailer, and a dock becomes free, the GH needs to know which truck or trailer to call that has this GH as destination. Earlier we decided that trucks with a reservation or with a soon due date have priority over others. Therefore, it is first checked if there is a priority truck or trailer waiting at the buffer area of the GH. If so, this priority truck will be helped first, before the trucks that are waiting at the CP. If multiple priority trucks are waiting, the selection is based on the longest waiting time. If not, it is checked if there are trucks with a priority trailer arriving soon. With soon we mean the time it takes to service a truck including the travel time to get to the GH. If there is one or multiple priority trucks arriving soon, the GH will not help another truck and will just wait till the moment either these priority jobs arrive, or till there are more docks available than incoming priority trucks. This is because the incoming priority truck will otherwise have to wait in line instead of being serviced right away. We decide that if there are no new incoming priority trucks to the yard, or there are more docks available than incoming priority trucks, the first truck in line at the GH waiting area is called. If there are no trucks waiting at the GH area, it is checked if there is a truck or container at the CP with a early due date. As mentioned before, we decide that these trucks have priority over others, and are therefore called first. This can either be a truck waiting at the buffer area of the CP, or a trailer at the (de)coupling area of the CP that is transported by a truck or AV. If there are no priority trucks or trailers at the CP, we call the longest waiting truck. The reason we decide to give waiting trucks more priority than waiting trailers is tied to the goal of decreasing the waiting time of trucks, one of the reasons a DP was introduced in the first place. Trucks waiting at the buffer area of the CP still experience waiting time. However, the trailers that are dropped off at the CP do not endure waiting time in the same way. It is important that the trailers are delivered at the GH before the due date, but it does not matter if that happens one or three hours before. Therefore, we prefer to help trucks waiting at the buffer area, over trailers waiting at the (de)coupling area. This results in the longest waiting truck being called. If there are no trucks waiting, a trailer is requested from the Decoupling Point, and transported to the GH by a truck or AV. In Figure 15 the flowchart of decisions when a dock becomes free is visualized. The blue decisions only apply when the information flow of improved connectivity with reservations and ETA is enabled, if not, these decisions will be skipped.

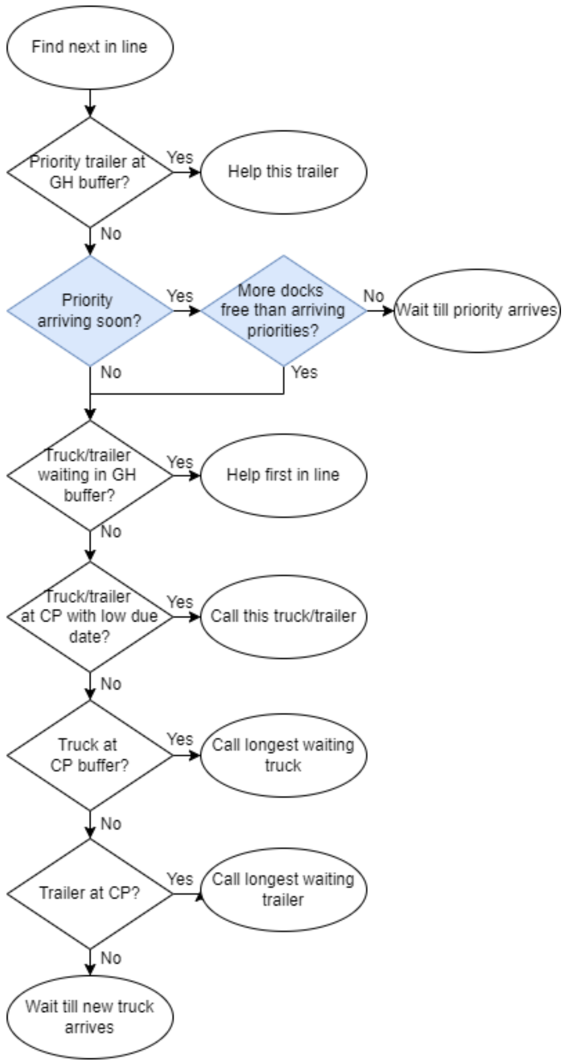

Figure 15: Flowchart to determine the next truck

Another decision we made is that, in case a (de)coupling point is included as intervention, we want to minimize the total number of empty trips made by internal vehicles. This means that if an internal vehicle drives to the GH to drop a trailer off, a check takes place to see if there is a truck waiting for a trailer from this same GH at the (de)coupling point. If so, the internal vehicle will pick up this trailer at the GH and bring the trailer to the (de)coupling point for this truck. We prefer to minimize these empty trips to make the flow of internal vehicles as efficient as possible, and to minimize unnecessary waste of energy by driving an empty internal vehicle back and forth. Additionally, this also slightly prioritizes trucks that are waiting at the (de)coupling area to pick up a trailer, since the AVs pick up a trailer at the GH more often. We decide that this is important as we prefer to keep the waiting times of trucks as low as possible. If trucks at the (de)coupling point would have to wait too long, the idea behind the (de)coupling point would be lost and trucks can better wait at the CP buffer area.

4.5 Conclusion

In conclusion, there are several concepts from literature that are suitable for the yard of Schiphol. The most suitable are the use of geofencing and an information-sharing platform. Geofencing can be used as a method to provide us with an accurate ETA. An information-sharing platform can do this as well, but it is also possible to work with a reservation system where truck drivers can make an appointment at the GH for a certain time. The use of knowing the ETA further ahead helps make data-driven decisions and reservations can work peak-shaving for the GH. Therefore we chose the information flow interventions and physical flow interventions as shown in Table 5.

Table 5: Interventions chosen

Nr	Information interventions
1	No use of connectivity
2	A given percentage of trucks have a reservation at the GH
3	Knowing the ETA of trucks, a certain time in advance
4	Using both reservations and ETA

Nr	Physical interventions
1	Current situation, trucks can only drive directly to the GH
2	Trucks can drive directly to the GH, or to the CP which can be used as a waiting area, till called by the GH
3	Trucks can drive directly to the GH, or to the CP. The CP can be used both as buffer and (de)coupling point. Last-mile transport by traditional trucks
4	Trucks can drive directly to the GH, or to the CP. The CP can be used both as buffer and (de)coupling point. Last-mile transport by AVs

5. Simulation model

Now that we have a clear vision on the physical flow interventions and the information flow interventions for this research, we need a simulation model to study the impact of the interventions. Before we design a computer model, a conceptual model is needed, which is described in Section 5.1. After this we discuss the implemented simulation model in Section 5.2 and the model verification and validation in 5.3.

5.1 Conceptual Model

A conceptual model is a non-software specific description of the computer model (S. Robinson, 2008). For this, we first describe the conceptual model framework in Section 5.1.1 and the problem situation in Section 5.1.2. In Section 5.1.3 we discuss the modelling and general project objectives of the model, then the model outputs can be found in Section 5.1.4, followed by the model inputs in Section 5.1.5. In Section 5.1.6 we discuss the scope and level of detail of the model and, lastly, in Section 5.1.7 the model content with flowcharts can be found.

5.1.1 Conceptual model framework

The framework for the conceptual model we use is the framework of Robinson (2008). The framework he presented is a commonly used framework that consists of five key activities that are performed in the order as shown below and in Figure 16:

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

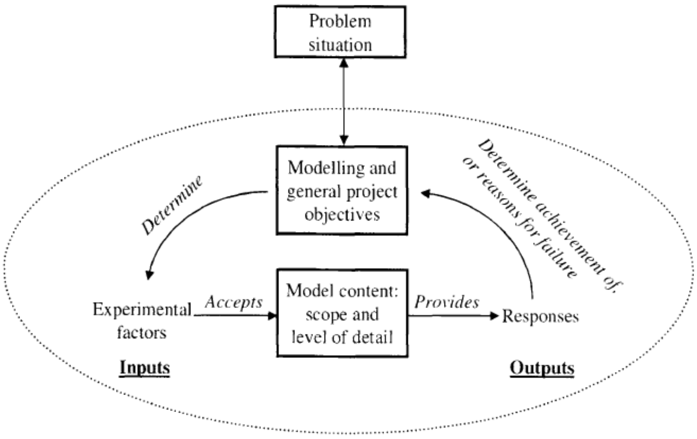

Figure 16: Conceptual model framework (Robinson, 2008)

5.1.2 Problem situation

The first step of the framework explains the problem that the simulation faces. We will link the problem we discussed in Section 1.2 to the conceptual model of the simulation. The simulation model of Schiphol should provide accurate insights into the impact of improved connectivity (the information flows) on the physical flows at the yard of Schiphol using different interventions. These interventions are both the physical flow interventions and the information flow interventions. Furthermore, the model should be feasible to build within data and time constraints. In this model, we study the impact of the three information flow interventions on the four different physical flow interventions. The information flow interventions are 1) knowing the ETA x time up front, 2) having a reservation, and 3) a combination of both. The physical flow interventions are 1) the current yard, 2) adding a central parking with a buffer space, 3) adding a central parking as buffer space and (de)coupling point using traditional trucks and 4) the third option, but now using AVs.

The trucks at Schiphol can follow different paths per physical intervention. Intervention 1 is the base intervention where trucks can only drive to the GH, and for the subsequent interventions we will include different extra paths for the trucks. The paths per scenario are described below and visualized in Figure 13:
Intervention 2: 1) drive to the CP to use as a truck parking, and 2) drive directly to the GH.
Intervention 3: 1) drive to the CP to use as a truck parking, 2) drive to the CP to use as a decoupling point. The trailer is handled by manual internal trucks. And 3) drive directly to the GH.
Intervention 4: 1) drive to the CP to use as a truck parking,2) drive to the CP to use as a decoupling point. The trailer is handled by AVs. And 3) drive directly to the GH.

As shown in Intervention 3 and 4, we only consider the application of manual vehicles or of AVs, and not a combination of both. Furthermore, trucks choose the optional paths based on other vehicles in the system and the occupancy at the GH and CP. Moreover, we assess a few different scenarios, where the number of truck arrivals is different. Since we did not have information on the number of trucks actually arriving at Schiphol, but only the number of vehicles driving on the N201 road next to Schiphol, we compared our arrivals with the arrivals of van Heuveln (2020). Based on the total number of arrivals and using his arrival rates, we estimated the percentage of all passing vehicles on the N201 road that take the exit to Schiphol. This percentage based on the arrivals of van Heuveln (2020) is 84,2%. However, our distribution of arrivals over the day is very different than the distribution of van Heuveln (2020). We therefore decided to assess our described interventions on both our arrival rate, as well as the arrival rate of van Heuveln (2020). Besides this, we decided to only model one type of day as input for the model. This means that we only model the most busy day, or only a normal day, but not a combination. By doing this we can research the impact of our interventions and decisions on specific days. The arrival rates we use as starting point can be found in Appendix A, which are the arrival rates of the most busy day. On this arrival rate, we later use a factor to calculate a normal day, and a more busy day to experiment. More information about this can be found in Section 6.2. For the three information flow interventions we have chosen from literature, we assess “what if”-scenarios that are based on the notion of ‘what if x percent of arrivals makes a reservation’ or ‘what if we know the ETA x time in advance’.

5.1.3 Modelling and general project objectives

This simulation model aims to provide insight into the impact of improved connectivity on the flow of the yard of Schiphol, given a certain number of arrivals. This involves assessing the logistical performance of the system by analysing the impact on throughput times for trucks and trailers, waiting times for both trucks and trailers, and travel times for trailers. Furthermore, we assess the utilisation of the GHs, CP, and internal handling trucks or AVs.

By changing the model inputs, the simulation model is flexible to be adapted to specific situations. The simulation model should be feasible to build within the given time and data constraints, should be credible and trustworthy, and should be validated to be an accurate representation.

5.1.4 Model outputs

To be able to provide insights into the impact of improved connectivity on the flow of the yard of Schiphol, the model should provide insights into the logistical performance of the system. We plan to measure the KPIs as averages over each run, including the minimum, maximum and standard deviation. For this we use the following key performance indicators:

- **Throughput times** – The throughput time is the time between the arrival of a truck or trailer at the yard of Schiphol until it leaves the yard. The throughput time of trucks show the benefit of connectivity to carriers. The throughput times of trailers show the efficiency of the flow of trailers within the yard of Schiphol. The total throughput time consists of the following times:
  - The total travelling time required, which is the time in which the trailer is being moved by a vehicle.
  - The total waiting time, where the trailer stands still waiting for the next event.
  - The total processing time at the CP and the GH.
- **Travel times** – The travel time for the trailer is the time in which the trailer is being transported by a vehicle. For the trucks, the travel time is the time the trucks are driving.
- **Waiting times** – The waiting time is the time where the truck or trailer stands still and nothing happens. Of course, the waiting time of trailers is not as bad as long as the trailer is on time. However, the waiting times of trucks are more important, especially to carriers. The following waiting times are assessed separately for trucks and trailers:
  - The waiting time at the CP.
  - The waiting time at the GHs.
- **Peak occupation rate** – The peak occupation rate is measured to track the peak moments per location. We will assess the occupation rate of each of the LCs, CP buffer area and the CP decoupling area.

5.1.5 Model inputs

Below are all model inputs needed for the simulation model:
- A map of the yard of Schiphol and the public roads.
- Location of GHs and the connection of the GH to the public roads.
- Location of CP and the connection of the CP to the public roads.
- Number of docks at each of the GHs.
- Processing times at each of the GHs.
- Number of trucks arriving per hour of the day, can also be found in Appendix A.
- Due date per trailer.
- Capacity at CP in terms of parking spots for trucks, trailers and internal vehicles.
- Couple/decouple time for trucks at the GHs and CP.
- Couple/decouple time for AVs at the GHs and CP.
- The speed limit of trucks on the public roads in the yard of Schiphol.
- The speed limit of AVs on the public roads in the yard of Schiphol.
- Distribution of drop off, pick up, drop off and pick up of trailers by all arriving trucks for each GH.
- Distribution of trucks over the different GHs.

5.1.6 Model scope and level of detail

The scope of our model includes the export and import process of trailers and the five GHs. We include the arrival of trucks, with or without a trailer, at the yard of Schiphol. Each truck has a certain operation, which means that they either drop off, pick up, or drop off and pick up a trailer at a GH. Each arriving trailer has a due date at one of the GHs and it is preferred that this trailer is on time. Furthermore, arriving trucks can have a reservation. We will not model the reservation process at a platform but only the results of this. Our focus is on studying the impact of connectivity on the flow of the yard of Schiphol, which is measured by the KPIs mentioned in Section 5.1.4. Furthermore, we will not take into account if a trailer belongs to a certain carrier and should be returned to this carrier. In further research, the trailer ownership can be assessed. Also, AV battery management will not be considered in this research.

The following assumptions are made:

GH assumptions

- GHs are always able to receive trailers.
- GHs and their docks are always open.
- Trailers can be internally moved at the GHs without explicit modelling of operations.
- The loading and unloading time at GHs is equal for all trucks and internal vehicles.
- There is no need for additional equipment to drop trailers at the buffer area of the GHs, such as a reach stacker.
- (Un)loading operations have a fixed duration for both trucks and AVs.

CP assumptions

- The truck parking at Schiphol can function as a CP for both the buffering and (de)coupling of trucks.
- There is no need for additional equipment to (de)couple and store trailers at the CP.
- The CP can function as an idling location for internal vehicles.
- The travelling time inside the truck parking is considered to be included in the (de)coupling time at the CP.
- (De)coupling operations have a fixed duration for both trucks and AVs.

Truck and trailer assumptions

- Arriving trailers for import and export all have the same characteristics, we will not make any differentiation in cargo types.
- Arriving trucks have the same characteristics (e.g., speed and manoeuvring).
- Internal handling trucks have the same characteristics (e.g., speed, manoeuvring, and ability to perform (de)coupling).
- Internal trucks and their drivers are always available, so no downtime occurs.
- The arrival of trucks follows a Poisson distribution.
- Trucks drive all day, breaks or shifts are not considered in the model.
- Each arriving trailer equals one full truckload.
- Trucks will always take the shortest route from A to B within the yard of Schiphol.
- The due date follows a gamma distribution.
- The distribution of drop off, pick up, or drop off and pick up is considered as a percentage.
- Travel times are deterministic.

AV assumptions

- AVs have the same characteristics (e.g., speed, manoeuvring, and (de)coupling).
- AVs will always take the shortest route from A to B within the yard of Schiphol.
- AVs are always available and never fail. So, no downtime occurs.
- The battery of AVs is never depleted.

5.1.7 Model content

The last part of the conceptual model determines the model content. Here the implementation of both reservations and using ETA is provided, as well as a high-level flowchart with the simulation process. Furthermore, important events of the simulation model are described and visualised in flowcharts.

Implementation of reservations

The reservations are implemented with a modelling technique. We already described that we only model the results of making a reservation, and not the process of making a reservation itself. When a truck makes a reservation at the GH, this reservation will be earlier than the due date. We described in Section 2.4 that truck drivers normally always arrive just before the due date. Therefore, we know that the normal arriving moment of trucks will be just before the due date. Since the reservation is earlier than this due date, we know that if a truck makes a reservation, this reservation will be either at the same time as they normally would have arrived, or earlier. If they arrive earlier, this might result in peak shaving for the GHs, as also mentioned in Section 4.2.2.

The modelling trick we use is that we generate all arrivals for a day at the beginning of that day. We use the arrival rates per hour, which gives us the base distribution of arrivals over the day. The timeslots we use are one hour, which is equal to the distribution of the arrivals over the day. To implement the reservations, we have a fixed input of, for example, 25% of all trucks that want to make a reservation. The trucks in the model that have a reservation are randomly picked over all arrivals of the day. These trucks with a reservation are then distributed over the day according to the method described below.

To facilitate a peak shaving effect, and to implement that GHs only make the time slots available that suit them, we use another technique. We count the number of arrivals within each hour, and then try to move as many trucks as possible from the most busy time slot to the least busy slot that is earlier than the current time slot, by only offering time slots for appointments in those hours. We do this at the start of the day. For example, if there are on average 50 trucks arriving per time slot, but time slot fourteen is the most busy and has 70 trucks arriving, and time slot nine is the least busy and has 39 trucks arriving, we can try to move the trucks with a reservation in time slot fourteen to time slot nine, until the average of 50 trucks is reached at time slot nine. Of course, when there are no more trucks in slot fourteen with a reservation, we cannot move any more trucks from this time slot. We then check and compare the most busy and the least busy time slot again, and continue this process until no trucks can be moved anymore *or all timeslots are around the average truck arrival rate*. It is not possible to move a truck to a later time slot than the normal arriving time slot, since we want to avoid trucks arriving later than their due date. What should be known is that if we move a truck from one time slot to another, we only change the hour of the day the truck arrives, but not the minutes. In practice, this could mean that multiple trucks arrive exactly at the same time, but we decided that this represents the real-world more accurately than choosing the exact moment a truck arrives to the yard. Furthermore, as mentioned in Section 4.2.2, we use this approach to allow us to study if the direction of our solution could work for the Schiphol use case.

Implementation of ETA

The implementation of ETA works twofold, one is when a new truck arrives to the yard, the other is when a dock becomes available. If a truck arrives with low priority, so it is not close to the due date, and has no reservation, it is checked if there are one or more trucks arriving with a higher priority within the processing time of the GH. We already discussed the steps that happen next in Section 4.4. However, we did not explain why we chose the processing time as a reference point. Even though we might have the ability to know the ETA further in advance than the processing time, we will only look in the arriving trucks table for trucks arriving within the processing time. We explain this with an example. If the processing time is 30 minutes, and the travel time to the corresponding GH is 5 minutes, and there is a truck A that just arrived at the yard of Schiphol with a low priority. It is only important to know if there is a truck B with high priority arriving within 30 minutes, to decide on the route of truck A. This is because if truck B arrives after that, for example after 31 minutes, then truck B will be at the GH after 36 minutes. Since the driving time and processing time at the GH together is 35 minutes, truck A will be gone before truck B arrives. Therefore, when a truck arrives, we only look the processing time ahead in the arrival table.

The other aspect of the ETA implementation is looking ahead on which trucks will arrive at the yard in the future when it is not busy at the GH. This can be done x time ahead, dependent on the x that is experimented with. In the model we do this with an arrival table that contains all arrivals of the day. We only look the x time ahead and not further than that. We do this to see if there are trucks that only need to pick up a trailer, so we can prepare this trailer and already bring this trailer to the CP. This way, the incoming truck only needs to visit the CP without waiting time to pick up the trailer and leave the system. This also results in peak shaving for more busy moments at the GH, since less trucks need to visit the GH.

High-level flowchart

Figure 17 shows the process flowchart of the transport process of the simulation model. The blue coloured blocks are explained in events in this section. This flowchart is a high-level flowchart which summarizes all flows in the yard.

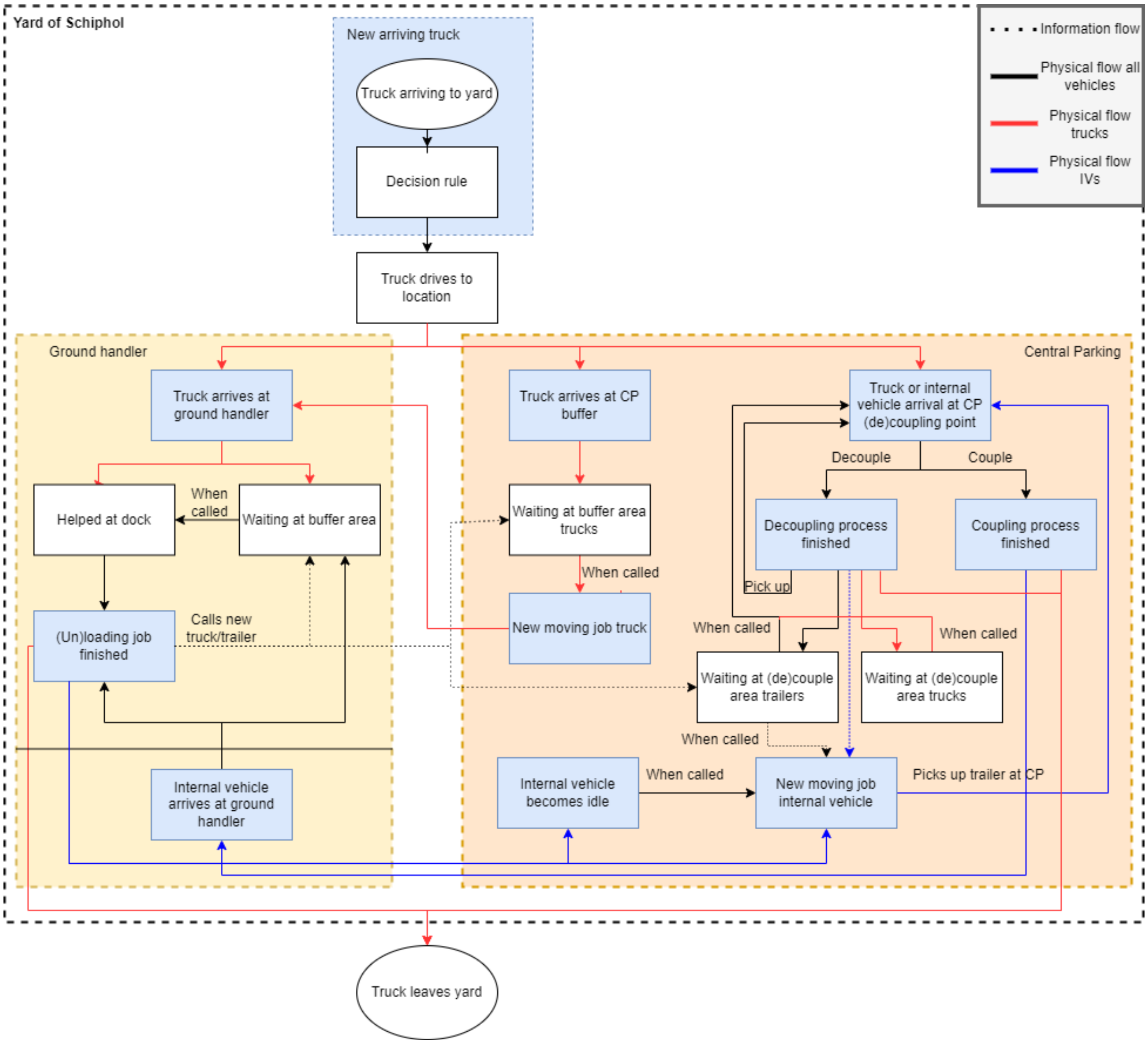

Figure 17: Process flowchart of transport process

New arriving truck

Figure 18 shows the flowchart of the event of the arrival of a new truck. The arrivals follow a Poisson distribution, and the intensity differs based on the hour of the day and the day itself. The truck is created with certain attributes, like if the truck needs to drop off, pick, or drop off and pick containers. If the truck needs to drop off, or drop off and pick a trailer, a trailer is created with certain attributes. Then, the truck and trailer are coupled, and both the truck and trailer get an unique ID. The creation time is logged as arrival time in the system, which can later be used to calculate throughput time and travel time. At that point, the route is determined based on the prioritization decision rule in Section 4.4. A route is returned and the truck drives to the location of this route, which can be the GH, CP buffer or CP (de)coupling point.

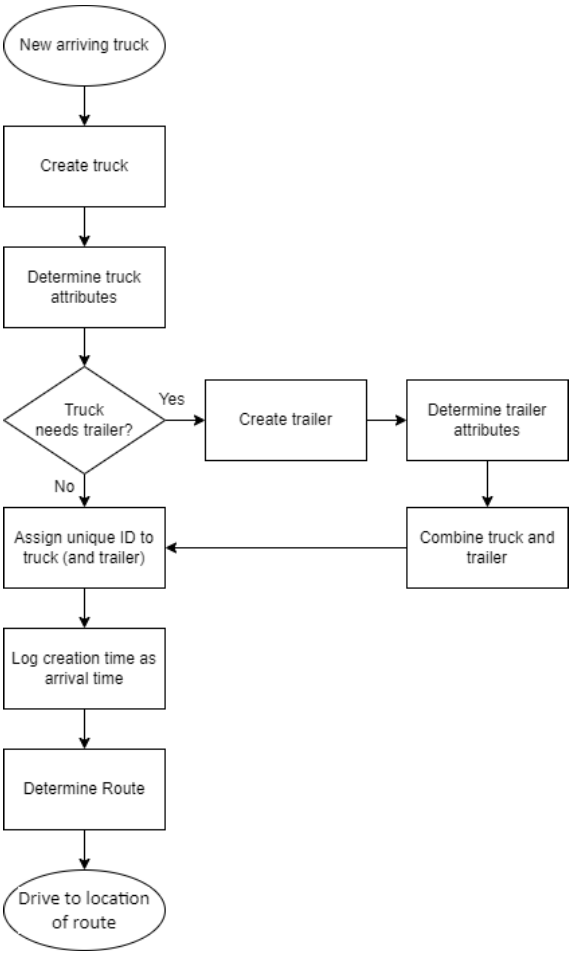

Figure 18: Flowchart new arriving trucks

Truck arrival at CP buffer

When the truck arrives at the CP to buffer, the flowchart in Figure 19 is triggered. First the arrival time is logged, and the travel time is calculated. Then the truck waits till it is called by the GH.

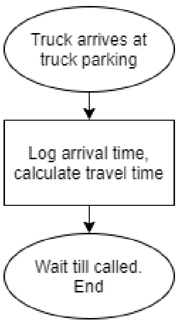

Figure 19: Flowchart truck arrival at CP buffer

Truck or internal vehicle arrival at CP (de)coupling point

The flowchart in Figure 20 is triggered when a truck or internal vehicle arrives at the CP. First, the arriving time is logged, the travel time is calculated, and the idle time for the internal vehicle is calculated. It is first checked if the truck or internal vehicle needs to drop off or pick up. If the truck or internal vehicle needs to drop off, the waiting time is calculated, and the decoupling process is started. If the truck or internal vehicle needs to pick a trailer, it is first checked if the trailer is already at the CP. For internal vehicles, the trailer is always available, since the internal vehicle is called to pick up a certain trailer, this only happens if the trailer is already at the CP. For trucks, it can happen that the trailer is not yet arrived at the CP. Then, the truck waits in the buffer area till the trailer arrives. If the trailer is at the buffer area, both the truck or internal vehicle and the trailer are moved to the couple area and the waiting time is calculated. Finally, the coupling process is started.

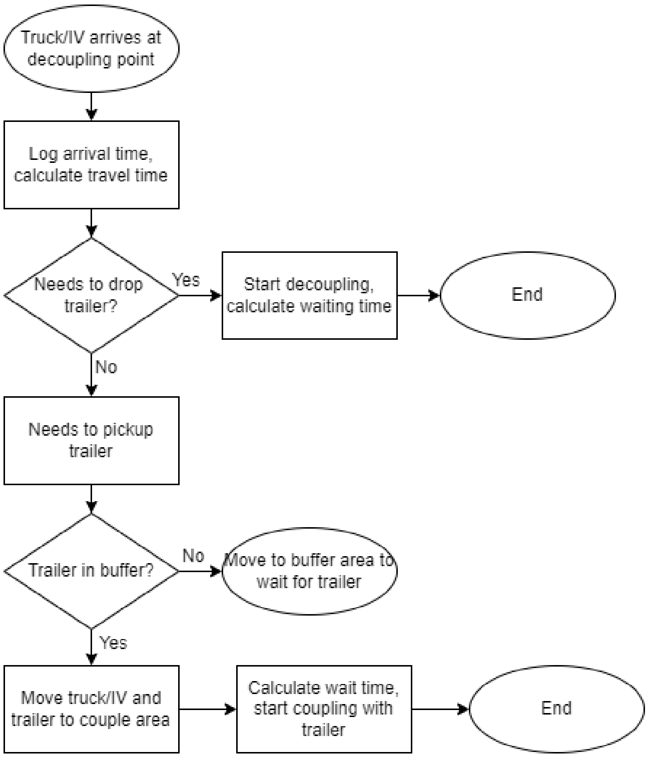

Figure 20: Flowchart truck/IV arrival at CP (de)coupling point

(De)coupling process finished

The flowchart in Figure 21 is triggered when the coupling or decoupling process is finished. For the coupling process, the processing time is calculated, and a new destination is set. For trucks, this destination will be to leave the yard since they picked up their trailer and now need to deliver this trailer at another destination. For internal vehicles, the destination will be one of the GHs to drop off the trailer, dependent on the destination of the trailer. Then, they move to this destination.

When the decoupling process is finished, the decoupling time is calculated. Then, for trucks or internal vehicles it is checked if they need to pick up a trailer. If they need to pick up a trailer, they will move to the entrance of the CP (de)coupling point and the flowchart in Figure 20 is triggered. If they do not need to pick up a trailer, a new destination is set. For trucks, this destination will be to leave the yard since they dropped off their trailer and do not need to pick up a trailer at this yard. For internal vehicles, this destination is the idle area to wait for a new job. For the trailer that is decoupled, it is checked if there is a truck waiting for this trailer. If there is a truck waiting, both the trailer and the truck are moved to the coupling area and the waiting time is calculated. Then, the coupling process starts. If no truck is waiting for this trailer, the trailer is moved to the buffer area and waits till it’s called.

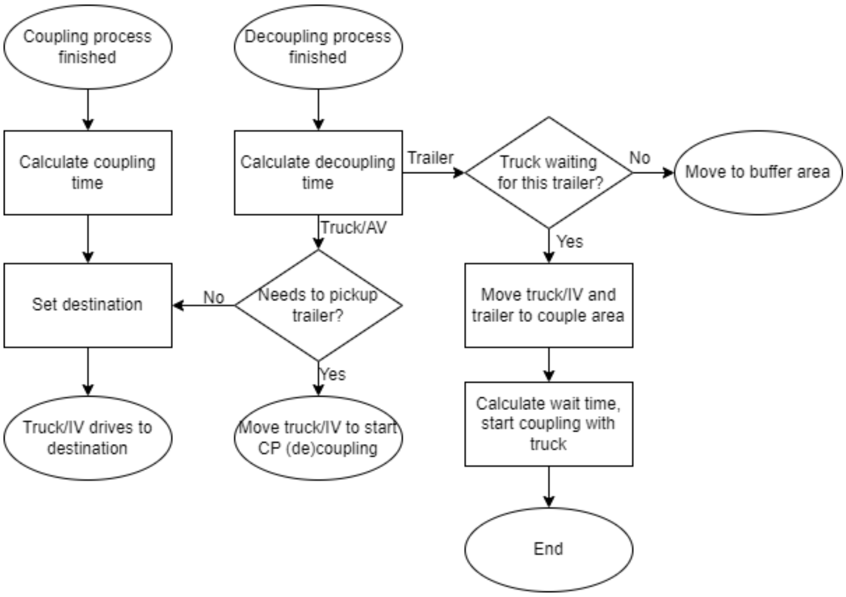

Figure 21: Flowchart (de)coupling process finished

Truck arrives at GH

The flowchart in Figure 22 is triggered when the truck arrives at the GH. First, the arrival time is logged, and the travel time is calculated. Then, it is checked if the truck had a reservation or is close to the due date. If so, this truck has priority over others that are waiting. If no dock is available, the truck will wait at the buffer area of the GH first in line. If a dock is available, the truck will move to the dock, the waiting time is calculated, and the unloading process will start. Regarding an arriving truck without priority, it is checked if there is a dock free and there are no others waiting at the buffer area. If there are no others waiting, the truck moves to the dock and the waiting time is calculated. The unloading process starts. If there are others waiting at the waiting area, the truck moves to the waiting area and waits in line, the reason behind this can be found in Section 4.4.

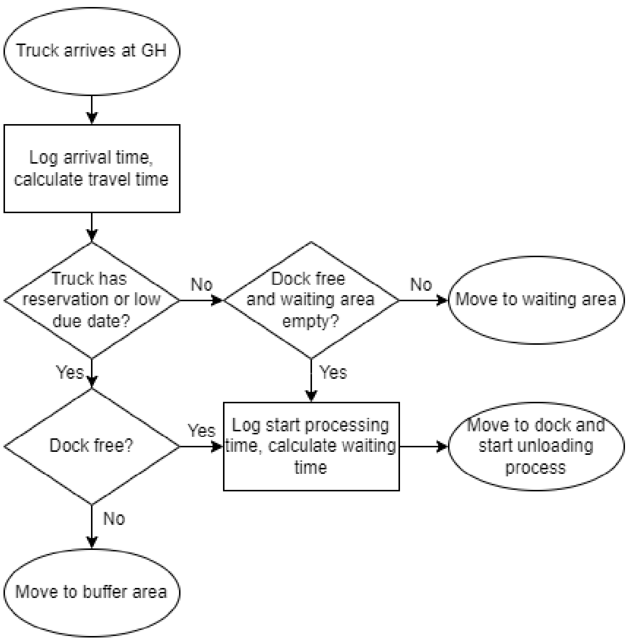

Figure 22: Flowchart truck arrives at GH

Internal vehicle arrives at GH

The flowchart in Figure 23 is triggered when the internal vehicle arrives at the GH. First, the arrival time is logged, and the travel time is calculated. Then it is checked if the internal vehicle needs to drop off or pick up a trailer. If a trailer needs to be dropped off, it is checked if there is a truck waiting at the

CP for a trailer from this GH. If the internal vehicle does not need to pick up a trailer, it is checked if a dock is free, and no others are waiting in the waiting area of the GH. If so, the trailer the internal vehicle carries is dropped off at the dock and the unloading process starts. If the dock is not free, or others are waiting, the trailer is dropped off at the waiting area at the GH to wait in line. The internal vehicle becomes idle and will move to the idle waiting area. If the internal vehicle does need to pick up a trailer for a waiting truck at the CP, the internal vehicle will both drop off this trailer and pick up a trailer for the waiting truck. Now the same path is followed for when the internal vehicle only needs to pick up a trailer. It is checked if a dock is free and there are no others waiting at the waiting area of the GH. If so, the internal vehicle moves to the dock and the unloading process starts. Otherwise, the internal vehicle waits in line at the waiting area of the GH. So, if the internal vehicle only needs to drop a trailer off, it will drop off the trailer, but will not wait for the unloading process. The internal vehicle continues with other jobs.

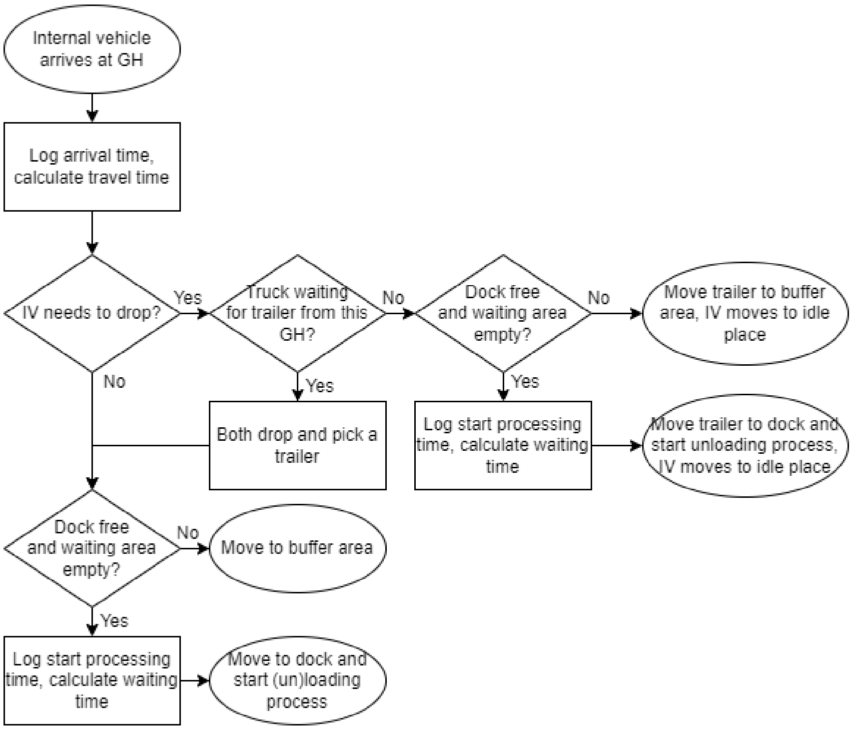

Figure 23: Flowchart internal vehicle arrives at GH

(Un)loading job finished

The flowchart in Figure 24 is triggered when the GH finishes the (un)loading job. First the finishing time is logged and the processing time is calculated. Then the truck or internal vehicle is moved to the exit of the GH to continue its path. Also, a dock became free, so the prioritization decision rule for a dock that becomes available in Section 4.4 is triggered to find the next in line for the GH.

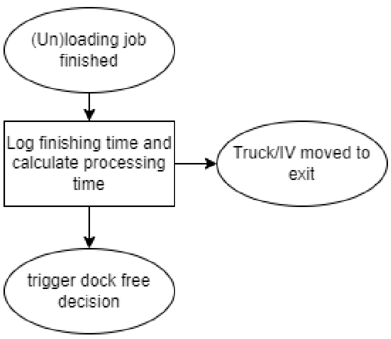

Figure 24: Flowchart (un)loading job finished

New moving job truck

The flowchart in Figure 25 is triggered by the prioritization decision rule for a dock that becomes available in Section 4.4 if a truck is requested from the truck parking. First, the truck claims the dock at the GH to make sure it is still free upon arrival. Then the truck determines the route to the GH. The time of departure is logged to calculate waiting time. Last, the truck moves to the GH.

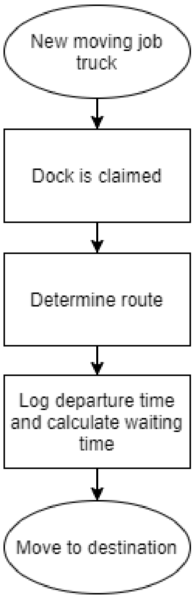

Figure 25: Flowchart new moving job truck

New job request

The flowchart in Figure 26 is triggered by the prioritization decision rule for a dock that becomes available in Section 4.4 if a trailer is requested from the CP or a trailer needs to be picked up from the GH to the CP. It checks if an internal vehicle is idle and thus available to move the trailer to the GH or pick up a trailer at the GH to bring to the CP. If so, the "New moving job internal vehicle" flowchart is triggered, as shown in Figure 28. If there is no vehicle idle, the new job is logged, and the model waits till an internal vehicle becomes idle to pick up the trailer.

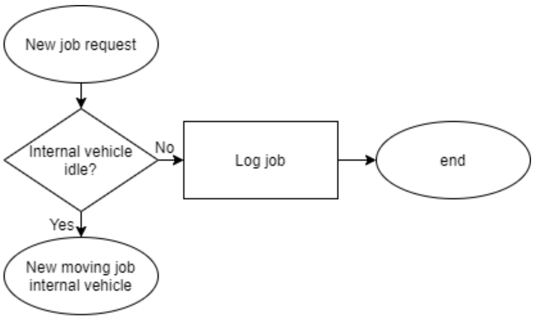

Figure 26: Flowchart new job request

Internal vehicle becomes idle

The flowchart in Figure 27 is triggered when the internal vehicle finishes its task, moves to the location that is defined as the idle place for internal vehicles and becomes idle. The model checks if there is a trailer that needs to move from the GH to the decoupling point or the other way around. If so, the "new moving job internal vehicle" flowchart is triggered, as shown in Figure 28. Otherwise, the vehicle stays idle and waits.

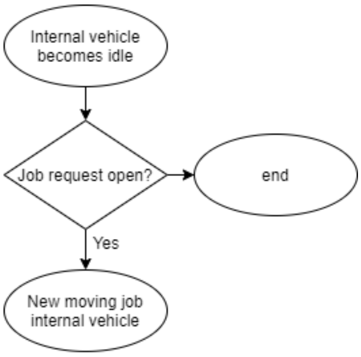

Figure 27: Flowchart internal vehicle becomes idle

New moving job internal vehicle

The flowchart in Figure 28 is triggered either by the “New Job request” flowchart, Figure 26, or by the “internal vehicle becomes idle” flowchart, Figure 27, given a certain internal vehicle. First, it is checked if the vehicle moves to the GH or the decoupling point. If moving to the GH dock, the vehicle claims the dock. Then, in both scenarios the vehicle determines the route to the destination, logs the start of moving time, calculates idle time, and then moves to the destination.

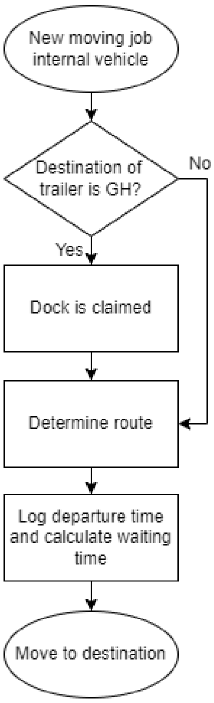

Figure 28: Flowchart new moving job internal vehicle

5.2 Computer Model

To implement the conceptual model into a computer simulation model we used the licensed discrete-event simulation software Tecnomatix Plant Simulation from Siemens. The software facilitates object-oriented programming and 3D modelling. Object-oriented programming is used to create a flexible and feasible model for the yard of Schiphol, and we have created a 3D animation of the yard for better visualization and modelling of traffic flows. Figure 29 shows the 3D visualization of the yard of Schiphol from the top. In the left upper corner, the control panel can be found, where the input, output and statistics can be found. The five GHs are visualized in green in the middle of Schiphol.

Figure 29: Top view of simulation model

The input variables are designed to be flexible. In the Input screen, the variables can be changed. For example, the number of GHs, the distribution among the GHs, the number of internal vehicles, thresholds, the due date of trailers, and the experimental settings. All of these can be adjusted. Figure 30 shows the input screen of the simulation model.

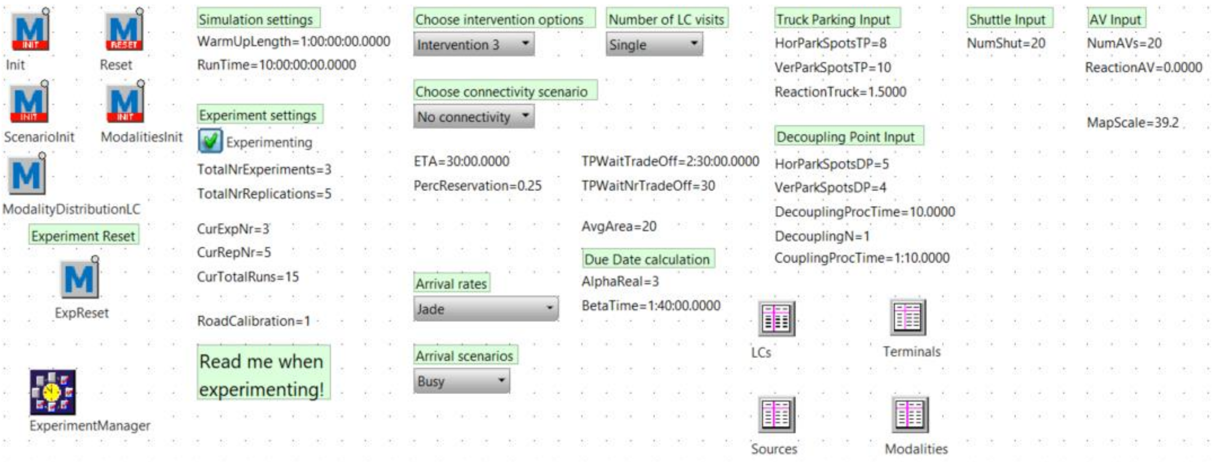

Figure 30: Input screen simulation model

When zooming in to one of the GHs, as shown in Figure 31, we see the trucks that are handled at the docks. The red trucks are the trucks coming from outside the yard to drop off, pick up, or both drop off and pick up a container. The purple trailers are internal vehicles, in this case traditional trucks. They move trailers between the GH and the CP.

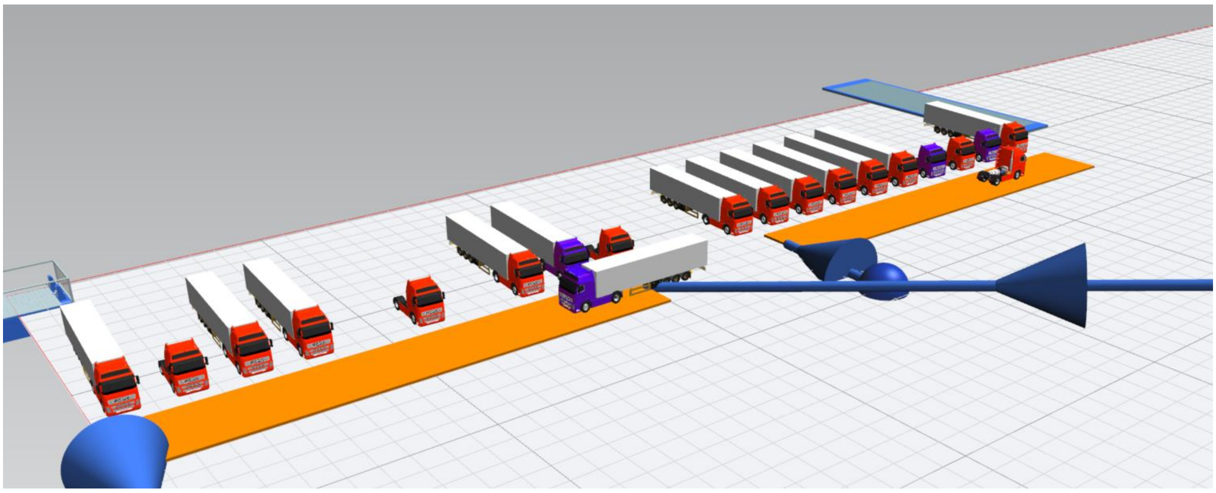

Figure 31: Ground handler visualization

5.3 Verification and validation

In order for our simulation model to be used for decision making, it is important to verify and validate the model. The verification of the model ensures that the conceptual model is correctly transformed into a simulation model. Validation of the model ensures that the model is sufficiently accurate for the purpose of this research.

5.3.1 General verification

For the process of verification, we used the eight verification techniques of Law (2014). For our simulation model we use seven of the eight techniques. One of the techniques was not applicable to our model, due to missing historical data from the original situation. The other seven techniques and the effect of them on our model is described below:

- **Write and debug the computer program in modules or subprograms** - For our simulation model, we first made and debugged the basic model. Then, we added more difficult parts and debugged the model every time a new part was added, in order to make sure all components were incorporated correctly. Furthermore, we used frames, i.e., classes, for different parts of our model. For example, there is a frame for the GH, a frame for the (de)coupling area, and a frame for the source of trucks. These frames can be inserted in the model multiple times. When something changed in a specific frame, it is also changed in all objects derived from this class.
- **More than one person reviews the computer program** - For this simulation model, we discussed and checked the basic model with other researchers that are researching one of the other use cases of a smart yard described in Section 1.1.1. After this, we made alterations to the model for the Schiphol specific use case of which the concepts were discussed before and during implementation. This to make sure all different subprograms work as they are supposed to work.
- **Run the simulation under a variety of settings of input parameters** - To test and verify our model we used a variety of input parameter settings. For example, we changed the number of internal vehicles from 1 to 50, we changed the arrivals of truck from very low to very high and we changed the processing time at the GH from 0 minutes to a few hours. We then checked what happened within the model. When we had only one internal vehicle the number of trucks and trailers at the CP kept increasing, and a decrease of that number was observed when we had a lot of internal vehicles. Furthermore, with a processing time of 0 minutes there were no queues at the GHs, but with a processing time of a few hours very large queues occurred. We used this technique on all input parameters and in all settings the model responded in a logical manner.

- **Debug the model using traces** - To verify our model we also made use of multiple traces. For example, during the run of a simulation we keep track of where trucks and trailers are in the system, and what route they take. We also have tables that store information on the trucks, internal vehicles, and trailers both waiting and being helped at the docks of each LC, and tables that store information on the trucks and trailers waiting at the CP. The latter tables contain the trucks and trailers' arrival time at the CP and their respective destinations. Moreover, Tecnomatix Plant Simulation features a debugger for step-by-step tracing of all events and lines of code in the simulation. This helped us to check if the model worked correctly and vehicles are at the correct place.
- **Run the simulation under simplified assumptions** - We ran our simulation model with simplified interventions of both the physical and the information flow to verify that the model behaves correctly during each intervention. We tested each physical flow intervention separately without information flow interventions. When these responded correctly, we tested each information flow intervention while making use of the physical interventions. The model behaved as expected on all intervention combinations.
- **Observe the animation of the simulation output** - Since our model is created as a 3D environment of Schiphol, we used the visual moving units that resemble trucks, internal vehicles, and trailers to verify the flow on the yard. We used the 3D moving units to check if vehicles followed the correct route and to visualize the queues at waiting areas. In this case, the model components all behaved as expected.
- **Use a commercial simulation package** - For this simulation model we used the software package of Tecnomatix Plant Simulation. This simulation package helped us to reduce the amount of programming required, since the package provides certain tools that can be used. Examples of these are the different processing stations and the already included statistics that can be used.

5.3.2 Verification of input

We also have to verify the input of the simulation model to check if the model provides the correct results. To test the input, we ran ten different runs of the model and used the output of those runs to calculate average counts, percentages, and the differences. Below, we will describe the verification of the arrival rate of trucks, the drop off/pick up/drop of & pick up distribution of arrivals and the distribution of trucks over the different GHs.

Arrival of trucks

The data for verification of the arrival rate of trucks can be found in Table 6. We model varying arrival rates per hour of a day. For this test we visualize the example of the arrival rate of van Heuveln (2020), which can be found in Appendix A. Table 6 shows the average number of arrivals per hour based on 10 runs of the simulation model. On average there is an increase of 2,54 trucks in the system per day compared to the actual arrival rate per hour. The absolute difference per hour varies from 0,06 to 5,42 and the percentual absolute difference varies from 0,10% to 7,97%. This equals to an average absolute difference in percentage of 0,14% compared to the actual rate. This shows that there is a small difference between the actual rate and the rate that is put out by the simulation model. On a daily basis this deviation is very small, and therefore we conclude that the arrival input in the model is verified.

Table 6: Verification of the arrival rate

Hour	Input	Avg nr.	Absolute difference	Absolute difference %
00:00-00:59	77	77.62	0.62	0.81%
01:00-01:59	68	68.70	0.70	1.03%
02:00-02:59	74	73.92	0.08	0.11%
03:00-03:59	75	76.40	1.40	1.87%

04:00-04:59	65	60.70	4.30	6.62%
05:00-05:59	57	58.02	1.02	1.79%
06:00-06:59	59	58.94	0.06	0.10%
07:00-07:59	48	50.18	2.18	4.54%
08:00-08:59	47	47.26	0.26	0.55%
09:00-09:59	38	39.84	1.84	4.84%
10:00-10:59	35	34.42	0.58	1.66%
11:00-11:59	33	35.18	2.18	6.61%
12:00-12:59	57	56.92	0.08	0.14%
13:00-13:59	68	62.58	5.42	7.97%
14:00-14:59	74	76.42	2.42	3.27%
15:00-15:59	75	76.36	1.36	1.81%
16:00-16:59	89	88.80	0.20	0.22%
17:00-17:59	107	105.16	1.84	1.72%
18:00-18:59	119	123.32	4.32	3.63%
19:00-19:59	123	124.76	1.76	1.43%
20:00-20:59	128	127.46	0.54	0.42%
21:00-21:59	132	135.28	3.28	2.48%
22:00-22:59	114	110.30	3.70	3.25%
23:00-23:59	107	103.00	4.00	3.74%
Total	1869,00	1871.54	2.54	0.14%

Drop off/pick up/drop off & pick up distribution

The data for verification of the distribution of drop off/pick up/drop off & pick up can be found in Table 7. We used the shown percentages as distribution of trucks that will only drop off, only pick up, or both drop off & pick up cargo. The averages shown in the table below are an average of the output over 10 runs of the simulation model. This shows that the absolute differences vary between 0,04% and 0,10%. On a daily basis this is a very small difference and therefore we conclude that the distribution works properly and is verified.

Table 7: Verification of the distribution of drop/pick up/drop&pick up

Operation	Input	Avg nr.	Avg perc.	Absolute difference %
Drop	25.00%	2339.40	24.95%	0.05%
Pick up	25.00%	2353.40	25.10%	0.10%
Drop&Pick	50.00%	4684.90	49.96%	0.04%

GH distribution

The data for verification of the distribution of trucks over the different GHs can be found in Table 8. As is shown, we used the shown percentages as distribution among the GHs as input for the model. The averages shown in the table below are the average over 10 runs of the simulation model. This shows that the absolute differences vary between 0,02% and 0,43%. On a daily basis this is a very small difference and therefore we conclude that the distribution works properly and is verified.

Table 8: Verification of the GH distribution

GH	Input	Avg nr.	Avg perc.	Absolute difference %
Dnata	5,00%	460.90	4.91%	0.09%
KLM	50,00%	4651.60	49.60%	0.40%
MZ	20,00%	1916.00	20.43%	0.43%
SP	15,00%	1408.90	15.02%	0.02%
WFS	10,00%	940.30	10.03%	0.03%

5.3.3 Validation

For the validation of our simulation model, we use the various techniques described by Robinson (2014). Robinson (2014) describes six forms of validation. However, the lack of a real-world system to compare our model with makes it hard to compare the simulation model to reality. Still, we do use some of the techniques to make sure the model is sufficiently accurate for its purpose.

Conceptual model validation

The conceptual model, on which our simulation model is based, is described in Section 5.1. In the conceptual model we described the scope, assumptions, and level of detail to validate the conceptual model. Both the assumptions, of which it is not known that they will represent the real world accurately, and the simulation model are shown to subject experts of TNO. They are confident that the model is accurately enough to study the impact of connectivity on the yard of Schiphol. However, they are not confident about the absolute numbers that come from the simulation model, but they have sufficient trust in the relative differences that come from the model. To be able to represent the real-world accurately enough to use the absolute numbers, more accurate data should be gathered, and all stakeholders of Schiphol should be involved in making agreements for the model.

Data validation

The main issue is that we lack accurate data to use for our model, or to compare our model to. However, Robinson (2014) provides two ways of dealing with unavailable or inaccurate data. The first way is to estimate the data, and the second way is to treat the data as an experimental factor rather than as a fixed parameter. For this research we estimated and assumed some parameters to fill the data gaps. However, we do experiment with these parameters to ensure usability of our results if parameters are different than assumed. Furthermore, our goal is not to solve a specific problem, but to provide preliminary insights on new technology and processes. Specifically, we study the impact and effectiveness of connectivity to the yard of Schiphol in the simulation model. The simulation model allows for a first analysis by showing the effects of connectivity through various experiments.

Black box validation

The last validation form we use is the black box validation to validate the overall behavior of our simulation model. With this form we check if the input parameters in the simulation model give a logical and realistic output. These outputs are also discussed with experts from TNO to validate the model. For each test we run ten replications, using physical flow intervention 1 and no implemented connectivity. This means that there is no CP and trucks can only drive to the GHs. For the first test, we change the arrival rate of trucks from a normal, calm and busy scenario using the factors 1, 0.7, and 1.5 respectively. The output is shown in Table 9. As can be seen, the average throughput time and average waiting time decrease when there are less trucks arriving on a day. On the other hand, both are increasing when more trucks are arriving. This makes sense, since if less trucks are arriving, there is less waiting time at the ground handler and therefore the throughput time is also lower. Thus, the results of this black box validation test seem logical.

Table 9: Validation results of arrival rate test

Exp.	Arrival rate	Factor	Avg. throughput time (hour:min:sec)	Avg. travel time (hour:min:sec)	Avg. waiting time (hour:min:sec)
1	Normal	1	00:59:34	00:13:45	00:15:42
2	Calm	0,7	00:44:49	00:13:48	00:00:52
3	Busy	1,5	05:35:36	00:13:07	04:51:20

For the second test we change the processing time of the GHs to 20 minutes, 0 minutes, and 2 hours to see if the output seems logical. Table 10 shows the output of these experiments. As can be seen, the throughput time and waiting time decrease when the processing time is lowered to zero. This makes sense since trucks can immediately leave after reaching the docks. Therefore, there will not be any waiting time and the throughput time will also be lower. When the processing time is increased to two hours, the queue at the GHs will grow and trucks have to wait for a long time. The waiting time is therefore high and the throughput time is high. The results of this test seem logical.

Table 10: Validation results of processing time test

Exp.	Processing time (hour:min:sec)	Avg. throughput time (day:hour:min:sec)	Avg. travel time (hour:min:sec)	Avg. waiting time (day:hour:min:sec)
1	00:20:00	00:59:34	00:13:45	00:15:42
2	00:00:00	00:13:52	00:13:52	00:00:00
3	02:00:00	1:10:54:27	00:13:47	1:07:33:9

5.4 Conclusion

This chapter provided the conceptual model for a simulation model. We described the problem situation, objectives, outputs, inputs, the scope, and assumptions. Furthermore, we provided a high-level flowchart of the simulation and described the events. Besides this, the simulation model is showed and the implementations of connectivity within this model are explained. Lastly, we verified and validated our model.

6. Experimental design and analysis of results

In this chapter, we describe the different experiments as well as analyse the results. In Section 6.1, the experimental settings are described. In Section 6.2, the experimental factors are provided and, in Section 6.3, the analysis of the results can be found. Last, the conclusion is in Section 6.4.

6.1 Experimental settings

To get results from the simulation model, we have to determine the experimental settings for the simulation model. For this, we calculate the warm-up period in Section 6.1.1, the run length in Section 6.1.2, and the number of replications in Section 6.1.3. We calculate the experimental settings on the throughput times of trucks since these times include the travel and waiting time as well.

6.1.1 Warm-up period

For our research, we only want to gather results on the steady-state behavior of the system. Since our simulation model is non-terminating, it is necessary to calculate the warm-up period. The warm-up period is the period of time the simulation model needs to get in this steady-state. These results are not gathered to avoid any bias due to an initially empty system. Following Welch's approach, we determine this warm-up period by using ten independent replications of twenty days, which results in around 37 thousand observations per replication. We then use the mean of each i^{th} observation to calculate the moving averages with different window sizes of the runs. It should be kept in mind that the maximum window size is calculated by the following equation: $w \leq \frac{1}{4}m$, where m is the number of observations per replications. Our window should therefore be equal to or smaller than 9250. Figure 32 shows the result of Welch's approach. It can be concluded that the simulation model shows a steady-state after 1042 trucks, at the orange arrow. Since around 1900 trucks arrive per day, we take a warm-up period of one day.

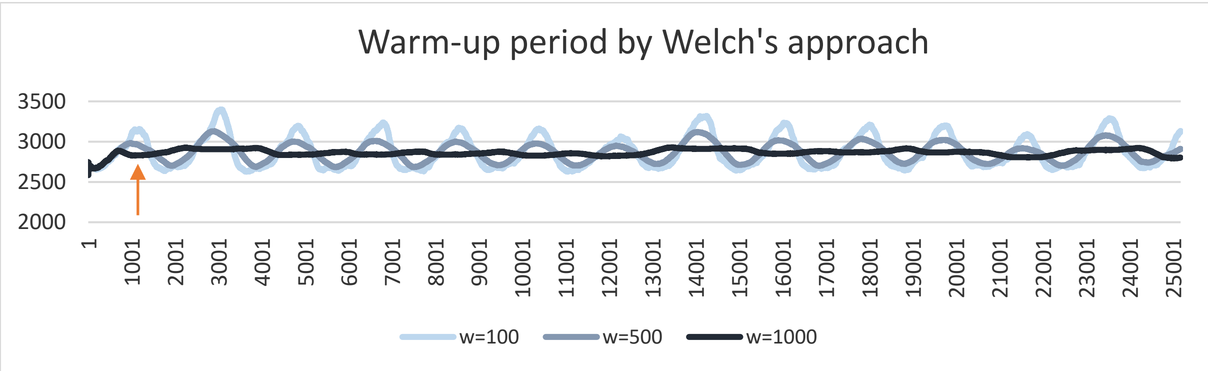

Figure 32: Warm-up period by Welch's approach

6.1.2 Run length

The run length is the time the simulation model will run to collect results. The run length should be long enough to make good conclusions on the results, but the longer the run length, the longer the computation time. Therefore, the run length should not be too long. We calculate the run length by using a common rule of thumb: the run time should be at least ten times the warm-up period. Our warm-up period is one day; therefore, we use a run length of 10 days.

6.1.3 Number of replications

To confirm that the results we gather from the simulation model are statistically significant, we run all experiments multiple times, using the same input values, but using a different random number variant. The number of times we need to run the same experiment, defined by the number of replications, can be calculated. For this, we use the commonly used value of the significance level of 95% with a relative error of 5%. To determine the number of replications we run 20 independent replications with the just determined run length, excluding the warm-up period. We calculate the actual relative error which is calculated by $\gamma' = \frac{\gamma}{1+\gamma} = 0{,}048$, where gamma is the relative error. The minimal number of replications is calculated by the following formula: $\frac{t_{n-1,1-\propto/2}\sqrt{S^2/n}}{\bar{X}} < \gamma'$. Using this formula, the error is below γ' after three replications, therefore three replications are required, as is also shown with light green in Table 11. However, to accommodate for another rule-of-thumb on the minimum replications required which is five replications, it is chosen to run five replications for each experiment within this research. The entire table of the calculations of the number of replications can be found in Appendix B.

Table 11: Calculation number of replications

n	Average of 10 runs	Average	StDev	T-value	Delta	Error
1	2896.008	2896.008	0.000	0.000	0.000	0.000
2	2851.878	2873.943	31.205	12.706	280.363	0.098
3	2914.416	2887.434	32.139	4.303	79.837	0.028
4	2940.299	2900.650	37.246	3.182	59.267	0.020
5	2846.448	2889.810	40.349	2.776	50.099	0.017

6.2 Experimental configurations

To research the impact of connectivity on the transport flow at the yard of Schiphol, we defined six different arrival scenarios of trucks that can be found in Table 12. These scenarios are used to measure the impact when other factors are changed, namely the arrival rates, the truck arrival intensity, and the operation rate. More on the arrival rates can be found in Section 5.1.2. The truck arrival intensity is a multiplier over the arrival rates to get a more calm or busy scenario. For the truck arrival intensity, we use a multiplier of 0.7 for a normal scenario, and 1.5 for a very busy scenario. The operation rate is the percentage of all trucks that come to the yard to drop off, pick up, or drop off & pick up cargo. Specifically, the balanced rate is one-third for all three options, and the unbalanced rate is 25%/25%/50% respectively. The lowered or increased arrival rates and the balanced or unbalanced operation rate does also function as a sensitivity analysis to check the impact of a change in the arrival of trucks.

Table 12: Arrival scenarios for simulation model

Scenario	Arrival rates	Truck arrival intensity	Operation rate
1	Current research	Busy	Balanced
2	Current research	Busy	Unbalanced
3	Current research	Normal	Balanced
4	Current research	Normal	Unbalanced
5	Current research	Very busy	Balanced
6	Current research	Very busy	Unbalanced

The analysis of results is split into sections per physical intervention first. We compare the different information interventions on each physical intervention separately and after that a more high-level comparison can be found between the four physical interventions. For the information interventions we have four options, namely: 1) no connectivity, 2) using reservations, 3) using a known ETA, 4) using both the reservations and the known ETA. For the reservations, we have three different values we experiment with, for the known ETA we have four different values we experiment with, which can be found in Table 13.

Table 13: Experimental factors reservations and ETA

Factor	Value 1	Value 2	Value 3	Value 4
Reservation percentage	25%	50%	75%	-
ETA time in advance	30 minutes	2 hours	5 hours	12 hours

Furthermore, we experiment with three other factors, which can be found in Table 14. The first factor is the due date. We shorten due dates to check how the simulation model responds to this change and what the impact is on the KPIs. The second factor is the CP buffer threshold to study the impact of having a lower or higher threshold than the default of twenty trucks. The last factor is the peak time of the arrival rates, shifted to a later moment in the day. To do this, we use the arrival rates of van Heuveln (2020) that can be found in Appendix A. Van Heuveln (2020) has the same total number of trucks arriving per day, but the peak of his arrivals is more in the evening, whereas our arrival rates peak during the day. With this change, we check the impact of the arrivals' peak time on the KPIs. These three factors also contribute to the sensitivity analysis of this research.

Table 14: Other experimental factors

Factor	Value 1	Value 2	Value 3
Due date	Gamma(3;100)	Gamma(3;75)	-
CP buffer threshold	20 trucks	10 trucks	30 trucks
Arrival rate	Early peak moment, current research	Later peak moment, van Heuveln (2020)	-

6.3 Analysis of experimental results (KPIs)

In this section, we analyse the experimental results gathered from the simulation model. We split the results into sections per physical intervention and compare the results between each section. It should be known that we compare the results in the different physical intervention sections to the experiments that do not use connectivity, to see the impact of using connectivity per physical intervention. After the individual physical interventions, some other experiments were performed, which are explained in Section 6.3.5. After this, we compare the information interventions on the four different physical interventions together, which can be found in Section 6.3.5.

To lower the number of experiments, we first define the best combination of both the information interventions, the reservation percentage and a known ETA, and then we analyse the results per physical intervention. We performed these information experiments on physical intervention 3, a very busy traffic scenario with an unbalanced operation rate. This is the most complex and busy scenario. Furthermore, all other factors are kept the same while experimenting. Table 15 shows the combinations used for these experiments.

Table 15: Experimental factors combination reservations and ETA

Experiment	Information intervention	ETA time known in advance	Reservation %
1	Both	30 min	25%
2	Both	30 min	50%
3	Both	30 min	75%
4	Both	2 h	25%
5	Both	2 h	50%
6	Both	2 h	75%
7	Both	5 h	25%
8	Both	5 h	50%
9	Both	5 h	75%
10	Both	12 h	25%
11	Both	12 h	50%
12	Both	12 h	75%

Table 16 shows the results of these experiments. As can be seen, the results are similar but there are small differences. When looking to the lowest throughput times (TPT), the average TPT of Experiment 9 is the lowest, closely followed by Experiment 6. Experiment 12 is only 30 seconds longer than Experiment 9. One thing that becomes clear from the results, is that the combinations with a reservation percentage of 75% seem to be the best combinations based on TPT. There is less of a visible difference between the various ETAs. However, an ETA of 30 minutes has worse results than the other three options with regards to the TPT. For the best combination, we took Experiment 6, 9 and 12 in consideration. All these results were very close on the TPT, so we also checked the travel time (TT) and waiting time (WT). The TT of these three experiments is almost the same, but the WT of Experiment 6 and 9 is slightly lower than that of Experiment 12. Therefore, we decided to choose between Experiment 6 and 9. We decided to use the factors of Experiment 9 since this had the shortest TPT and since the peaks moments of arrivals of trucks take several hours, we decided that looking ahead for more than two hours is preferable for this combination of information interventions. Therefore, we decided to go for Experiment 9, and not for Experiment 6. In all the following experiments, whenever we consider the fourth information intervention option, of both reservations and ETA, we use the configurations of 75% as reservation percentage and knowing the ETA five hours in advance.

Table 16: Results of combination reservations and ETA

Truck						
Exp nr	Avg TPT	Abs diff	Avg TT	Abs diff	Avg WT	Abs diff
1	01:23:18	+30.26%	00:15:31	+7.21%	00:37:55	+66.69%
2	01:15:12	+17.60%	00:14:52	+2.72%	00:31:12	+37.12%
3	01:06:07	+3.39%	00:14:28	+0.00%	00:25:01	+9.95%
4	01:20:31	+25.89%	00:15:34	+7.66%	00:35:09	+54.53%
5	01:11:53	+12.40%	00:14:56	+3.20%	00:27:57	+22.88%
6	01:03:58	+0.03%	00:14:31	+0.34%	00:22:49	+0.31%
7	01:19:07	+23.71%	00:15:36	+7.81%	00:33:51	+48.80%
8	01:11:38	+12.00%	00:14:58	+3.50%	00:27:44	+21.93%
9	01:03:57	+0.00%	00:14:33	+0.56%	00:22:45	+0.00%
10	01:19:23	+24.13%	00:15:36	+7.83%	00:34:06	+49.89%
11	01:12:23	+13.20%	00:14:58	+3.49%	00:28:28	+25.12%
12	01:04:32	+0.91%	00:14:33	+0.55%	00:23:19	+2.52%

6.3.1 Physical intervention 1: Current Situation

The first physical intervention only considers two options for the information interventions. Either not using connectivity or using reservations. In fact, knowing the ETA a certain time ahead does not make a difference, since all the trucks drive to the GH directly. The truck drivers will wait in line and are helped first in first out (FIFO), thus knowing which trucks will arrive soon does not impact the process. Contrarily, the information intervention of reservations can make a difference, since truck drivers that have a reservation arrive mostly around the time they made the reservation, and the arrival distribution therefore is different. For the experiments of physical intervention 1, we tested the eight configurations in Table 17 on each truck arrival (busy, normal, and very busy), for a total of 24 experiments.

Table 17: Configurations for the experiments

Experiment	Operation rate	Information intervention	Reservation %
1	Balanced	No connectivity	-
2	Balanced	Reservations	25%
3	Balanced	Reservations	50%
4	Balanced	Reservations	75%
5	Unbalanced	No connectivity	-
6	Unbalanced	Reservations	25%
7	Unbalanced	Reservations	50%
8	Unbalanced	Reservations	75%

As shown in Figure 33, the results of these experiments show that the use of reservations does not make a difference in both the busy and normal truck arrival scenario. There is only a difference of a few minutes in TPT of trucks and the maximum difference in WT is 91.10%, but this is a difference of 3 minutes and 20 seconds comparing Experiment 6 to Experiment 5. Using reservations does not improve this scenario significantly, which can be explained by the peaks of arrivals of trucks on the day. These peaks are not very high, and therefore there are only very small queues at the GH to handle these peaks. Using reservations, so moving trucks to another time, does result in almost no waiting time, which can be beneficial in the real-world. However, reducing the WT by a maximum of a few minutes might not outweigh the investments for a reservation system. Still, in practice, the use of reservations within a comparable scenario of arrivals could make a difference. The flow is more controlled, and more is known on when trucks arrive. This can help GHs to manage their staff better, and it can help carriers prevent unnecessary waiting times. So, these benefits might be a reason to invest in a reservation system. The average TT is the same since the trucks drive directly to the GH.

For the very busy scenario, the use of reservations makes the most difference. The average TPT with a balanced operation rate lowers by around 25 minutes, which is equal to a maximum absolute difference of 35.22% comparing Experiment 2 to Experiment 1. This lower TPT is caused by the lower WT of around 25 minutes. For the unbalanced operation rate, this difference is even higher. The average TPT lowers by around 42 minutes, which is equal to a maximum absolute difference of 38.65% comparing Experiment 6 to Experiment 5. This is also caused by a lower WT of around 42 minutes. Here, the experiments with the 25% reservation percentage scores the best results. However, also in this case the use of a higher percentage of reservations does give a more controlled flow in practice, which can be beneficial.

Since trucks and trailers are not separated in the current situation of physical intervention 1, the trailers experience the same results as for trucks. However, trailers on average do experience less WT, since trailers that are picked up at the GH do not experience any WT. This lowers the average.

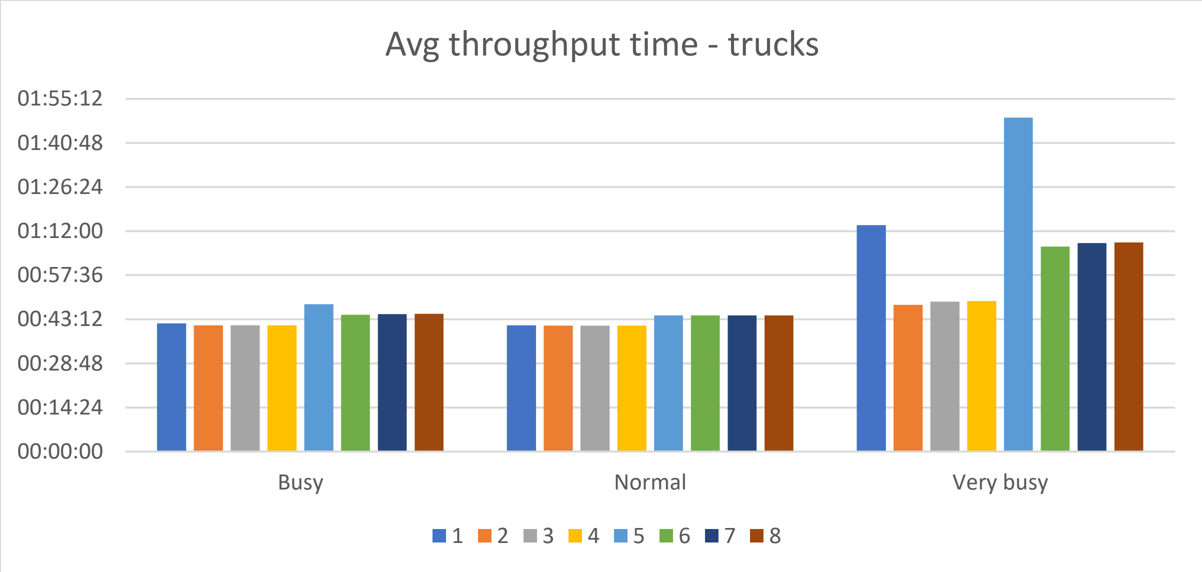

Figure 33: Results of physical intervention 1

When considering the number of trucks waiting at the GH at the peak moment of the day, the results of using reservations do show a difference in the peak. In Table 18, these results can be found. At all three options of truck arrival, there is a decrease on the number of trucks waiting at the peak moment of the day, which is beneficial. This means that the queue of waiting trucks is lower. The biggest improvement is with the very busy truck arrival scenario. Here, the total number of trucks waiting at peak moments at all GHs is lowered by a maximum absolute difference of 60.12% using a 25% reservation percentage in the balanced operation rate, and 51.50% lower using a 25% reservation percentage in the unbalanced operation rate. The exact numbers of trucks waiting at the GHs at the peak moment of the day is not realistic, as also mentioned by experts, however, it does show the relative impact of using reservations. It should also be known that the number of waiting trucks consists mostly of trucks without a reservation, since trucks with a reservation have priority and are helped first.

In conclusion, the difference of using reservations is most visible in the very busy arrival scenario. The use of reservations leads to a peak shaving effect and helps with the flow of trucks at the yard of Schiphol. In our model the differences 25%, 50%, or 75% as reservation percentage are very close and do not make a big difference in results, and also the use of reservations in the other arrival scenarios are not as beneficial. The reason behind this is mostly because it is not possible to make the arrivals more balanced with the current implementation of reservations. However, in practice there can be other advantages of having a higher percentage than now tested with the model. For example, in practice the use of reservations can be beneficial in all arrival scenarios, since the flow becomes clearer and more controlled. Furthermore, the higher the reservation percentage is, the more data-driven decisions can be made by the GH to, for example, adjust the number of staff on certain times, based on these reservations. For carriers, reservations mean less waiting time and helps them transport more in less time. The results shown only give an impression of the benefits of using reservations.

Table 18: Results vehicles at peak moment physical intervention 1

Experiment	Settings	Truck arrival	GH together (vehicles)	Abs diff
1	Balanced, 0%	Busy	53	0.00%
2	Balanced, 25%	Busy	23	56.60%
3	Balanced, 50%	Busy	30	43.40%
4	Balanced, 75%	Busy	30	43.40%
5	Unbalanced, 0%	Busy	87	0.00%
6	Unbalanced, 25%	Busy	32	63.22%
7	Unbalanced, 50%	Busy	40	54.02%
8	Unbalanced, 75%	Busy	41	52.87%
1	Balanced, 0%	Normal	12	0.00%
2	Balanced, 25%	Normal	3	75.00%
3	Balanced, 50%	Normal	5	58.33%
4	Balanced, 75%	Normal	5	58.33%
5	Unbalanced, 0%	Normal	17	0.00%
6	Unbalanced, 25%	Normal	7	58.82%
7	Unbalanced, 50%	Normal	9	47.06%
8	Unbalanced, 75%	Normal	9	47.06%
1	Balanced, 0%	Very busy	321	0.00%
2	Balanced, 25%	Very busy	128	60.12%
3	Balanced, 50%	Very busy	155	51.71%
4	Balanced, 75%	Very busy	159	50.47%
5	Unbalanced, 0%	Very busy	468	0.00%
6	Unbalanced, 25%	Very busy	227	51.50%
7	Unbalanced, 50%	Very busy	241	48.50%
8	Unbalanced, 75%	Very busy	252	46.15%

6.3.2 Physical intervention 2: Central parking as a buffer with a calling system

In physical intervention 2, the trucks wait at the CP till called by the GH. Because of this, all information interventions are possible and can influence the flow. The experiments we therefore test can be found in Table 19. These experiments are tested on each truck arrival (busy, normal and very busy). These experiments are also used for physical intervention 3 and 4. For this section, we split the results in subsections of busy, normal and very busy arrivals. The results of the KPIs on trailers are not different from that of trucks, since trucks and trailers are not separated. Therefore, we do not mention the results of trailers separately in this section.

Table 19: Configurations for the experiments

Experiment	Operation rate	Information intervention	ETA time known in advance	Reservation %
1	Balanced	None	-	-
2	Balanced	Reservation	-	25%
3	Balanced	Reservation	-	50%
4	Balanced	Reservation	-	75%
5	Balanced	ETA	30 min	-
6	Balanced	ETA	2 h	-
7	Balanced	ETA	5 h	-
8	Balanced	ETA	12 h	-
9	Balanced	Both	5 h	75%
10	Unbalanced	None	-	-

11	Unbalanced	Reservation	-	25%
12	Unbalanced	Reservation	-	50%
13	Unbalanced	Reservation	-	75%
14	Unbalanced	ETA	30 min	-
15	Unbalanced	ETA	2 h	-
16	Unbalanced	ETA	5 h	-
17	Unbalanced	ETA	12 h	-
18	Unbalanced	Both	5 h	75%

Busy truck arrivals

In Figure 34, the results can be found for the KPIs TPT, WT and TT. Both the balanced and unbalanced operation rate show a lower average TPT when using reservations as information intervention. The maximum difference with a balanced operation rate is 12.12%, and with an unbalanced operation rate 23.66%. This difference also shows in the average WT of trucks. When using reservations, the maximum difference in WT for a balanced operation rate is 93.06% lower, and for the unbalanced operation rate 93.23% lower. The average TT lowers by around a minute, which is around 9% with both operation rate options, this difference is mostly because less trucks need to travel to the CP buffer and can drive to the GH directly, due to the different arrival rate distribution over the hours of the day. The results also show that the difference between a 25%, 50%, or 75% reservation rate is negligible. This can be explained by the peak moment of the day being in the morning till around 15 hour, which gives less opportunity to move trucks to an earlier moment in the day and obtain a peak shaving effect.

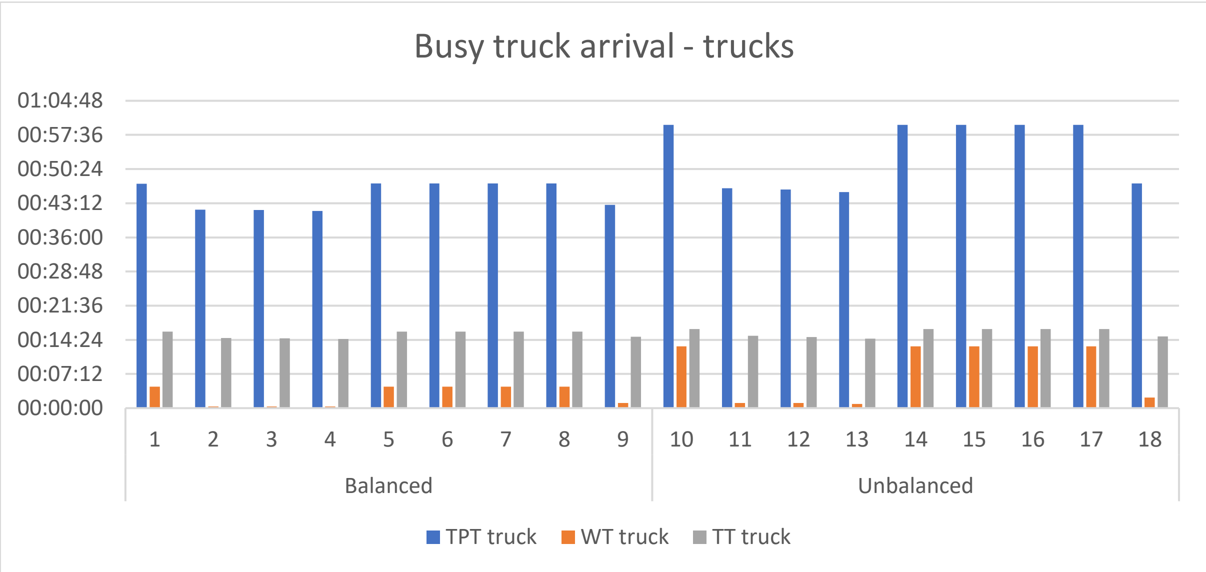

Figure 34: Results for the busy scenario in physical intervention 2

Knowing the ETA of trucks a certain time ahead does not lead to better results for the flow of trucks. The average TPT, WT and TT stay the same. The reason behind this is that at the GH some docks sometimes do not service a waiting truck, since there is another truck arriving with a tight due date or a reservation. This truck with priority is serviced right away, however, the already waiting truck experiences more WT. This does not improve the flow. Not using a dock, and waiting till a priority truck arrives soon, leads to unused minutes and a balance needs to be found in order to make the use of ETA with this rule successful. A solution might be that an agreement is made with the trucks that make reservations, that their waiting time is at most the time of handling one other truck, but if a dock becomes free, they are helped earlier. This way the handling of trucks continues without breaks and is more efficient.

The combination of using both reservations and ETA shows an improvement on the basic scenario without connectivity. However, these results do not show a lower average TPT than using reservations only. The reason that this option does not give the best results is presumably due to the same reasons that using ETA only does not work well. The improvement of reservations are opposed by the ETA.

For the peak occupation rate at the CP buffer and the different GHs, shown in Table 20, we see a shift from trucks waiting at the GH (physical intervention 1) to trucks waiting mostly at the CP buffer. Since it is preferred not to have too many trucks waiting at the GH, trucks drive to the buffer more often and wait here till called. The use of reservations lowers the maximum number of trucks waiting at the CP buffer significantly by a maximum difference of 79,03% in the balanced operation rate and 81,65% for de unbalanced operation rate. However, the maximum number of trucks waiting at the peak moment at the GHs together is higher by using reservations. This can be explained by the fact that trucks that have reservations drive to the GH directly. If there are many trucks arriving with a reservation around the same time, this can cause congestion at the GH. This can be avoided by maintaining a balance in the number of reservations planned in a timeslot. Within our model we did not do this, and this can improve the outcome in further research. The use of an ETA keeps the maximum number of trucks waiting at the peak moment of the day equal. The GH does not handle another truck, but waiting on trucks arriving with preference, does not have an effect on the total number of trucks waiting at the peak moment. The use of both reservations and ETA leads to a slightly higher peak than using only reservations, but still lowers the peak moment by around a third in comparison with not using connectivity. The reason behind this is because through the ETA it is known which trucks arrive within a certain time. Therefore, the GH waits more often on an arriving truck with preference instead of calling a truck from the CP buffer, where with only reservations a truck from the CP buffer is called. Therefore, the peak is higher than with only using reservation.

Table 20: Results vehicles at peak moment physical intervention 2

Experiment	Settings (oper. Rate, ETA, res)	CP buffer	Abs diff	GH together (vehicles)	Abs diff
1	Balanced, 0m, 0%	62	0.00%	2	0.00%
2	Balanced, 0m, 25%	13	79.03%	2	0.00%
3	Balanced, 0m, 50%	18	70.97%	9	350.00%
4	Balanced, 0m, 75%	13	79.03%	18	800.00%
5	Balanced, 30m, 0%	62	0.00%	2	0.00%
6	Balanced, 2h, 0%	62	0.00%	2	0.00%
7	Balanced, 5h, 0%	62	0.00%	2	0.00%
8	Balanced, 12h, 0%	62	0.00%	2	0.00%
9	Balanced, 5h, 75%	24	61.29%	15	650.00%
10	Unbalanced, 0m, 0%	109	0.00%	4	0.00%
11	Unbalanced, 0m, 25%	24	77.98%	5	25.00%
12	Unbalanced, 0m, 50%	26	76.15%	12	200.00%
13	Unbalanced, 0m, 75%	20	81.65%	25	525.00%
14	Unbalanced, 30m, 0%	109	0.00%	4	0.00%
15	Unbalanced, 2h, 0%	109	0.00%	4	0.00%
16	Unbalanced, 5h, 0%	109	0.00%	4	0.00%
17	Unbalanced, 12h, 0%	109	0.00%	4	0.00%
18	Unbalanced, 5h, 75%	32	70.64%	21	425.00%

In conclusion the average TPT is decreased most by using only reservations, but the results of experiments in which a reservation percentage is used are very close to each other. The use of an ETA does not improve the flow when using physical intervention 2 and a busy arrival rate. Using both an

ETA and the reservations does lower the average TPT, but not as much as using reservations only. In practice, the use of ETA can help significantly by knowing more about which trucks are coming and making data-driven decisions on that. A right balance needs to be found in order to make using ETA work and make sure no time is lost when waiting for priorities, further research is necessary for this. We expect the use of both ETA and reservations to work better as soon as the ETA becomes more efficient on its own, i.e., the design of the ETA process is further analyzed.

Normal truck arrivals
The results of the experiments with normal truck arrivals show no improvement with using connectivity. This can be explained by the lower number of trucks arriving, the lower peak and the extra option of driving to the CP buffer. Since trucks can now drive to both the GH and the CP buffer, the extra time it takes to drive to the GH is not considered to be waiting time. Therefore, it can be that the time it takes to get to the CP buffer, is enough to be called immediately from the buffer to the GH. However, in the end the truck spends the same time at the yard, just driving instead of waiting. The experience of waiting is maybe perceived as shorter, but it is not beneficial for trucks to be driving around the yard unnecessary for both the costs of fuel and emissions, as well as the unnecessary traffic on the road. Therefore, this is considered a flaw of the model and should be investigated in further research. Next to this, the system with normal truck arrivals is already pretty balanced and at the peak moments there are at most 10 vehicles waiting at the CP buffer for all GHs combined. This means that the queue per GH is very low. Connectivity therefore shows no improvements to this flow. However, in practice, as also mentioned in Section 6.3.1, there could be more benefits of using information interventions.

Very busy truck arrivals
Figure 35 shows the results for the very busy truck arrivals rates. The results show the same outcome as with the busy arrival rate, i.e., that using reservations alone gives a better result than using the ETA alone. However, a difference with the busy arrival rates of physical intervention 2 and the very busy arrival rate of physical intervention 1 is the selection of the reservation percentage. The higher the percentage of reservations used, the lower the average TPT of trucks is, as well as their average WT. Since more trucks arrive, the number of trucks that can be moved to an earlier moment is higher, and therefore the peak shaving effect is more visible. Therefore, trucks experience less WT and the TPT is decreased. Another difference in this scenario is that the combination of using both an ETA and reservations gives a lower average TPT and average WT than using only a 25% reservation percentage. The use of only an ETA still does not give lower results than not using connectivity at all, for the same reasons as we already described earlier this section. For the peak moment occupation rate, we see the same behaviour mentioned above for the busy arrival rate.

In conclusion, the difference of using reservations is most visible in the very busy arrival scenario, however also in the busy scenario there is a noticeable difference. The use of reservations still leads to peak-shaving and in total less trucks are at the yard at the same time. In our model, the outcomes with 25%, 50%, or 75% as reservation percentage are very close and do not make a big difference in results, however, for the very busy scenario the higher the percentage, the lower the average TPT. Anyhow, in practice there can be other advantages of having a higher percentage than now tested with the model, as also mentioned in the conclusion of Section 6.3.1. The use of ETA is not as beneficial as we hoped. The reason behind this is that at the GH some docks sometimes do not service a waiting truck, since there is another truck arriving soon with a tight due date or a reservation. When this truck with priority arrives, it is serviced right away. A disadvantage of this is that trucks already waiting experience more WT, and the GH dock is not in use for some time. So, a better balance should be found to be able to fix this. This can be done by making agreements with the trucks (i.e., carriers) that make reservations. For example, the truck waiting time should be at most the time of handling one other truck, but if a dock becomes free, they are helped earlier. This way the handling of trucks continues without breaks and is more efficient. We expect the combination of using reservations and ETA to give better results then as well.

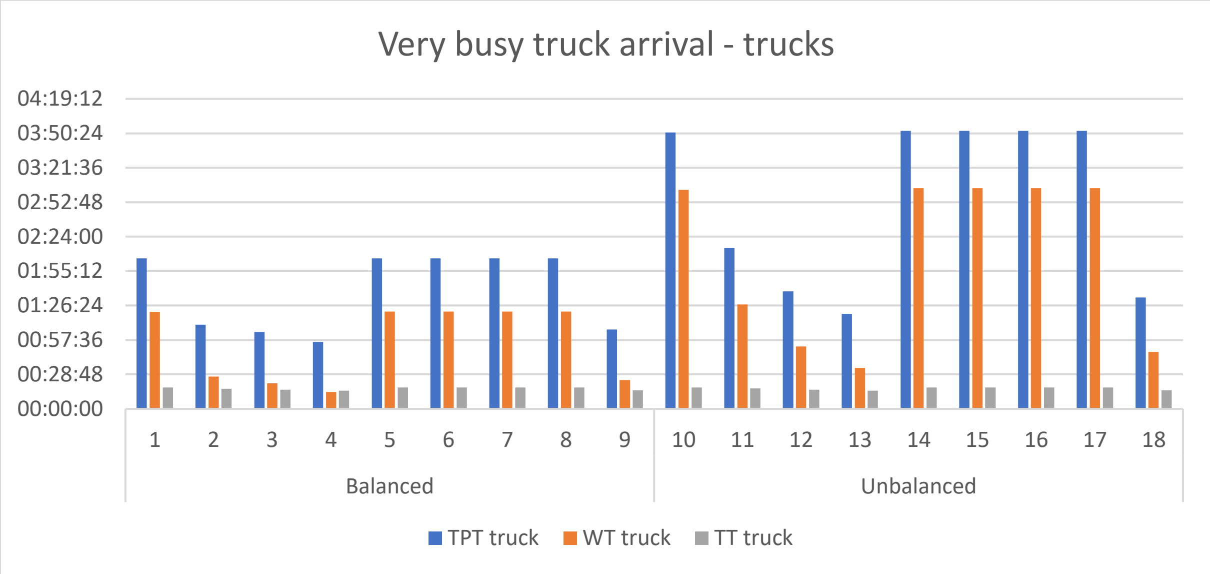

Figure 35: Results for the very busy scenario in physical intervention 2

6.3.3 Physical intervention 3 and 4: Central parking (buffer and decoupling point)

For physical intervention 3 and 4, the truck can also (de)couple at the CP. Because of this option, all information interventions are possible and can influence the flow. Physical intervention 3 and 4 are combined in this section because there were no significant differences between the use of traditional trucks and automated vehicles, with regards to our KPIs. Since we decided to show only the results of physical intervention 3 below, it should be kept in mind that the average TPT of the physical intervention 4 is always around 3% higher than that of physical intervention 3. This difference can be explained by the implementation of slower speed for AVs. But the same conclusions exist for physical intervention 4 as for physical intervention 3. The experiments we test for these two physical interventions are the same of that of physical intervention 2 and can be found in Table 19. These experiments are tested on each truck arrival (busy, normal and very busy). For this section, we follow the same structure as in the previous section, except for the normal scenario that is excluded from the analysis. There came no new insights from the results of the normal scenario, and there was almost no improvement using connectivity, just as also mentioned for the normal scenario of Section 6.3.2, i.e, physical intervention 2.

Busy truck arrivals

When considering the busy arrival rate, we see a small improvement on the KPIs of trucks, as shown in Figure 36. Reservations and the ETA separately do both improve the average TPT of trucks in comparison to using no connectivity. For using reservations only, the maximum difference is an 11.68% decrease of the average TPT, for ETA this is an 9.62% decrease. The reason the ETA improves the average TPT for this physical intervention is that knowing which trucks will arrive, gives the opportunity to bring trailers at a calm moment from the GHs to the (de)coupling point. This way, some trucks at busy moments do not have to queue at the yard of Schiphol to go to the GH to pick up the trailer, but they can directly go to the CP and pick up their trailer. As also shown by the results, knowing the ETA further ahead gives opportunity to prepare more trailers for pick up at the CP. Therefore, the average TPT decreases when the ETA is known further ahead. Also, the combination of using both the ETA and reservations gives a lower average TPT and average WT than using no connectivity. The maximum difference is an 13.59% decrease for the unbalanced arrival rate. Another benefit of using a CP as a (de)coupling point is that, at peak moments, trucks can drop off the trailer at the CP and leave the yard or pick up another trailer without having to wait in queue at the GH. This too contributes to improving the average TPT of trucks.

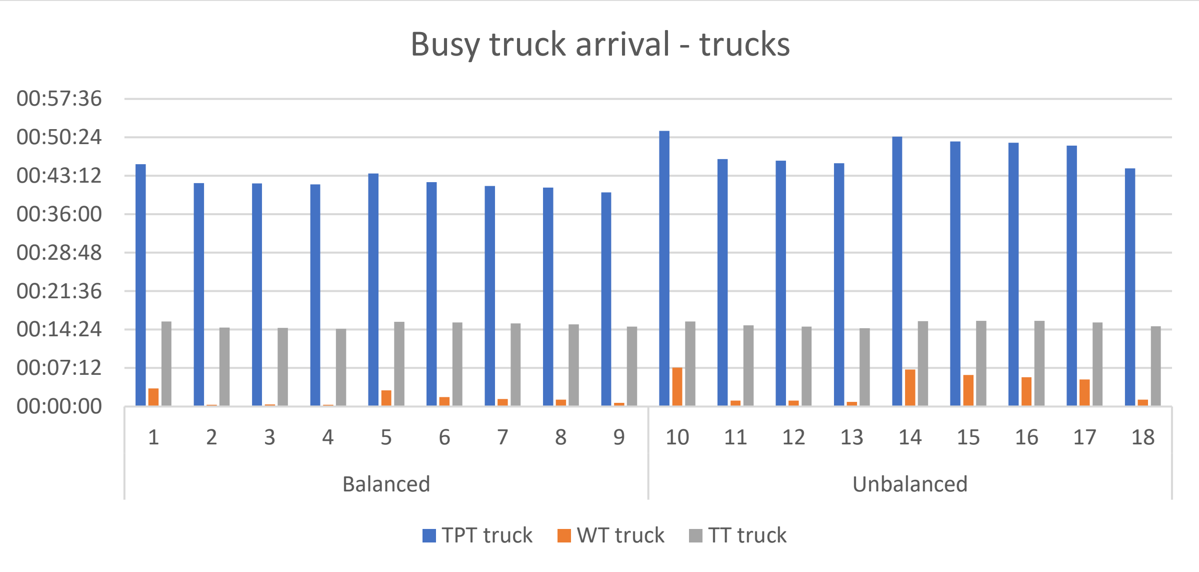

Figure 36: Results for trucks and the busy scenario in physical intervention 3

Since trucks and trailers can move through the yard separately, we can discuss the results of trailers separately as well. Figure 37 shows the results on the KPIs of trailers. As expected, the WT of trailers increases when using an ETA. This is because trailers are brought to the CP at a calm moment to prepare for the more busy moments. Because of this, the trailers have a longer average WT. Furthermore, trailers can also be brought to the CP by trucks at peak moments, where it will wait till called by the GH, which can also increase the WT of trailers. However, when a trailer is brought to the CP, it does not matter if it waits there for one hour or 4 hours, as long as it is brought to the GH on time or picked up by a truck whenever the truck arrives. The WT at the CP does not matter.

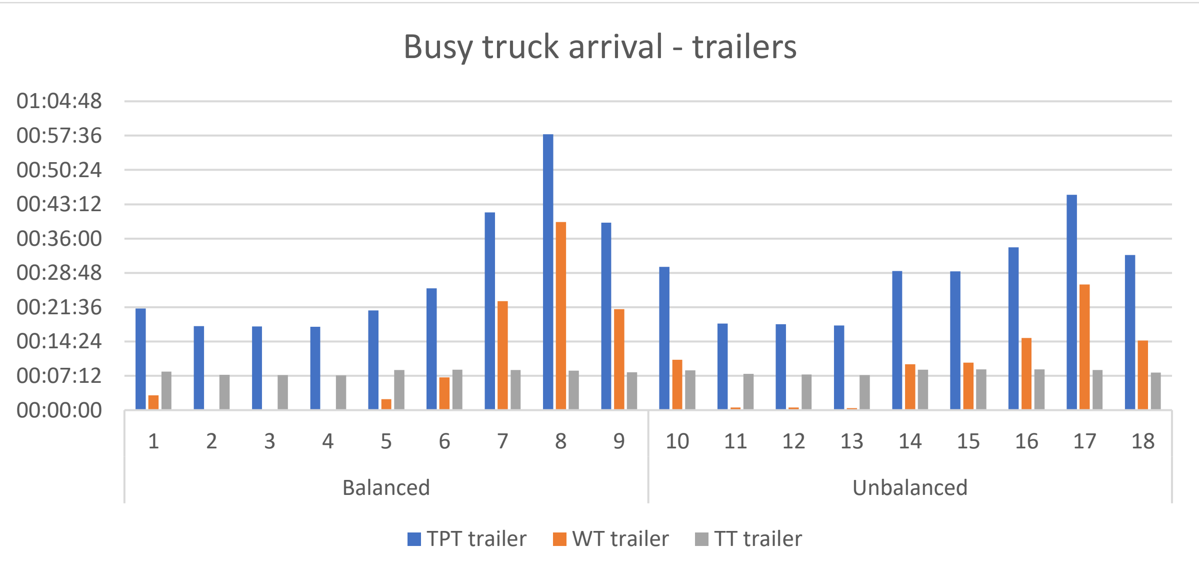

Figure 37: Results for trailers and the busy scenario in physical intervention 3

When considering the number of trucks or trailers waiting at the peak moment of the day at the CP and GHs, as shown in Table 21, we see that the queue is also mostly at the CP instead of the GH. This is beneficial, because it prevents trucks from waiting on the side of the road. However, the number of trucks and trailers waiting at the CP increases a lot when using ETA. Trailers are brought to the CP at calmer moments to prepare for more busy moments, but this also means that at a certain time the number of trailers waiting there is quite significant. The result is that a queue arises at the CP (de)coupling area, since it takes time to (de)couple and too many trucks and trailers arrive at this point to handle the peak. The idea of using ETA to prepare for peaks seems promising, but more research could be performed on finding the right balance in preparing for more busy moments, and still having enough space and capacity of (de)coupling at the CP to prevent a long queue. For example, only giving GHs that cannot handle peak moments the opportunity to prepare for busy moments, while other GHs are not allowed to do so. Overall, using reservations lowers the number of trucks at peak moments and spreads these trucks over the day. The ETA helps to prepare for peak moments, but does require more space at the CP.

Table 21: Results vehicles at peak moment physical intervention 3

Exp	Settings (oper. Rate, ETA, res)	CP buffer	Abs diff	CP (de)-coupling	Abs diff	GH together (vehicles)	Abs diff
1	Balanced, 0m, 0%	31	0.00%	75	0.00%	10	0.00%
2	Balanced, 0m, 25%	13	58.06%	0	100.00%	2	80.00%
3	Balanced, 0m, 50%	18	41.94%	0	100.00%	9	10.00%
4	Balanced, 0m, 75%	13	58.06%	0	100.00%	18	80.00%
5	Balanced, 30m, 0%	31	0.00%	73	2.67%	9	10.00%
6	Balanced, 2h, 0%	28	9.68%	43	42.67%	5	50.00%
7	Balanced, 5h, 0%	27	12.90%	93	24.00%	4	60.00%
8	Balanced, 12h, 0%	25	19.35%	173	130.67%	3	70.00%
9	Balanced, 5h, 75%	13	58.06%	78	4.00%	14	40.00%
10	Unbalanced, 0m, 0%	35	0.00%	145	0.00%	20	0.00%
11	Unbalanced, 0m, 25%	23	34.29%	7	95.17%	5	75.00%
12	Unbalanced, 0m, 50%	24	31.43%	12	91.72%	12	40.00%
13	Unbalanced, 0m, 75%	19	45.71%	2	98.62%	25	25.00%
14	Unbalanced, 30m, 0%	34	2.86%	137	5.52%	20	0.00%
15	Unbalanced, 2h, 0%	34	2.86%	124	14.48%	18	10.00%
16	Unbalanced, 5h, 0%	31	11.43%	111	23.45%	11	45.00%
17	Unbalanced, 12h, 0%	32	8.57%	158	8.97%	12	40.00%
18	Unbalanced, 5h, 75%	19	45.71%	64	55.86%	17	15.00%

Very busy truck arrivals

For the very busy truck arrivals, the results on the KPIs of trucks are comparable with the busy truck arrival scenario, only more trucks arrive and that results in more congestion at the yard and a longer average TPT and WT, as can be seen in Figure 38. What stands out most is that with an unbalanced operation rate, the use of reservations lowers the average TPT and WT significantly. The maximum difference is a 79.39% decrease in average TPT. This gives promising results for practice. Although trucks and trailers can be separated, we have the exact same results for trailers, only the times are lower. Therefore, we only show and discuss results for trucks.

The peak occupation rate of vehicles in the yard shows the same, but more extreme results, as also shown with the busy scenario. The numbers are not very realistic in this scenario, since there are almost 2000 trucks and trailers in the yard, but this is also due to the fact that trailers are brought to the CP to prepare for more busy times. There is no balance right now between pre-shunting trailers and having enough capacity to prevent a long queue at the CP.

In conclusion, the results show that using reservations as improved connectivity always performs better on the KPIs for trucks than not using connectivity. The use of the ETA improves the results slightly and the use of both reservations and ETA gives a better result than no connectivity. For both reservations and ETA, we see that a higher number of reservations or looking further ahead leads to a lower average TPT. For trailers, the average TPT and WT increases when using the ETA, because of waiting longer at the CP. However, this WT is not a problem as long as the trailer arrives at the CP on time. Still, in practice, this will not work for all trailers. For example, trailers containing perishable items, e.g., reefer trailers, might not be able to wait at the CP. This should be considered in further research. The big learning point is that when using ETA, a balance needs to be found in preparing for more busy moments, and still having enough space and (de)coupling capacity at the CP to prevent a long queue.

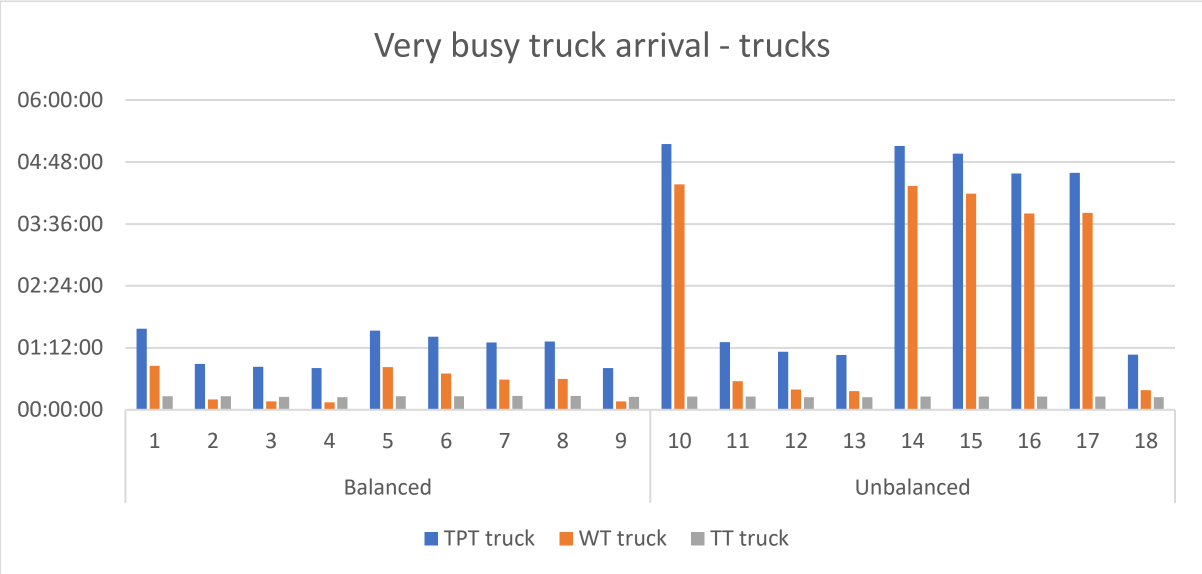

Figure 38: Results for trucks and the very busy scenario in physical intervention 3

6.3.4 Other experiments

Next to the experiments per physical intervention, we also want to see what impact the due date has on the freight flow of the yard. We therefore experimented with shorter due dates. When using the busy truck arrival, we did not notice any difference in KPIs of trucks and trailers, and not in the peak moments at the yard. We therefore also experimented with the shorter due dates in a very busy truck arrival, but also here no differences were noticeable in the KPIs of both truck and trailers or in the peak moments at the yard. We therefore concluded that changing the due dates from Gamma(3;100) to Gamma(3;75) does not have an impact on the flow; however it probably does make a difference in how many due date violations are made, but this is currently not measured. Further research could be done with considering the number of violations and to analyse what impact arriving shorter before the due date has on the model, since in practice trucks currently arrive close to their due dates.

We also experimented with the CP buffer threshold, i.e., the allowed maximum number of trucks waiting at the CP, to see what impact this would have on the flow of the yard. Table 22 shows the impact on the KPIs of trucks and trailers. We see that the average TPT is slightly higher when the threshold is higher, and lower when the threshold is lower. Moreover, if more trucks wait in the CP buffer because of the higher CP buffer threshold, the average TPT increases, since more trucks stay in the yard instead of (de)coupling at the CP. Similarly, the number of trucks waiting at the CP buffer at peak moments is lower if the threshold is lower, and vice versa, which seems logical considering the threshold change.

Table 22: Results on KPIs of trucks and trailers

CP buffer threshold	TPT truck	WT truck	TT truck	TPT trailer	WT trailer	TT trailer
Normal	00:45:22	00:03:24	00:15:55	00:21:21	00:03:08	00:08:04
Lower	00:44:06	00:02:49	00:15:42	00:21:56	00:03:29	00:08:05
Higher	00:46:18	00:03:54	00:16:01	00:20:45	00:02:36	00:08:04

Next to the due date and CP buffer threshold, we also experimented with the arrival rates of van Heuveln (2020), which has a later peak than the arrival rates used before. We want to check what the impact of connectivity is when the peak moment is later on the day. For this, we tested the experiments in Table 23 with very busy truck arrival and an unbalanced operation rate. We chose these settings of a very busy truck arrival and an unbalanced operation rate because this is the most complex busy arrival of trucks. This leads to slightly more extreme outcomes and gives a better overview of what difference this can make on the KPIs.

Table 23: Configurations for the experiments

Experiment nr	Arrival rates	Information intervention	ETA time known in advance	Reservation %
1	This research	None	-	-
2	This research	Reservation	-	75%
3	This research	ETA	5 h	-
4	This research	Both	5 h	75%
5	van Heuveln (2020)	None	-	-
6	van Heuveln (2020)	Reservation	-	75%
7	van Heuveln (2020)	ETA	5 h	-
8	van Heuveln (2020)	Both	5 h	75%

The results of these experiments can be found in Figure 39. It shows that the overall average KPI results of the arrivals of van Heuveln (2020) are lower than those of our arrivals. This is partly because the peak of van Heuveln (2020) is late in the evening, and therefore not all trucks left the yard at the end of the day. After 10 days of running the simulation, the trucks that are still in the yard are not considered in the results, since they did not leave the yard. This can give a lower overall TPT. Furthermore, the arrivals of van Heuveln (2020) are more distributed over the day, and differences between high arrivals and low arrivals are not as big as with our arrivals, as also shown in Appendix A. However, overall we see that the effect of using reservations and the ETA is the same with the arrivals of van Heuveln (2020) as it is with ours.

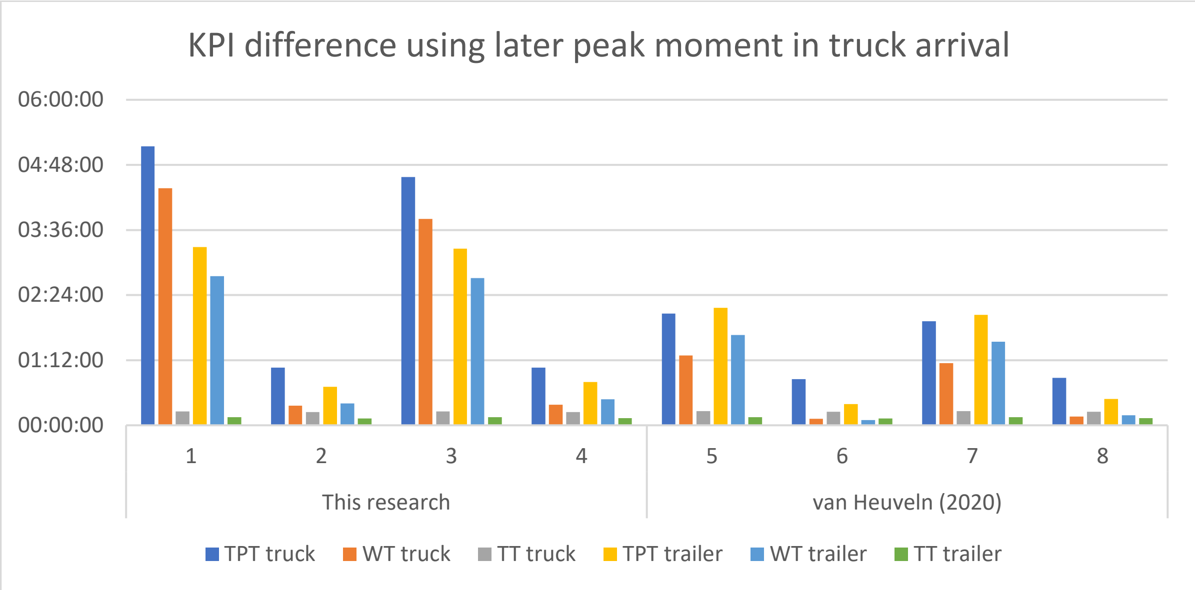

Figure 39: Results for the different peak moments

6.3.5 Differences between physical interventions

When comparing the different combinations of information interventions and physical interventions, we achieve further insights. Table 24 shows the settings we use to compare the results of average TPT shown in Figure 40. As visualized, the same impact occurs when using reservations on each of the four physical interventions. In every physical intervention, the use of reservations is beneficial. However, with physical intervention 1 and 2, ETA does not have a positive or negative effect. However, with physical intervention 3 and 4 the effect of using ETA is slightly positive. It slightly lowers the average TPT. However, the effect is not as impactful as the use of reservations. As already mentioned, the problems that occurred are that GHs sometimes were idle, waiting on a priority truck or trailer to arrive. Another problem is that when preparing trailers at the CP (de)coupling point for peak hours, there is not a right balance yet. When these two problems are improved, ETA might give a decrease in average TPT. Within the model, there is currently no reason to use both reservations and ETA, since the use of only reservations always works better. However, in practice, the use of both can give benefits like a peak-shaving effect, but also to make it possible to make data-driven decisions based on knowing the ETA of trucks in advance.

Table 24: Settings comparison for the different physical interventions

Experiment	Operation rate	Information intervention	ETA time known in advance	Reservation %
1	Unbalanced	None	-	-
2	Unbalanced	Reservation	-	25%
3	Unbalanced	Reservation	-	50%
4	Unbalanced	Reservation	-	75%
5	Unbalanced	ETA	30 min	-
6	Unbalanced	ETA	2 h	-
7	Unbalanced	ETA	5 h	-
8	Unbalanced	ETA	12 h	-
9	Unbalanced	Both	5 h	75%

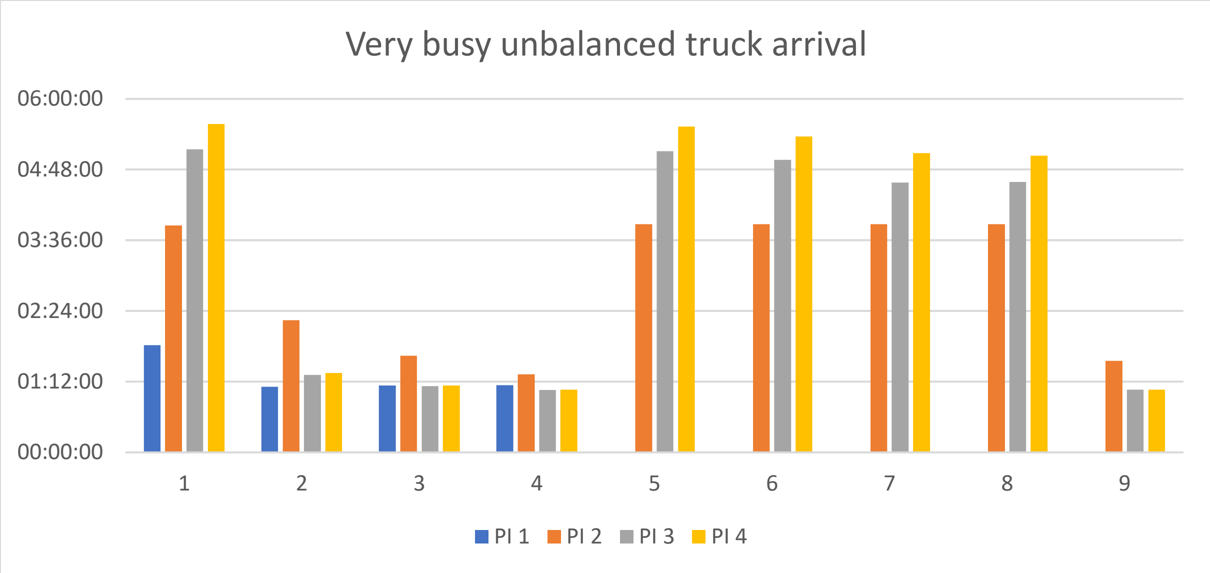

Figure 40: Comparison different physical interventions

6.4 Conclusion

In conclusion, we see that in all experiments reservations have a positive impact on the average TPT of both trucks and trailers. With physical interventions 1 and 2 it does not matter what the percentage of reservation is. However, with intervention 3 and 4 it does show a slight difference: the higher the percentage is, the lower the average TPT and WT of trucks and trailers is. In reality, the difference of percentage of reservations can however make a big difference, as more is known about the arrivals. Reservations also lower the number of trucks and trailers at the CP and/or GHs at the peak moment of the day. Overall, using reservations has a peak shaving effect for GHs and benefits the flow of the yard.

Furthermore, using the ETA does not influence physical interventions 1 and 2, but it does have more effect with interventions 3 and 4. However, using reservations only is way more preferable then using the ETA only. The effect of the ETA lowers the KPIs of trucks, but increases the KPIs of trailers, since they experience increased WT. The reason behind this is because trailers are brought to the CP by trucks if they arrive early and still have time till the due date. Furthermore, trailers are brought to the CP by internal vehicles at calm moments, to prepare for peak moments. Some trucks can pick up their trailer at the CP instead of going to the GH. This increases the average WT of trailers. However, this WT is unimportant, as long as trailers are at their destination on time. Last, the negative impact of using the ETA is shown on the number of trucks and trailers at the CP at peak moments. As mentioned, the arising queue at the CP negatively impacts the average TPT and WT. More research is necessary to find the right balance in preparing for peak moments, and still having enough space and capacity for (de)coupling at the CP. Furthermore, using ETA is less efficient at the GH, since there are moments where a dock is not in use, but waiting on a priority truck or trailer that is arriving soon. We do think using ETA could be very beneficial in reality since this allows for better data-driven decisions to be made.

The combination of using both the reservations and the ETA also has a positive impact on the KPIs, but with physical interventions 1 and 2 this is not as effective as using reservations only. For physical interventions 3 and 4, the impact is more significant, but again the problem of the ETA arises when long queues form at the CP. In reality using both allows for the most information on arrivals to be known and we think this could give the best results in reality.

7. Conclusion and recommendations

In this chapter, we first answer our sub-questions and the main research question of this research. This can be found in Section 7.1. After this, recommendations for further research can be found in Section 7.2.

7.1 Conclusion

The main question of this research is:

"How can improved connectivity be achieved within the yard of Amsterdam Airport Schiphol, and what will be the impact of this improved connectivity on the cargo transport flow within the yard, by making use of a Central Parking and preferably automated vehicles?"

We answer this main question by discussing the outcomes per research question.

What are the characteristics of the yard of Schiphol and what does the* cargo *transport flow look like?
For the yard of Schiphol, we took five GHs into account. There are three truck parking's that can be used as a CP area for trucks to buffer till called by the GH or to (de)couple cargo. The cargo is transported between the CP and GH by internal trucks, which can either be traditional trucks, or AVs. The yard of Schiphol has two entrances for trucks, namely: an entrance on the South-side of the landing strip, which is an exit of the N201 road, and an entrance on the North-side of the landing strip, which is an exit of the E19 road. Furthermore, the arrival rates of trucks are also examined.

What is connectivity and what different concepts of improved connectivity are defined within literature?
Connectivity can be described as the digital communication between all actors in a process, which preferably happens in real-time. This can be seen as an information flow between stakeholders. This allows decisions to be made based on the data, and to optimize the freight flows. Within the literature we see different concepts of connectivity. The clearest concepts are track and trace, geofencing and the use of platforms.

Which concepts from literature are the most suitable for the use case of Schiphol?
The concepts that are the most suitable for the use case of Schiphol are geofencing and an information-sharing platform. As one of the problems in the Schiphol use case is the unknown arrival time of trucks, we use geofencing as a method to provide us with an accurate ETA. This method enables to make a data-driven decision on which truck is helped next at the GH. The other method we use is an information-sharing platform. Within such a platform there are two options for the yard of Schiphol. The first option is to make it possible for truck drivers to make an appointment at a GH for timeslots that are dictated by the GHs. This method allows peak-shaving for the GHs, since the options for making an appointment can be at less busy hours. This is a more advanced way of sharing data, allowing for both peak-shaving to occur, but also to make it possible to make data-driven decisions based on knowing the ETA of trucks in advance.

With these concepts we created the information and physical interventions in Table 25 to evaluate with the simulation model.

Table 25: Interventions chosen

Nr	Information interventions
1	No use of connectivity
2	A given percentage of trucks have a reservation at the GH
3	Knowing the ETA of trucks, a certain time in advance
4	Using both reservations and ETA

Nr	Physical interventions
1	The current situation, trucks can only drive directly to the GH
2	Trucks can drive directly to the GH, or to the CP which can be used as a waiting area, till called by the GH
3	Trucks can drive directly to the GH, or to the CP. The CP can be used both as buffer and (de)coupling point. Last-mile transport by traditional trucks
4	Trucks can drive directly to the GH, or to the CP. The CP can be used both as a buffer and (de)coupling point. Last-mile transport by AVs

How to design a simulation model to study the impact of the improved connectivity concepts on the cargo transport flow within the yard of Schiphol?
We created a conceptual model in order to make a simulation model. Within the conceptual model we explained the problem situation, project objectives, model outputs and inputs, a scope and level of detail and we provided flowcharts of the simulation. We determined KPIs which are the throughput times, travel times and waiting times of both trucks and trailers, as well as the peak occupation rate at the GHs and CP. We then made a computer model of the yard of Schiphol and implemented the different information interventions. After this we verified and validated the model.

What is the potential impact of the chosen improved connectivity concepts on the cargo transport flow at the yard of Schiphol?
The results of the experiments in the simulation model show that the use of improved connectivity can greatly help in lowering the average TPT and WT of trucks and trailers, as well as lowering the occupation rate at peak moments in the yard of Schiphol. When looking at using reservations, it shows that in all scenarios using reservation improves the flow at the yard of Schiphol. Reservations do work peak-shaving since trucks arrive more divided over the day. The percentage used for reservations in the model does not always give very large differences. However, in practice it would be beneficial to have a larger percentage, since more of the arrivals are known ahead, which can give more control.

The use of ETA does not provide an improvement for physical intervention 2, however with physical intervention 3 and 4 the effect of using ETA is slightly positive. Using ETA slightly lowers the average TPT. However, the effect is not as impressive as the use of reservations. Two problems occurred, which are GHs were idle more waiting for priority trucks which is inefficient. The second problem is that the balance between preparing for peak hours and number of trailers waiting at the CP was not right. Further research is necessary in these two problems. Within the model, there is currently no reason to use both reservations and ETA, since the use of only reservations always works better. However, in practice the use of both can give benefits like both a peak-shaving effect, but also to make it possible to make data-driven decisions based on knowing the ETA of trucks in advance.

Overall, the impact of using improved connectivity is proved within the assumptions made. When more real-world data is gathered, the simulation can be adjusted to this real-world situation and might provide even better results to this situation.

7.2 Recommendations for further research

Based on this research, we will now provide recommendations that can be used for further research. This section is separated in two parts, the recommendations on choices and assumptions and the recommendations on improvement of the model.

Recommendations on choices and assumptions

The first recommendation is about gathering accurate real-world data from the yard of Schiphol to implement in this model. Furthermore, stakeholders from the yard of Schiphol and all stakeholders should be involved to make agreements and help to make the model more accurate in representing this real-world situation. The model can be adjusted to this data and the expertise, and experimental factors can be determined as well. The results from the model can then be used to further investigate the impact of improved connectivity.

Another recommendation for further research is that the current model assumes that all parties involved follow the given rules exactly. Everyone sticks to these. However, in practice this might not be the case. Further research should be done on this implementation case. Furthermore, a similar problem can occur with the two rules around the arrival of a truck and when a dock becomes free. Currently, when a truck arrives just before its due date, it gets preference. On the one hand, in practice, trucks can take advantage of this by arriving just before the due date, and the rule will reward this opportunistic behaviour. On the other hand, it is important for all stakeholders that the cargo is delivered before the due date since airplanes have a tight schedule. Agreements should be made to prevent opportunistic behaviour of trucks.

Some other choices that need further research are about perishable items in trailers, the ownership of a trailer, and the security of the CP. For perishable items, trailers waiting at the CP with these items in them, or reefer trailers, might not be able to wait at the CP. In our research we did not consider this option, however, in practice these trailers exist, and it might be needed to treat them differently, e.g., by providing a certain number of electric plugs for reefer trailers. Agreements on this should be made, as well as a distinction within the simulation model. Furthermore, we did not consider the ownership of trailers. Currently, the trailers are dropped off and picked up at the CP, and there is no ownership to a specific truck, forwarder, or carrier. In practice this is different and more research on the effect of this should be done. Besides this, the security of trailers waiting on the CP should be researched as well. During transport, the carrier is responsible for the cargo. When dropped off at the GH, the GH takes the responsibility. However, when a container is placed at the CP and waiting, it should be known who is responsible for the trailer, and how it is ascertained that nothing happens to it.

When the decision is made to make use of improved connectivity, it can be beneficial to also further research planning and scheduling algorithms based on these reservations and the real-time information of the yard and arriving trucks. Currently, if many trucks arrive around the same time with a reservation, this can cause congestion. This can be avoided by maintaining a good balance in the number of reservations planned per time slot, but also how long a time slot should be. Within our model we did not consider the balance between number of reservations and not reservations within a time slot. The implementation of more advanced planning and scheduling algorithms can influence the potential impact and effectiveness of improved connectivity.

Model recommendations

To make the model more realistic, we recommend to extend the model by implementing more road obstacles, like passenger vehicles, traffic lights, or constructions. Furthermore, a big difference between AVs and traditional trucks is that AVs must be charged, more research could be done on the charging stations of AVs and strategies. Furthermore, currently the yard is always open with full capacity. This might not be the most realistic situation. Therefore, when more is known about the opening times of GHs and driving times of trucks, and the charging of AVs is implemented, a more clear difference might be visible between the use of traditional trucks or AVs within the model.

Another aspect that the model can improve on is the arrival decision, for example by forcing a truck to drive to the CP. Upon arrival at the CP, the truck is called to go to the GH, with (almost) no waiting time. The perceived waiting time of the truck is lower than if the truck drove to the GH directly and waited for its turn. However, it might not be beneficial to let the truck drive to the CP unnecessarily. In this case, the model should look further ahead to consider letting the truck drive to the GH directly to prevent unnecessary travel time. Also, more vehicles driving around the yard, and more emissions are not beneficial for the yard as well.

Another improvement on the current model is researching the impact of different versions of rules and choices, as well as making more dynamic rules. Examples of this can be for the arrival of trucks at the yard, as well as when a dock becomes free to make this more dependent on characteristics or based on the hour of the day. Another example is that the reservations could be more dynamic. This can help react based on the real-time situation. Furthermore, the improved connectivity concepts can be implemented more dynamically as well, for example, based on the specific characteristics of the incoming trailer or carrier, or based on the time of the day. Regarding knowing the ETA a certain time ahead, it would also be beneficial if some changes are made to the model regarding the generation of arrivals. Currently all arrivals of the day are generated at the start of each day. Generating these arrivals earlier or for a longer period than one day makes it possible to also plan over days instead of only the 24 hours itself. This way, the preparation for peak moments by placing trailers at the CP can also be done earlier, e.g., in the evening for the next day.

To make the model more representative of the real-world situation, further research should be done in splitting cargo drop off and pick up at multiple GHs, and not always carrying a full truckload. Currently, the drop off, or pick up of cargo is done at one GH, but in practice it can be that a truck needs to go to multiple GHs.

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Appendices

A. Arrival Rates busiest day

Table 26 shows the arrival rates of the busiest day at the yard of Schiphol according to the NDW sensors and the assumed number of trucks arriving at the yard.

Table 26: Arrival Rates busiest day

Hour	Arrivals NDW sensors * freq.	Arrivals van Heuveln (2020)
00:00-00:59	27	77
01:00-01:59	22	68
02:00-02:59	27	74
03:00-03:59	42	75
04:00-04:59	84	65
05:00-05:59	109	57
06:00-06:59	119	59
07:00-07:59	141	48
08:00-08:59	152	47
09:00-09:59	159	38
10:00-10:59	152	35
11:00-11:59	168	33
12:00-12:59	157	57
13:00-13:59	151	68
14:00-14:59	125	74
15:00-15:59	98	75
16:00-16:59	85	89
17:00-17:59	76	107
18:00-18:59	74	119
19:00-19:59	63	123
20:00-20:59	55	128
21:00-21:59	47	132
22:00-22:59	45	114
23:00-23:59	39	107

B. Calculation number of replications

Table 27 shows the calculation of the number of replications necessary. In Figure 41 the error for number of replications is visualized.

Table 27: Calculation number of replications

n	Average of 10 runs	Average	StDev	T-value	Delta	Error
1	2896,008	2896,008	0,000	0,000	0,000	0,000
2	2851,878	2873,943	31,205	12,706	280,363	0,098
3	2914,416	2887,434	32,139	4,303	79,837	0,028
4	2940,299	2900,650	37,246	3,182	59,267	0,020
5	2846,448	2889,810	40,349	2,776	50,099	0,017
6	2873,594	2887,107	36,691	2,571	38,505	0,013
7	2852,291	2882,133	35,987	2,447	33,282	0,012
8	2840,510	2876,930	36,422	2,365	30,450	0,011
9	2815,614	2870,118	39,731	2,306	30,540	0,011
10	2846,148	2867,721	38,218	2,262	27,339	0,010
11	2896,008	2870,292	37,246	2,228	25,022	0,009
12	2883,088	2871,358	35,704	2,201	22,685	0,008
13	2877,915	2871,863	34,233	2,179	20,687	0,007
14	2819,327	2868,110	35,761	2,160	20,648	0,007
15	2868,282	2868,122	34,461	2,145	19,084	0,007
16	2881,733	2868,972	33,465	2,131	17,833	0,006
17	2906,062	2871,154	33,628	2,120	17,290	0,006
18	2903,528	2872,953	33,505	2,110	16,662	0,006
19	2930,413	2875,977	35,128	2,101	16,931	0,006
20	2818,337	2873,095	36,540	2,093	17,101	0,006

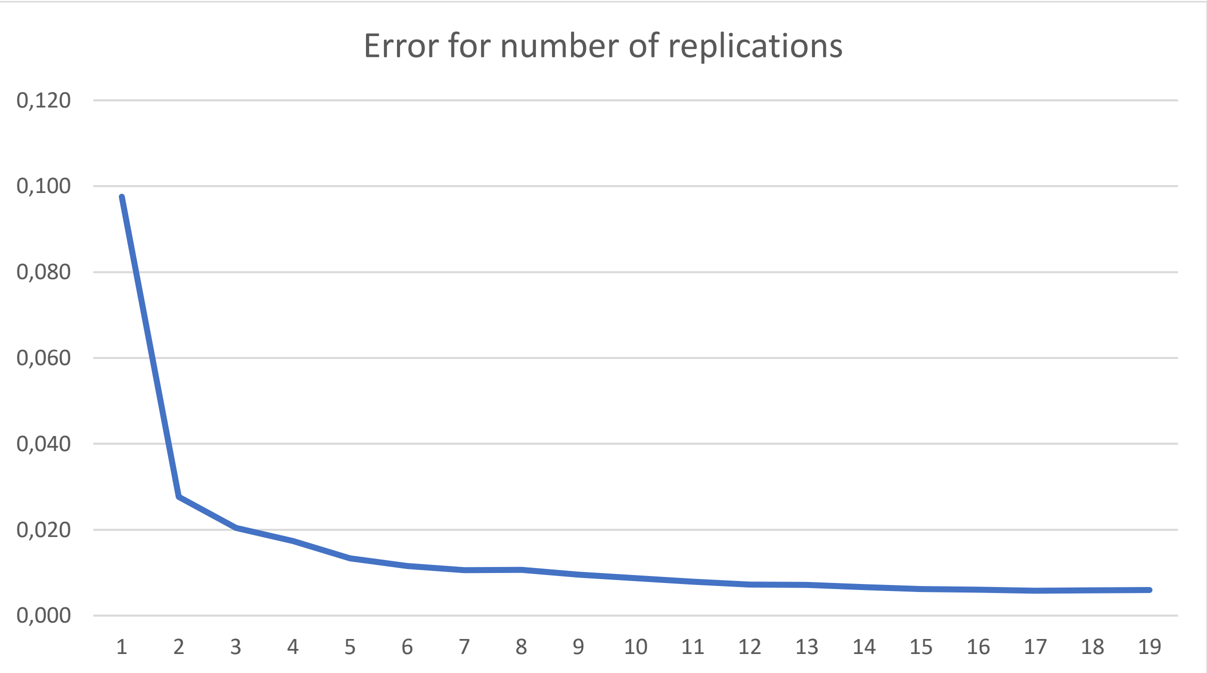

Figure 41: Error for number of replications