

**MASTER THESIS**

**DEFINING AND ANALYZING SMART  
YARDS: A SIMULATION STUDY**

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A study within the CATALYST Living lab

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# Management summary

Connected Automated Transport (CAT) is one of the key technological developments for future transportation in logistics. Connectivity makes processes controllable and automation makes it possible to manage and organize processes. Connectivity and automation integrated in the logistics sector results in constantly optimized processes to get a seamless integration within the supply chain. The field of freight automation is currently transitioning in the level of automation and in the areas of operation of highly automated vehicles from confined areas to hub-to-hub operations and open road. CAT applications can be introduced in a hub-to-hub environment to make a transition from a regular yard to a smart yard.

In this research we focus on the direct impact and effectiveness of a smart yard in logistic operations, answering the following research question:

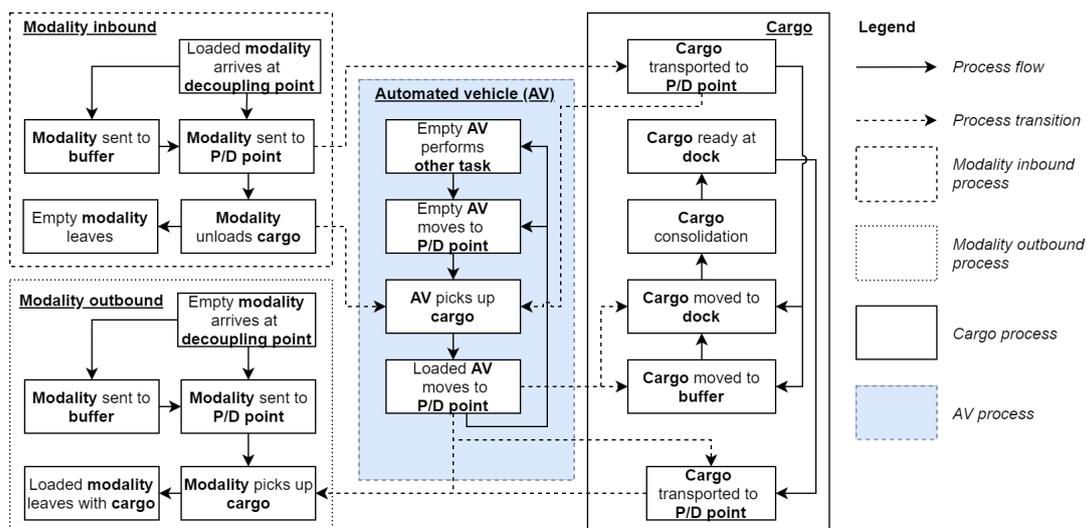
*How to define the characteristics of Connected Automated Transport and smart yard processes, and how to analyze their potential impact and effectiveness using simulation?*

To define the characteristics of CAT and smart yard processes, we develop two frameworks. The first framework visualizes the positions and connections of a smart yard and other CAT concepts and applications. The second framework can be used to determine the characteristics of a smart yard. We define decisive factors that substantiate the decisions on the key elements. The characteristics of a use case determine the outcome of the decisive factors.

A smart yard is characterized by the following three elements:

- Automated vehicles;
- Decoupling point;
- Connectivity through a seamlessly integrated network system.

A smart yard can be subdivided into a physical smart yard and a digital smart yard. The physical smart yard demarcates the area within a hub in which cargo flows. The digital smart yard demarcates the area between hubs in which the information flows. In this research, we focus on the direct impact and effectiveness of a smart yard in logistics operations. The figure below shows the generic processes of the physical smart yard.



Furthermore, the digital smart yard is a system in which information or data is exchanged. From a theoretical point of view, we define the following four potential impacts:

- Increased process efficiency;
- Peak shaving;
- Increased safety;
- Reduced congestion.

We apply the generic smart yard processes and potential impacts to various use cases included in the Connected Automated Transport And Logistics Yielding Sustainability (CATALYST) living lab. For each use case included in this living lab, we define a smart yard concept and show the potential impacts of a smart yard. We use the Schiphol case for our simulation study to show the potential impact and effectiveness of a smart yard. Schiphol is the main airport in the Netherlands and besides passenger flight, Schiphol also transports air cargo. We research the cargo handling process at the landside of Schiphol by using a smart yard.

In the current situation, arriving trucks drive directly towards a ground handler, which services the cargo in and out of the aircraft. Limited space and unregulated deliveries causes congestion within the area. We implement the following three interventions in the current situation at Schiphol:

- Truck Parking that is used as a buffer, where the waiting trucks are called when a dock becomes available;
- Decoupling point including internal manual vehicles, where trailers are decoupled;
- Decoupling point including internal automated vehicles, where trailers are decoupled.

To conduct the simulation study, we construct a conceptual model and describe multiple aspects such as the scope, the assumptions, and the level of detail. We implement the conceptual model in the discrete-event simulation software Tecnomatix Plant Simulation from Siemens.

We verify and validate the conceptual model and the computer model by using several techniques, e.g., traces, animations, and black-box validation. This ensures that the model is correct and sufficiently accurate. We conclude that the simulation model behaves as expected and with the approval by the subject experts from Schiphol, we assume that the simulation is valid.

To further extent this research, we derive results from experimentation to assess the impacts and effectiveness of a smart yard applied to a use case. We use the paths of a trailer, the number of internal vehicles, and the truck arrival intensity as experimental factors in various experiments. The results of the experiments reveal multiple potential impacts and effects. First, we find that the throughput time and the waiting time of trailers increases with the implemented interventions. However, the waiting time shifts from ground handlers to the truck parking and decoupling point. Second, we find that the throughput time and waiting time of a truck driver decrease. Last, we conclude that the interventions reduce the congestion within the hub.

For further research, we recommend providing more details and make the factors quantitative in the conceptual framework for smart yards, so that the characteristics of a case can be easier related to this framework. Next, we suggest developing similar simulation models for the other use cases included in the CATALYST living lab. Eventually, a generic smart yard can be developed to actually analyze its impact and effectiveness. Furthermore, the connectivity part of CAT should be researched as well. The impact on aspects such as legal, economical, and environmental should be researched further.

We recommend extending the simulation model and research the impact and effectiveness, to provide answers for the Schiphol case. We recommend to recreate the real life situation of Schiphol in the simulation model further by implementing, for example, the other ground handlers, the import process, and additional stochastic processes. Furthermore, we recommend to increase the real life situation of smart yards in the simulation model by implementing, for example, road obstacles, conflict avoidance and maneuvering of the internal vehicles, and including charging stations and charging strategies.

# Preface

This thesis has been written to finish the Master's degree in Industrial Engineering and Management at the University of Twente. It is a result of eight years of studying across the world. After an adventure of three years in Groningen, one year in Asia, half a year in the Achterhoek region, and 3 years in Enschede, it is time to start a new adventure. Although 2020 might be one of the strangest years, I am happy that I was given the opportunity to conduct my research within the CATALYST living lab at Distribute.

First, I would like to thank Berry Gerrits who made the assignment possible. We have had numerous interesting discussions, which helped me to reach a higher level for this thesis. Besides that, you provided me a really pleasant working environment. In addition, I would like to thank my other colleagues of Distribute, Robert, Stef, and Diederik for all the activities we did together, which always gave me a nice distraction.

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Furthermore, I want to thank all the people from TNO for helping me, providing me with documents, and giving me feedback. Especially Luc Oudenes, thank you for your help. You were always available for a call and our weekly meetings really helped me.

Last but not least, I want to thank all the people that were involved in their own way. My study mates, friends all across the Netherlands, and my family. Thank you for supporting me all those years. Mom and dad, everything will be fine!

Jelle van Heuveln  
Enschede, September 2020

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## List of Abbreviations

|          |  |
|----------|--|
| ACS      | Automated Stacking Crane   |
| AFTS     | Automated Freight Transport Systems  |
| AGV      | Automated Guided Vehicle   |
| ALICE    | Alliance for Logistics Innovations through Collaboration in Europe         |
| ALV      | Automated Lifting Vehicle  |
| ARCADE   | Aligning Research and Innovation for Connected Automated Driving in Europe |
| AV       | Automated Vehicle  |
| CAT      | Connected and Automated Transport  |
| CATALYST | Connected Automated Transport And Logistics Yielding Sustainability        |
| DP       | Decoupling Point   |
| DSY      | Digital Smart Yard   |
| ERRAC    | European Rail Research Advisory Council                                    |
| ERTRAC   | European Road Transport Research Advisory Council                          |
| GH       | Ground Handler   |
| IV       | Internal Vehicle   |
| KPI      | Key Performance Indicator  |
| LSP      | Logistics Service Provider   |
| MZ       | Menzies  |
| P/D      | Pick up and Drop off   |
| SAE      | Society of Automotive Engineers  |
| SP       | Swissport  |
| TP       | Truck Parking  |

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# 1. Introduction

This chapter introduces this research for the Master's degree in Industrial Engineering and Management at the University of Twente. In Section 1.1 we motivate our research. Section 1.2 gives the problem context. In Section 1.3 we describe our research setting. Section 1.4 gives the research problem and questions. Finally, in Section 1.5 we give the research outline.

## 1.1 Research motivation

Innovations in automation and connectivity are developing fast in transport and logistics and the introduction of Connected Automated Transport (CAT) plays an important role in the logistics transportation sector. The development of CAT is one of the key technologies for future transportation. Connectivity means that real-time data is exchanged, making processes controllable. Automation makes it possible to manage and organize processes, to make processes more efficient. When connectivity and automation are integrated within the logistics sector, processes can constantly be optimized to get a seamless integration within the supply chain.

CAT is included in innovations such as truck platooning and smart dollies. Gerrits et al. (2019) describes truck platooning as a concept where trucks are able to drive autonomously in a convoy with short following distances by using connectivity technology. A platoon is created by using Cooperative Adaptive Cruise Control, so that the trucks are virtually connected and are able to communicate with each other. A smart dolly is an automated yard tractor, which is used in confined areas such as container terminals or distribution centers. These smart dollies are, for example, used to handle trailers and chassis with containers. By using smart dollies, the handling process can be more efficient. These innovations are the result of the fast-developing technologies in the transport and logistics sector.

Due to the increased interest in CAT, multiple projects and platforms in the Netherlands and Europe have been formed. An overview of projects that support the development of automated driving is shown in Figure 1.1.

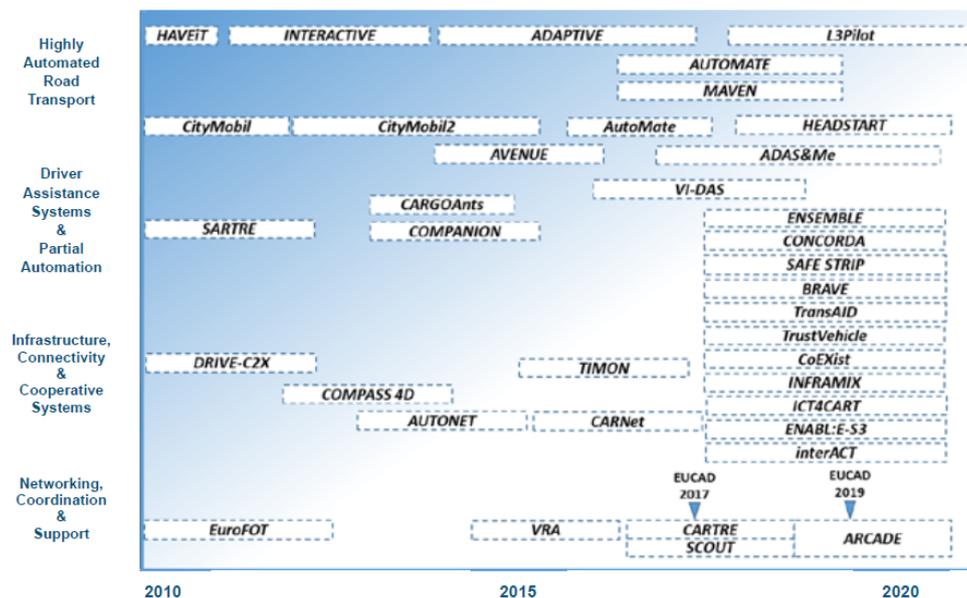


Figure 1.1: Overview of European CAT projects, taken from ERTRAC (2019a)

This overview shows the increasing interest in the development of automated driving in multiple research fields, as more projects have started in recent years. This also shows that research is not solely focused on automated driving systems, but also on, e.g., automated road transport and systems that are connected and cooperative. Some initiatives that support the innovations in connected and automated driving have started recently, like the Aligning Research and Innovation for Connected Automated Driving in Europe (ARCADE) project. ARCADE helps to build consensus for the deployment of connected, cooperative, and automated driving in Europe. Other initiatives already exist for a long time, like the European Road Transport Research Advisory Council (ERTRAC). ERTRAC is a European technology platform for road transport and is recognized and supported by the European Commission. The task of ERTRAC is to provide a vision for road transport research and innovation in Europe and define strategies and roadmaps for the coming years. ERTRAC (2019a) provides an overview of development paths for connected and automated driving. These paths are divided into passenger cars, freight vehicles, and urban mobility vehicles. In this research, we specifically focus on cargo transport. Figure 1.2 shows the prediction of applications in the coming years for freight vehicles.

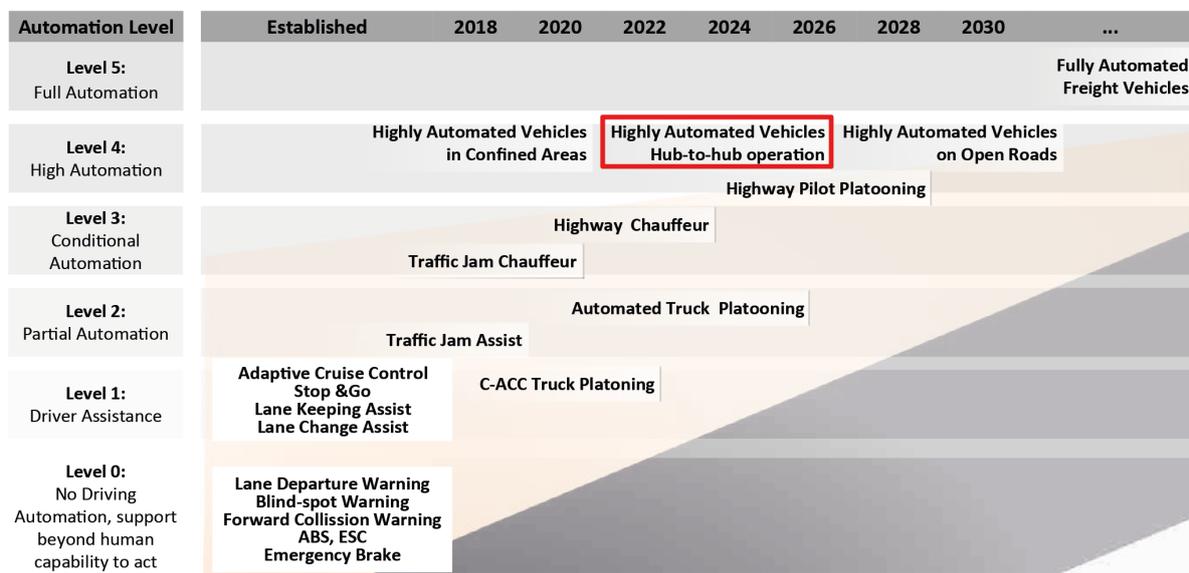


Figure 1.2: Development path for freight vehicles, taken from ERTRAC (2019a)

This figure shows the transition that is going on in the field of freight automation. The Society of Automotive Engineers (SAE) developed a taxonomy related to automated driving systems for on-road motor vehicles, where levels in automation are subdivided. The J3016 standard defines six levels of automation ranging from level 0, which is equal to no driving automation, to level 5, which is equal to full automation (SAE J3016, 2018). The main transition that is going on, is the use of Advanced Driver Assistance Systems (level 0 to level 2) to actual automation (level 3 and higher). Besides the main transition, there is a transition in level 4, from automated vehicles in confined areas to automated vehicles in hub-to-hub operations and open roads. Our research focuses on the transition from highly xautomated vehicles in confined areas to highly automated vehicles in hub-to-hub operations. This is indicated by the red box in Figure 1.2. Additional challenges need to be addressed, as we move away from a confined area. Hub-to-hub operations can be seen as relative short distance transportation between Logistics

Service Providers (LSPs), for example between a seaport, an airport, and a distribution center. In a hub-to-hub environment, uncontrollable factors such as other transportation means (passenger vehicles) and road traffic (obstacles) are additional challenges. Once highly automated vehicles are developed for hub-to-hub operations, further research can be conducted on the transition to highly automated vehicles on the open roads and later to fully automated freight vehicles. The transition to the open road is outside the scope of our research.

The current situation at LSPs can be described as “regular yards”, where at most automated guided vehicles are used in confined areas, but are not connected. Presumed CAT applications<sup>1</sup> can be introduced in a hub-to-hub environment to make the transition from a regular yard to a smart yard, so moving away from confined areas. These CAT applications should be able to handle the uncontrollable factors in a hub-to-hub environment. The relation between CAT and smart yards is that CAT concepts<sup>2</sup> are implemented to make the transition from regular yards to smart yards.

### Smart yard

The intended smart yard system in a hub-to-hub environment can be subdivided into a physical smart yard and a digital smart yard. The physical smart yard demarcates the area within a hub, in which cargo flows. The digital smart yard demarcates the area between hubs, in which the information flows. A visualization of a generic smart yard concept and the area for Automated Vehicles (AV) is given in Figure 1.3.

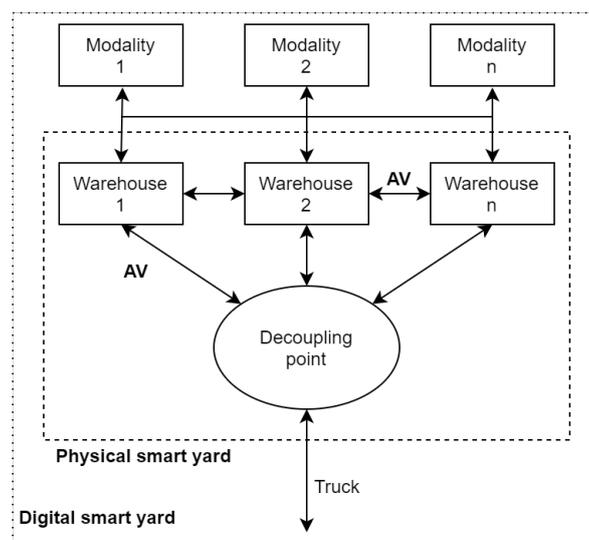


Figure 1.3: Generic smart yard concept

It is called a smart yard, as smart refers to intelligently using data and collecting this data. Yard refers to the area in which the transshipment operations are carried out at the LSPs. Various external modalities (e.g., barges, trucks, trains, and aircraft) arrive at the physical smart yard and the cargo is consolidated in a warehouse. When the cargo is ready, it is transported by internal AVs<sup>3</sup> from and between the

<sup>1</sup>Throughout this research we use the term application as a technological idea for a particular purpose

<sup>2</sup>Throughout this research we use the term concept as an overarching idea that can consist of multiple applications

<sup>3</sup>Definitions of automated and autonomous, and the substantiation of the use of AVs is given later on

warehouses and decoupling point. At the decoupling point, the cargo is (de)coupled from the external trucks and the internal AVs. A more detailed description and the impacts of the smart yard concept is given in Chapter 4.

Elvik et al. (2019) conducts a systematic review to identify the potential impacts of CAT. They conclude that in total 33 potential impacts have been identified, where a distinction between direct-, systemic- and wider impacts can be made. This report reviews multiple studies and among them the article by Milakis et al. (2017). They propose a conceptual model to show the sequential effects on several aspects of mobility and society that automated driving might bring. This conceptual model is shown in Figure 1.4.

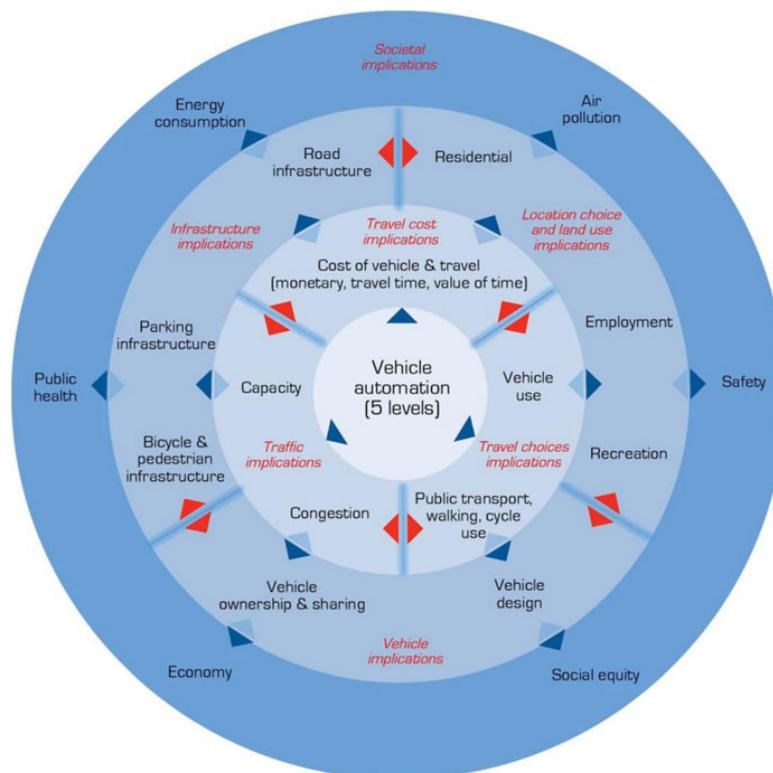


Figure 1.4: The ripple effect of automated driving, taken from Milakis et al. (2017)

This figure shows three layers or ripples as they are called, which implies different orders of impacts. The first layer implies the impact on travel choices, traffic, and travel costs. The second layer implies the impact on location choice and land use, vehicle, and infrastructure implications. The third layer contains the societal implications. This shows that CAT can have an impact on multiple aspects. For example, CAT can have an impact on the reduction of air pollution. Automated vehicles can be electrically powered, and produce fewer emissions if their electricity comes from renewable energy sources. This research focuses on the first layer of direct impacts in logistic operations, such as waiting times and utilization.

Now that we motivated this research by introducing CAT, smart yards, and the impacts of automated driving, we can describe the knowledge gap that we address. This substantiates why we focus on the direct impacts of logistical operations.

## 1.2 Problem context

Since we face a transition from regular yards to smart yards in hub-to-hub operations, there is a knowledge gap that needs to be addressed. The main knowledge gap is the following:

- *It is unknown how CAT in hub-to-hub operations for freight logistics should be defined, and what the impact and effectiveness of a smart yard is.*

We want to close the knowledge gap for future research so that innovations in hub-to-hub operations can eventually be implemented in practice. The first step is to research how CAT can be defined in hub-to-hub operations to assess the impact and effectiveness. This can result in further research in CAT on open roads and fully automated freight vehicles.

Extensive research is done on CAT for passenger vehicles, but no research has been done on CAT in hub-to-hub operations for cargo transport. For example, there are definitions and a taxonomy for CAT in passenger vehicles; this is described in J3016 standards by (SAE J3016, 2018). However, there are no definitions or frameworks for CAT in smart yards for freight logistics. Therefore, we need to develop a theoretical framework for CAT in smart yards. It is known how current yards, without CAT, are designed. However, it is unknown how CAT concepts for smart yards should be designed. A generic design approach is preferred because every case, where CAT can be introduced, possibly differs from each other. When CAT is implemented in smart yards, it can have potential impacts and might add value for a business. Smart yards have not been developed so far and therefore the potential impacts and effectiveness, when CAT is introduced, are unknown. Therefore, our focus is on the direct impacts of logistical operations, to show the first potential impacts and effectiveness.

## 1.3 Research setting

An analysis method needs to be selected to research CAT in a smart yard. According to Law (2014), there are several methods to gain insights into a system. An overview of different methods is shown in Figure 1.5. A decision has to be made on which analysis method is used to research the system.

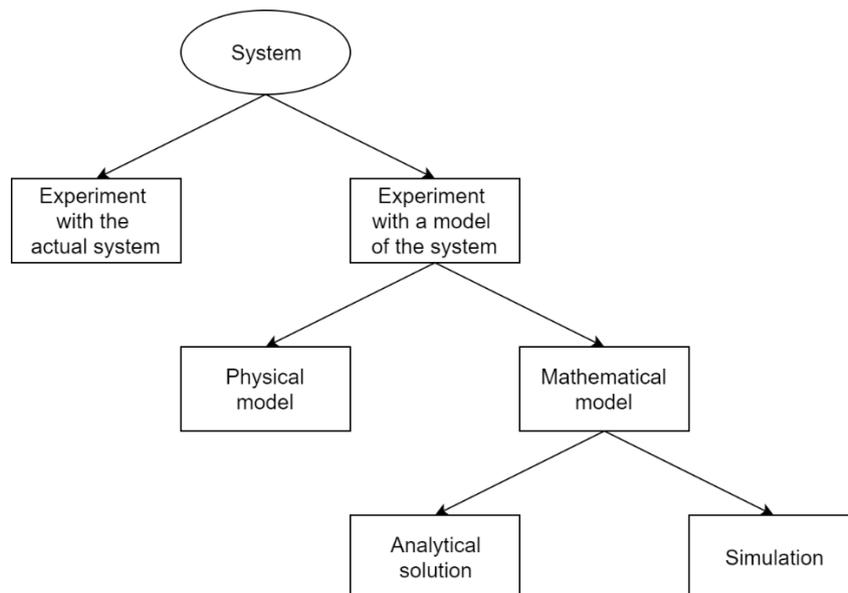


Figure 1.5: Overview of system study methods, taken from Law (2014)

There is no actual system (smart yard) present at this moment; therefore we need to experiment with a model of the system. Besides that, it is not feasible to create a physical model because of the lack of knowledge on the design of smart yards and the high investment costs. A smart yard is a highly complex system with a lot of different aspects, requiring vast computing resources, precluding any analytical solution. Therefore, a simulation model is the preferred option. For the simulation model, we use discrete-event simulation with a software package from Plant Simulation.

In the simulation model, different input settings can be tested, to research various output measurements. We want to research the impact and effectiveness of a smart yard, by analyzing different interventions. These interventions will represent steps towards the implementation of a smart yard. The final intervention is the smart yard concept. These interventions will be explained later on.

### 1.3.1 CATALYST

The Connected Automated Transport And Logistics Yielding Sustainability (CATALYST) living lab is a consortium that aims to exploit the automation of the end-to-end transport and logistics on yards and corridors. A living lab is a methodology that helps to address complex multi-stakeholder challenges, in which innovations are developed and deployed in practice. The goal of this living lab is to identify and define the requirements of CAT to implement this in practice. This contributes to the overall goal to achieve a durable ecosystem by implementing sustainable practices that improve different factors as, e.g., efficiency, traffic throughput, and costs. The CATALYST living lab is divided into multiple integrated subprojects that all focus on CAT innovations.

The project leader of CATALYST is TNO and multiple partners are accompanied, among them the University of Twente. Multiple LSPs within the Netherlands are participating in this living lab. The LSPs are involved in a specific working group within this project, focusing on smart yards and consist of two ports (Port of Moerdijk & North Sea Port), a distribution center (DPDgroup), and an airport (Schiphol). We refer to these LSPs as cases. Other LSPs have shown interest in the use of smart yards, who may join the CATALYST living lab and can be used. An overview of the CATALYST consortium is shown in Figure 1.6.



Figure 1.6: Overview CATALYST consortium

These cases have multiple purposes in this research. First, we analyze the cases to define the elements of a smart yard. Second, we use cases to define the general impacts that a smart yard can have. Finally, we use one case as input for the simulation model. Data from this case is used to verify the simulation model and assess the results of this research.

## 1.4 Research problem

The main research question of this research is stated as follows:

*How to define the characteristics of Connected Automated Transport and smart yard processes, and how to analyze their potential impact and effectiveness using simulation?*

We apply this main research question to the use cases and show the potential impact and effectiveness of a smart yard applied to one use case. The following research questions need to be addressed to answer the main research question:

### Research questions

#### 1. How should CAT be defined?

We conduct a literature study on CAT to define what CAT means and research what is already known and what still needs to be studied. The result of this literature study is an elaboration of CAT for smart yards, where definitions and various CAT concepts are discussed. This literature study includes keywords as:

- Connected
- Automation
- Autonomous

This results in two theoretical frameworks. The first framework is a theoretical CAT framework, where CAT concepts and applications are differentiated and linked with smart yards. The second framework is a conceptual smart yard framework that defines a smart yard, where the decisive factors form the taxonomy, and key elements form the decisions that need to be taken on the implementation of a smart yard.

#### 2. How should the generic smart yard processes be defined?

We research the current supply chain process, from the arrival (or departure) of cargo until the departure (or arrival) of modalities at different LSPs. For this, we use cases from the CATALYST living lab, see for further information Section ???. From here, we use the elements that should be implemented in the smart yard. To define the generic smart yard processes, we include the following:

- Physical smart yard
- Digital smart yard
- Information flow
- Impacts smart yard

#### 3. How to construct a simulation model for a smart yard?

After defining the smart yard processes, we build a model to analyze the system. As mentioned before, this is done by using the preferred method of simulation modeling. This simulation model is based on our generic taxonomy and a case study, so that as much real-life data as possible is used. For this, we analyze a case from the CATALYST living lab, where interventions define the smart yard system. A conceptual simulation model is developed and implemented in simulation. The simulation model includes:

- Several interventions
- Input variables (e.g., the number of docks, and number of arriving trucks)
- Verification and validation methods

#### 4. What is the potential impact and effectiveness of a smart yard?

The smart yard system is tested in the simulation model on different interventions. The results of the simulation study are used to analyze various output variables of the smart yard system in a case study. We assess the impact and effectiveness of the system for the following Key Performance Indicators (KPIs):

- Throughput time
- Travel time
- Waiting times
- Truck times
- Utilization

Answering these research questions lead to answering the research problem and result in the following deliverables:

1. A theoretical CAT framework.
2. A generic smart yard concept.
3. A simulation model based on a case.
4. A report containing the findings of this research.

### 1.5 Research outline

The research questions are answered in chronological order in which they are stated. Figure 1.7 shows how the research problem is solved.

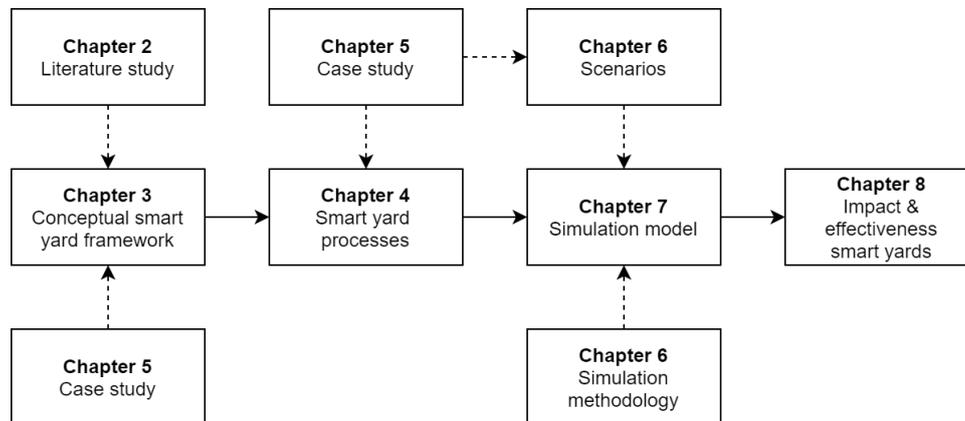


Figure 1.7: Research outline

To summarize, we first define a conceptual smart yard framework based on literature and a case study, where multiple cases are studied. This framework is used as the basis for this research. We then define the taxonomies of the use cases, where the characteristics are defined. Finally, we built a simulation model based on the conceptual smart yard framework and the taxonomy of a case. The simulation model is substantiated with a simulation methodology to define a conceptual simulation model. The simulation model is used to test different interventions and to assess the impact and effectiveness of a smart yard. Practical demarcations and assumptions are done once the case is studied. For example, if we conclude that a mixed traffic situation is too complicated to simulate, we make demarcations or assumptions.

## 2. Literature study

This chapter describes the relevant literature and will be used as input for the next chapter namely the conceptual smart yard framework. Section 2.1 introduces CAT. We describe CAT logistics related topics in Section 2.2. Section 2.3 describes smart logistics. In Section 2.4 we describe literature about automated transport. Section 2.5 gives the literature about connected transport. In Section 2.6 we describe comparable studies. Finally, Section 2.7 provides the conclusion of the literature study.

### 2.1 Introduction

A smart yard is a relatively new idea, which means that concepts of smart yards are scarce and to our best knowledge, there are no papers about the smart yard concept in literature. The state of the art of Connected Automated Transport (CAT) in smart yards are ideas about automation in hub-to-hub, where cargo is transported by automated vehicles on a short distance. The focus of the literature study is on CAT, as there are various technologies and applications developed. These will be discussed in this chapter.

Wood et al. (2012) provides terms for self-driving cars, which are as follows:

*Automated* connotes: "control or operation by a machine".

*Autonomous* connotes: "acting alone or independently".

In the context of self-driving car, most vehicles have a person in the driver's seat, are connected to other vehicles and the cloud, and do not make decisions to optimize a process. Thus, the concept of self-driving cars is most accurately described as automated. In addition, Shladover (2018) concludes that there is a diversity of usages for the terminology of automated vehicles. Therefore, a classification of automated vehicle systems is provided. Two important dimensions are mentioned: the level of automation and distinction between autonomous and cooperative. The level of automation is defined by the Society of Automotive Engineers (SAE) standards. The distinction between autonomous and cooperative is explained as follows: The word autonomous is related to "independence" and "self-sufficiency", which describes systems as self-contained decision making. However, if a vehicle is communicating with other vehicles to work collectively, this is considered as "cooperative". In our research, we refer to the vehicles used in the smart yard as Automated Vehicles (AVs). The vehicles will not act completely independently, due to the direct connection and collaboration with other vehicles and resources through a system that controls the vehicles.

According to SAE J3016 (2018), the automation of vehicles can be measured. SAE focuses on replacing human drivers' tasks for mainly passenger vehicles and to a lesser extent on freight vehicles. The six levels of the J3016 standard are shown in Figure 2.1.

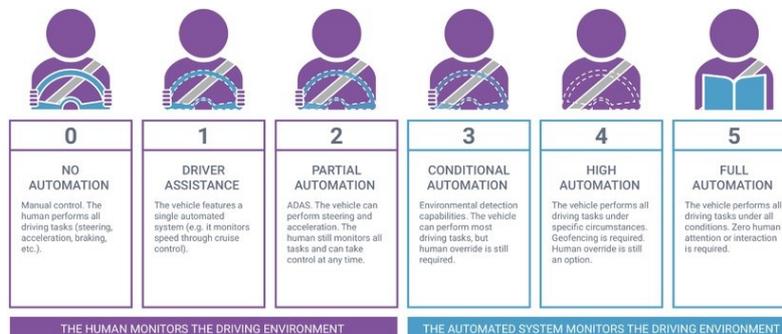


Figure 2.1: SAE levels of driving automation, taken from SAE J3016 (2018)

According to this J3016 standard, the highest level, full automation, is described as ‘zero human attention or interaction is required’. This means that the car is able to take over all human driving tasks. In this context, automated transport refers to the automated functionalities of a passenger vehicle. Measuring the level of automation is practical and useful. However, this standard focuses on single-vehicle automation and does not cover the abilities in logistics, thus it is missing substantial contexts for our research. In this research, we focus on automation in multiple vehicles. This means that levels in automation should be focused on the collaboration between vehicles. Therefore, we search for broader topics in automated transport. Literature and developments of CAT are discussed in the following sections.

## 2.2 CAT logistics

SETRIS (2017) provides a vision for a truly integrated transport system. This transport system focuses on sustainable and efficient logistics, which is based on an open and global system of transport and logistics assets, hubs, resources and services operated in an open environment, and framework conditions by individual companies (SETRIS, 2017). One of the challenges they focus on, is increasing the efficiency for smooth transshipment operations between transport modes, warehouses, and infrastructure. To achieve this, seamless transshipment (automation) technologies and operations should be developed. This should enable fast and low-cost handling of freight for any type of vehicle from any mode.

In the context of a fully integrated transportation system, five European transport platforms provide roadmaps to contribute to this overall goal. All projects have their own scope and approach. The following platforms are discussed:

- ACARE (Advisory Council for Aviation Research and innovations in Europe)
- ALICE (Alliance for Logistics Innovations through Collaboration in Europe)
- ERRAC (European Rail Research Advisory Council)
- ERTRAC (European Road Transport Research Advisory Council)
- WATERBORNE (European Maritime Industries Advisory Research Forum)

All platforms have their own contribution to the common goal. The platforms and their contribution are shown in Table 2.1.

Table 2.1: Overview of European transport platforms and their contributions

| <b>Platform</b> | <b>Contribution</b>  |
|-----------------|--|
| ACARE           | Improving aircraft operations in on-time performance, predictability, and resilience. Better infrastructure and airspace capacity. Efficient security checks and procedures  |
| ALICE           | Establishing collaborations across supply chains by improving business models and procedures, and market development collaborations. Integration of freight flows by ICT applications.   |
| ERRAC           | Improving rail freight operations. Improvements for higher capacity and performance, automation of handling and driving, electrification. Better customer information. Better integration of terminals/intermodal hubs. Results in lower costs, fast handling, and emission reduction. |
| ERTRAC          | Developments in electrification, automation, and connection by (semi)autonomous vehicles. Results in improvements for the environment, safety, health, and efficiency of freight transport.  |

|            |   |
|------------|---|
| WATERBORNE | (Semi)autonomous ships for freight. Optimization, automation, and robotization of maritime operations. Results in increased visibility, efficiency, safety, predictability, and reduction of emissions. |
|------------|---|

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Although the contributions are described in a high level of abstraction, it shows the vision of the development in technology and what the impact can be. A truly integrated transport system that is sustainable and efficient, should be the goal for the future. At the same time, it shows that there are many thoughts about transportation systems. From here, it is possible to develop concrete applications for transportation systems.

## 2.3 Smart logistics

Besides CAT, the terms smart and intelligent are often used in logistics and supply chain management. These terms are often used to indicate that logistics operations are planned, managed, or controlled more intelligently. McFarlane et al. (2016) provides several approaches to make logistics systems more intelligent. These approaches are the following: autonomous logistics, product intelligence/intelligent cargo, intelligent transportation systems, the physical internet, and self-organizing logistics. These approaches are discussed in the following paragraphs.

### Autonomous logistics

A definition of autonomous logistics is: "Autonomous control describes processes of decentralized decision-making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently. Autonomous control in logistic systems is characterized by the ability of logistic objects to process information, to render and to execute decisions on their own." (Hülsmann and Windt, 2007). Thus, an autonomous logistic system is able to detect other elements and make their own decision.

### Product intelligence

There are various definitions of product intelligence and most definitions describe the features of intelligent products instead of the meaning of product intelligence. A definition that does describe the meaning is: "A physical order or product instance that is linked to information and rules governing the way it is intended to be stored, prepared or transported that enables the product to support or influence these operations." (McFarlane et al., 2013). Also interesting, Wong et al. (2002) provides the levels for product intelligence, which are as follows:

- Level 1 Product intelligence: this allows a product to communicate its status (form, composition, location, key features), i.e., it is information oriented.
- Level 2 Product intelligence: this allows a product to assess and influence its function (e.g., self-distributing inventory and self-manufacturing inventory) in addition to communicating its status, i.e., it is decision-oriented.

There is a clear distinction in the levels between products that only communicate and products that can communicate and make their own decision. In addition, multiple projects conduct research related to intelligent cargo. One of these projects is EURIDICE, and provides the following six capabilities for intelligent cargo (Schumacher et al., 2009):

- Self-identification
- Context detection
- Access to services
- Status monitoring and registering
- Independent behavior
- Autonomous decision making

These capabilities can be related to product intelligence, as intelligent cargo can also communicate and make their own decisions.

### **Intelligent transportation systems**

Smith (2015) provides a framework for the deployment of intelligent transport systems in the field of road transport. The following definition is given: "Intelligent transportation systems are advanced applications which without embodying intelligence as such aim to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer, more coordinated and 'smarter' use of transport networks." (Smith, 2015). Intelligent transportation systems are interesting because of their broad scope, as it focuses not solely on products but also on transportation and traffic management by using information and communication technologies.

### **Physical Internet**

Montreuil et al. (2012) define Physical Internet as follows: "The Physical Internet is an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces, and protocols. It is a perpetually evolving system driven by technological, infrastructural, and business innovation." (Montreuil et al., 2012). This concept is an idealistic world, where cargo transport is an open market. This means that the networks all over the world are interconnected in a seamless manner, where physical objects are transported as efficiently as possible. Ultimately, this means that a container finds its own most efficient path in a network when given a destination and arrival time.

### **Self-organizing logistics**

Two definitions of self-organizing logistics are worth mentioning:

- "Self-organizing logistics system is a logistics system that can function without significant intervention by managers, engineers, or software control." (Bartholdi et al., 2010)
- "Self-organizing logistics system is an open, intelligent and holonic logistics system that aims to harmonize and lead individuals within the system towards a system-wide common goal, without significant human intervention from outside." (Pan et al., 2017)

Moreover, Pan et al. (2017) provide the following main functionalities (and interpretations) of a self-organizing logistics system:

- Openness (meaning that actors and assets can easily enter or leave the system). Three essential functions should be included in the openness functionality: connectivity, reconfiguration, and adaption.
- Intelligence (meaning the object-based capability of local real-time communication and activeness).
- Decentralized control (focusing on collaborative rules and communication protocols, that aim at preventing unexpected or undesirable system outcomes, rather than optimal planning).

So, self-organizing logistics can be described in the way that a chaotic system is able to be optimized by making autonomous decisions and planning of all items by using communication within the system without human intervention. This means that the system is able to optimize all processes by itself.

These six approaches all have in common that either an item/product or the whole system can communicate and make autonomous decisions to optimize the whole system. So, a smart yard system should have the ability to communicate and make autonomous decisions as well.

## 2.4 Automated transport

Literature on automated transport in the logistics sector can be found in all kinds of research areas. Specific studies on automated transport include topics like Automated Guided Vehicles (AGVs) in container terminals and warehouses, passenger vehicles, and last-mile delivery. To discuss these topics, we distinguish three areas where automated transport can be divided into. The various areas have different stakeholders and traffic situations. To comply with these situations the technology in automated transport has been evolving. The areas go from "simple" environments to more complex environments. ERTRAC (2019b) provides an overview of the areas and the characteristics, which is shown in Table 2.2.

Table 2.2: Overview of transportation areas

| Area              | Environment     | Tasks      | Road          | Traffic management |
|-------------------|-----------------|------------|---------------|--------------------|
| <b>Confined</b>   | simple          | repetitive | private area  | fully controlled   |
| <b>Hub-to-Hub</b> | relative simple | repetitive | partly public | partly controlled  |
| <b>Open road</b>  | complex         | tailored   | public        | not controlled     |

These areas, in the context of automated transport, are discussed in the following subsections.

### 2.4.1 Automated transport in confined area

In the logistics sector, automated and unmanned transport solutions are market-ready and have been widely adopted in container terminals and warehouses. Container terminals like those in Rotterdam and Singapore use AGVs in confined areas in their port. A consequence of these market implementations is that there are many studies conducted about the optimization of automated transport in confined areas. It has been demonstrated that automation could significantly increase throughput and reduce container terminals costs (liu et al 2002). Studies include specific topics like design and control issues of AGV systems and scheduling problems of AGVs in confined areas.

According to Vis (2006), AGVs are used for internal and external transport of materials in areas such as manufacturing systems, warehouses, container terminals, and external (underground) transportation systems. Kaoud and El-sharief (2017) provides a literature review about scheduling problems of AGVs in job shops, flow shops, and container terminals. All areas mentioned can be considered as confined areas.

Automated transportation can be categorized by dimension. Containers are transported in two or three dimensions (Steenken et al., 2005). Examples of automated vehicles in two dimensions are shown in the following figures:



Figure 2.2: AGV



Figure 2.3: AutoTUG

Figure 2.2 shows an electrically powered AGV, which is a driverless truck for picking up, moving, and placing unit loads (Rushton et al., 2010). A container can either be placed on top of the AGV, or the AGV drives under a container, lifts its platform and picks up the container. The AGV then automatically drives to a designated destination. Most AGVs drive automatically and not autonomously, since they are used in confined areas where the AGVs are in the same system. Figure 2.3 shows the AutoTUG from Terberg, which is used in practice <sup>1</sup>. The AutoTUG is another type that transports conventional container trailers. It uses a grid of transponders in the yard surface to drive automatically and is equipped with a scanner to avoid collisions. The AutoTUG has the ability to operate manually if needed.

Besides the two-dimensional automated transportation means, three-dimensional automated transportation means are used in confined areas. An Automated Lifting Vehicle (ALV) is shown in Figure 2.4 and an Automated Stacking Crane (ASC) is shown in Figure 2.5.



Figure 2.4: ALV



Figure 2.5: ASC

An ALV has the capability to handle stacking and horizontal transportation of containers. Other handling vehicles such as a reach stacker, are no longer necessary to stack the containers. These ALVs are market-ready and used in container terminals. ASCs are used for the storage of containers in terminals.

<sup>1</sup>retrieved from <https://www.terbergspecialvehicles.com/en/products/tractors/yard-tractors/autotug/>

Containers are stored and retrieved in and from temporary storage. These ACSs are used in a predefined storage area. This concept is market-ready and used in container terminals.

Automated transport in warehouses can be much smaller and compact because of the cargo sizes. Individual products like groceries or medicines can be transported in two dimensions by automated robots with batteries that are driving on a grid system. Such a system is used at Ocado, an online supermarket. Figure 2.6 shows a scene of the automated warehouse at Ocado <sup>2</sup>.



Figure 2.6: Automated transport in Ocado warehouse

The Ocado warehouse is an automated fulfillment system where robots drive around to pick up customer ordered products and drop them in the right crates. The robots are not intelligent but are coordinated by a centralized system so that they can be used as efficiently as possible. Artificial intelligence and machine learning are used to monitor technical problems and make the whole system smarter.

#### 2.4.2 Automated transport in a hub-to-hub environment

Hub-to-hub operation is defined as that it is partly public road, and partly controlled by traffic management. This means that between the hubs, the cargo is transported on open public roads (most of the time these roads are highways). Within a hub, the cargo is transported in a (semi) confined area. Some hubs can be fully confined and controlled, while other hubs can have public roads that are controlled. A concept that can be seen as hub-to-hub operations is intermodal transport. Lowe (2005) defines a definition for intermodal freight transport: "The concept of utilizing two or more 'suitable' modes, in combination, to form an integrated transport chain aimed at achieving operationally efficient and cost-effective delivery of goods in an environmentally sustainable manner from their point of origin to their final destination." (Lowe, 2005). This means that the process of intermodal transport is aimed at optimization and efficiency. However, most studies focuses on vehicle planning, logistic activities, and transport routes as shown in Agamez-Arias and Moyano-Fuentes (2017). These studies can be helpful within a smart yard system, but are out of scope for this research.

Figure 2.7 <sup>3</sup> shows the Volvo Vera. This autonomous vehicle can (de)couple trailers and transport the cargo to a designated destination. The Volvo Vera is able to make its own decisions and drives fully

<sup>2</sup>retrieved from <https://www.ocadogroup.com>

<sup>3</sup>retrieved from <https://www.volvotrucks.com/en-en/about-us/automation/vera.html>

autonomously. Still, this autonomous system is monitored by an operator in a control tower, who is responsible for transportation. This concept is not market-ready and is still being developed and tested. It is expected that this vehicle will be involved in short-distance transportation with a speed limit of 40 km/h.



Figure 2.7: Volvo Vera

Shin et al. (2018) provides an overview of trends related to intermodal Automated Freight Transport Systems (AFTS). First, existing AFTS across the world are described in an overview. These AFTS are interesting concepts and the applications that are used in these systems are provided in an overview. At last, an overview of recommendations for directions of AFTS developments is given. These directions should introduce a new concept of automated freight transport. The most interesting recommendations are the following: a new concept of (un)loading, mechanism operations with electronic controlling systems, and linkage with existing modes of freight transport. This shows that automated transport in a hub-to-hub is far from developed and should be researched further.

### 2.4.3 Automated transport on open road

Meyer and Beiker (2019) mentions the following four scenarios of automated driving in open roads:

- Private passenger vehicles
- Shared passenger shuttles
- Long-haul trucks
- Local delivery vehicles

Although there is a broad variety of scenarios for automated transport on open road, these four scenarios are described in a high abstraction level. These scenarios can be further subdivided into more specific concepts. In addition, for these scenarios, applications are being developed and implemented at this moment. The four scenarios are discussed in the following section:

- **Private passenger vehicles**

The research of transport automation on open road is mainly focused on passenger vehicles. A private passenger vehicle is a light-duty vehicle that can drive without human interaction. The

developments in automation for passenger vehicles is making its progress to level 5 in the SAE standards, where no human attention or interactions are required. Many car producers are developing self-driving cars (e.g., Tesla Autopilot). Even tech companies like Google (Google Driverless Car / Waymo One) and Apple (project Titan) are developing self-driving cars. These cars reach level 2 of the SAE classification. Due to legislation, it is not allowed at this moment to introduce full automation.

- **Shared passenger shuttles**

The idea of shared passenger shuttles is that travelers can use public transport where driverless vehicles are driving between pre-determined locations. This can be seen as a hub-to-hub. However, these shuttles will mainly be used for short trips in an urban area, so this can be considered as an open road. Low-speed automated shuttles are being used in pilots and demonstrations, so these automated transport vehicles are not market-ready at this point. One interesting application to mention are the six ParkShuttles used in Rotterdam. This fully autonomous vehicle is used to transport people on a route of almost two kilometers. Although this autonomous vehicle is fully able to drive by itself, it is used in a confined area.

- **Long-haul trucks**

Multiple concepts are being developed for long-haul truck operations. Long-haul trucks are being developed, but are not market-ready, that drive autonomously and driverless on the highway (e.g., Starsky Robotics). However, the long-haul trucks are remotely controlled the first and last-mile. In contrast to single automated vehicles, truck platooning focuses on multiple vehicle automation. An idea of truck platooning is that the truck in the lead is driven by a human driver and the following trucks are driverless. The two benefits are lowering operating costs, by reducing fuel consumption due to reduced aerodynamic drag and safety, by increasing automation in steering and longitudinal control. This can be realized by implementing data communication systems between the trucks, on-board sensors, and infrastructure.

- **Local delivery vehicles**

Self-driving delivery vehicles are being developed to transport goods for last-mile delivery. These vehicles can be small delivery robots or automated flying vehicles like drones. One of the market developments is the delivery robot from Starship (see Figure 2.8)<sup>4</sup>.



Figure 2.8: Starship delivery Robot

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<sup>4</sup>retrieved from <https://www.starship.xyz/>

These robots are advanced devices that carry goods within a 6km radius. At this moment the Starship robots are used at multiple University campuses in the USA with fleets up to 30 robots.

These concepts show that there is progress in the development of automated transport. However, the developments in open road transportation are not market-ready at this moment but it gives a good indication in which direction the development of automation transport will go. These indications can be used in our research to develop concepts for smart yards.

## 2.5 Connected transport

Literature on connected transport is scarce as most studies focus on connected vehicles and their applications, but do not focus on connected transportation systems. According to Miucic and Bai (2019), connectivity will be a key enabling technology for autonomous driving. This means that all autonomous vehicles will be connected with their environment. According to Shladover (2018), the environment can be divided into five options:

- Vehicle to vehicle (V2V)
- Vehicle to infrastructure (V2I)
- Infrastructure to vehicle (I2V)
- Vehicle to pedestrian (V2P)
- Vehicle-to-anything (V2X)

The information that is exchanged can be used by any means to make decisions. If a vehicle is connected and automated, it can use the obtained information to make an automatic action. On the other hand, connectivity can also be implemented without any automation. To obtain this information, various technologies that are developed can be used. These technologies are discussed in the following subsection.

### 2.5.1 Connected technologies

Connected technologies enable elements within an environment to communicate wireless with each other. An overview of wireless communication technologies in transportation is given in Shladover (2018):

- **Dedicated Short-Range Communications**  
Designed for road transportation applications. Low latency, limited range, and high reliability, which is ideal for fast-moving vehicles.
- **WiFi**  
Relatively high latency and when the channel is congested, it is vulnerable to delays and packet losses, so not ideal for critical information.
- **Cellular communications**  
Networks as 4G LTE, WiMAX, and 5G. Existing cellular systems can be used in a cost-efficient way. The infrastructure side of this system is essentially ubiquitous in built-up areas, so it does not need to be provided by public agencies, but users on both the vehicle and infrastructure side need to pay the network operators for data usage.
- **Satellite communication systems**  
Used in remote areas that lack cellular service. Significant cost, bandwidth, and latency limitations, so not suitable for all intelligent transport systems applications.

- **Bluetooth**

Short-range and low-bandwidth, services only support some intelligent transport systems applications.

## **2.5.2 Connected applications**

Many applications are developed that are connected by a wireless network. Some examples of connected domains are homes, wearables, and e-commerce. Some applications in these domains are, e.g., smart thermostats, connected lights, smart fridges, and smartwatches. These applications are connected to the cloud via the internet. When using a smartphone, the applications can be controlled, perform tasks, and provide information. More practical applications in the logistics sector are discussed in the following paragraphs.

### **Track & trace**

An application that is widely known is the track & trace concept. It is a process where the current and past locations of an item or property can be determined. An addition is that consumers can receive an estimated arrival - or departure time of their object. Two technologies that are used are barcodes or Radio-Frequency Identification (RFID). The barcode can be scanned to provide information such as traceability and production data. This can be used for the same information exchange except this technology can be used wireless.

### **Geo-fencing**

A geo-fence is a predetermined perimeter in a radius from a specific location, which could trigger an action when a device enters this perimeter. Information can be exchanged by using wireless technology. For example, freight can be tracked and monitored when entering a virtual boundary. This allows companies to exchange information, like arrival times, to their customers and themselves. The information on arrival times can impact capacity planning, such as resource utilization, throughput, and costs.

We conclude that there are many technologies and applications developed to connect elements within an environment with each other. These applications and technologies are used to exchange information. In a connected vehicle environment, information exchange can be divided into five options as mentioned before. However, these options are not sufficient to solely use in a smart yard, because they do not focus on a fully integrated system. A smart yard system should be able to receive information, but also take advantage by making autonomous decisions. This should be implemented in the smart yard framework.

## **2.6 Comparable literature**

In similar settings, simulation studies are used to study different kinds of transportation systems. To show how transportation systems are compared and analyzed, we describe two studies. Duinkerken et al. (2007) compares five transportation systems for inter-terminal transport at container terminals. These inter-terminal transport systems are:

- **Multi-trailer system with a manned traction unit and control & standard planning**

A train of trailers where containers can be placed on. The train is transported by a manned traction unit which is coupled to the train and drives to the destination.

- **Multi-trailer system with a manned traction unit and control & advanced planning**

The same multi-trailer system with a manned traction unit and control. Advanced planning is used, which generates better planning due to the allocation of manned traction units and empty trips.

- **AGV landside system**

AGVs are powered on their own and travel from the loading point to its destination. Cargo is loaded and unloaded by handling equipment. A landside layout is used where only a central area is used.

- **AGV waterside system**

Same AGV system as the landside system. A waterside layout is used where AGVs drive along tracks at the waterside of a stack.

- **ALV system**

Automated lifting vehicles that are powered on their own and travel from the loading point to its destination. Cargo is loaded and unloaded by the ALV itself.

The systems use control parameters such as planning algorithms and vehicle controls. Within the model, different input data such as origin-destination matrix, distance tables, vehicle speeds, and equipment capacity are used. The technique that is used is an object-oriented modeling technique. For all systems, the number of minimum vehicles is determined to provide acceptable performance. Then an analysis is done on the costs and utilization rate of the vehicles. This study provides an interesting approach to analyze different transportation systems. This can be used in our research to analyze the concept of smart yards. In our research, we focus on multiple logistics service providers instead of only container terminals, and the coupling between different modalities instead of only one form of transportation.

Another example is the study from Ebben (2001), where a simulation model is built for a case study. The goal of this research was to design and assess a logistics control structure for automated transport networks. A distinction is made between physical, control, and information objects. Furthermore, the processes in the network are subdivided into primary processes (transport and logistics) and secondary processes. The input for the simulation model is based on various designs of system layouts, terminal layouts and supply chains. This simulation model is used to test various scenarios and to assess the performance of different output measurements, among which the number of required AGVs, failure rates, and costs. This study is a good example for the approach of researching a new logistic concept applied to a use case. This study uses automated transport within a confined area, whereas we focus on automated transportation in a hub-to-hub environment and brings additional challenges.

## **2.7 Conclusion**

This chapter provided the literature about CAT and presented the state of the art applications. We conclude that a theoretical framework for CAT is necessary, automated transportation applications are not market-ready, and presented examples a vision for transport systems. The goal for the future is a truly integrated transportation system, which is sustainable and efficient. This should be supported by applications that are being developed. A conceptual framework for smart yards should be helpful as the basis for our research and is given in the next chapter. A smart yard framework that focuses only on how automation influences the role of the driver, is only partially useful. Therefore, this framework should address the impact and opportunities of automation and connectivity for logistics systems, rather than on individual vehicles. Moreover, automation and connectivity bring opportunities for automated decision-making by the vehicles and system itself, rather than only the ability to drive autonomously. Therefore, it seems logical that a smart yard system is to some extent self-organizing and can make its own decisions. Having described the literature about CAT, we can develop theoretical frameworks.

### 3. Theoretical frameworks

*This chapter describes the theoretical frameworks for our research. We use the literature study from the previous chapter and input from the cases, discussed later on. The theoretical frameworks will be used in the next chapter to determine the smart yard processes. In Section 3.1 we give the introduction for two different frameworks. Section 3.2 describes the framework for CAT concepts. In Section 3.3 we discuss the conceptual smart yard framework. Section 3.4 contains the conclusion.*

#### 3.1 Introduction

We develop two frameworks for this research. The first framework is a Connected Automated Transport (CAT) concepts and applications framework. In this framework, CAT concepts can be classified in a two-dimensional plane, based on distance and the number of unit loads. These factors are explained later on. The goal of this framework is to position smart yards into CAT and show that the development of smart yards is important. We show this by differentiating the CAT concepts and connecting the related CAT concepts, applications, and the smart yard concept.

The second framework is a conceptual framework to make smart yards more concrete. In this framework, we provide decisive factors that determine the outcome of the key elements in a smart yard. The key elements are subdivided into automation and connectivity elements and are categorized in strategic, tactical, and operational levels. The goal of this framework is to illustrate the potential role of smart yards in connected and automated transport. We state the factors that influence the decisions for a smart yard and state the generic key elements within a smart yard. Both of these frameworks have not been developed before. Thus, these frameworks have a scientific contribution and could be used in further research.

#### 3.2 CAT concepts and applications framework

We propose a framework for CAT concepts and applications to classify these CAT concepts at a high abstraction level and we do not quantify the categories. This means that we do not subdivide the x- and y-axis into ranges that can be measured. The framework shows the connection of a smart yard between the various CAT concepts and applications. To make a classification, a distinction is made in distance and number of unit loads. On the x-axis, the distance ranging from short to long is used and on the y-axis, the number of unit loads ranging from small to large is used. Furthermore, the arrows indicate a connection between concepts and applications. A connection means that the CAT concepts or applications can be linked or integrated. The framework of the CAT concepts and applications is depicted in Figure 3.1. This figure shows how the CAT concepts and applications can be differentiated from each other.

##### Distance

We use the distance, ranging from short to long, as a classifier because the transportation distance influences which type of cargo can be transported. For example, it is efficient to transport a full truckload on a long-distance instead of a short distance. The transportation of an individual package is only efficient at shorter distances. Also, the transportation distance influences what kind of system can be used. Complete systems, like an automated warehouse, are efficient if the transportation distance within this system is short. Distance is subdivided into three categories and is explained as follows:

- Long haul: long-distance transportation. Takes often more than a day.
- Hub-to-hub: transportation between logistics service providers.

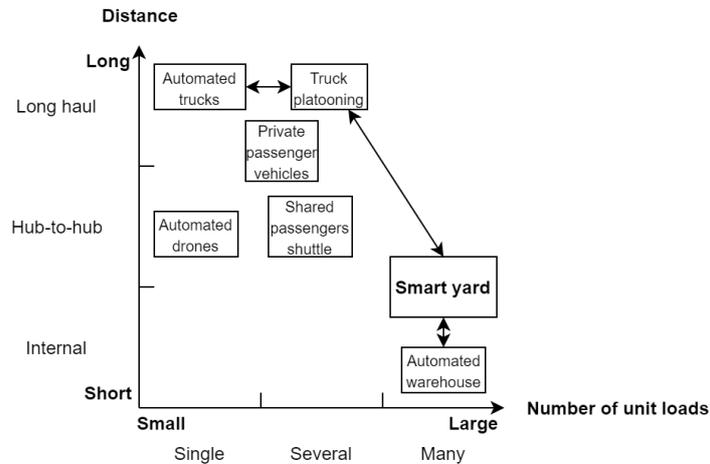


Figure 3.1: CAT concepts and applications framework

- Internal: transportation in a (semi) confined area.

These categories are not quantified, but a distinction between the CAT concepts and applications can be made.

### Number of unit loads

The number of unit loads, ranging from small to large, indicates how many cargo loads can be transported at the same time. For example, only a single cargo load can be transported by a single automated truck or drone, while an automated warehouse can transport multiple cargo loads at the same time. The number of unit loads is subdivided into the following three categories:

- Single: one cargo load can be transported at the same time. For example, an autonomous barge with dry bulk.
- Several: a few cargo loads can be transported at the same time. For example, a group of people in a shared passenger shuttle.
- Many: a large number of cargo loads can be transported at the same time. For example, an autonomous barge with many containers.

Since the categories couple and many are not quantified, there is room for interpretation. However, it is possible to make a distinction between various CAT concepts and applications.

### Connection

A smart yard enables the coupling between other CAT concepts. For example, the connection between a truck platoon and an automated warehouse is made through a smart yard. The cargo from a truck in a truck platoon is decoupled at the smart yard. From the smart yard, the cargo is transported to an automated warehouse. As more and more CAT concepts will be implemented, the smart yards become more and more needed to make the coupling between these CAT concepts. A connection between applications and concepts can also be made. For example, automated trucks can be integrated in truck platooning, which means that one of the functions of the automated truck is being able to connect to other trucks in a platoon.

The applications in the framework (automated drones, private passenger vehicles, shared passenger

shuttles) are not directly connected to this research. However, we include these applications to show that CAT applications from other research areas also fit in the framework. So, the framework can be used for other concepts and applications, and the connection between them.

### 3.3 Conceptual smart yard framework

We propose a conceptual framework for smart yards, that can be used to determine the characteristics of a smart yard. These decisive factors are the characteristics of a case and form the input for the smart yard concept. The decisive factors substantiate the decision on the key elements that should be included in the smart yard. The topics automation and connection are used to subdivide the key elements. The key elements are also classified in the levels of decisions: strategic, tactical, and operational. The overview of the conceptual framework for smart yards is given in Figure 3.2.

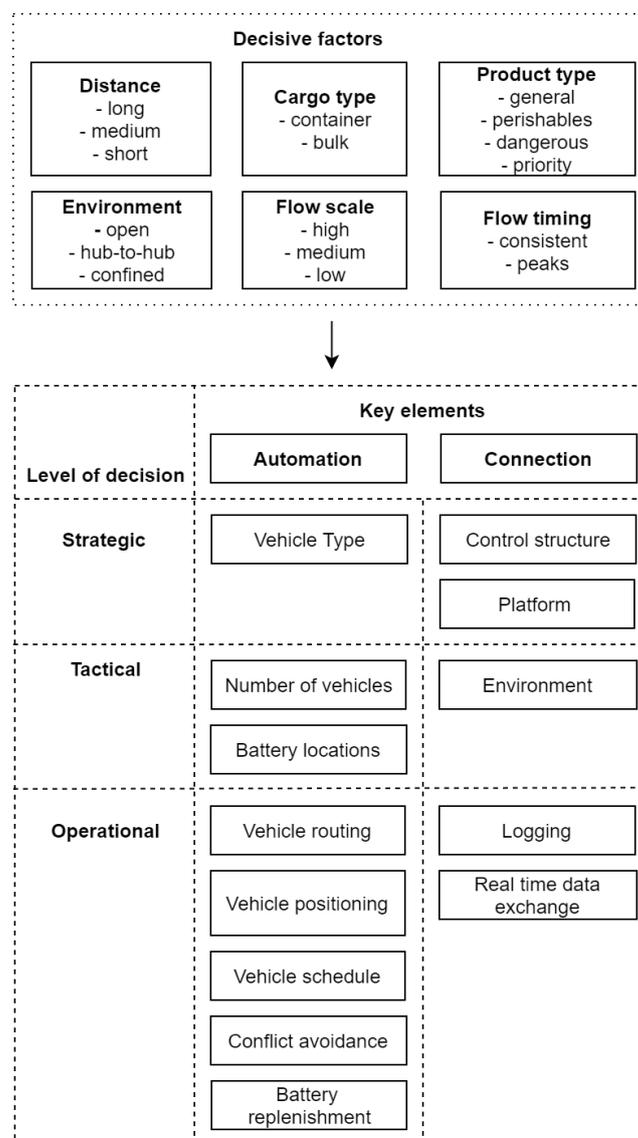


Figure 3.2: Smart yard conceptual framework

To indicate, we also propose secondary factors that are not included in the figure and conceptual smart yard framework. In the following subsections, we elaborate on the decisive factors and key elements from the conceptual smart yard framework.

### **3.3.1 Decisive factors**

We propose a list of decisive factors in the conceptual framework, that determines the characteristics of a smart yard. The decisive factors are based on the input from cases that are included in the CATALYST living lab. The inputs from the cases are based on a questionnaire, provided documents, and multiple discussions with experts.

In addition, we use the requirements and needed data for an internal transport system from Le-Anh (2005). These factors are the following: facility layout, pick up and drop off (P/D) locations, material flows, type of loads, type of vehicles, and guidance (Le-Anh, 2005). We place the factors from Le-Anh (2005) into a broader context, as smart yards are not internal systems.

The decisive factors can be filled in, based on case characteristics. These characteristics form the input for the smart yard concept. The characteristics of the case depend the most on which stakeholders are involved. For example, the characteristics of the case will be different if only one stakeholder (e.g., a distribution center) is involved compared to multiple stakeholders (e.g., multiple terminals). When the stakeholders are known, the input for the decisive factors can be determined. Even though the categories for some factors are not quantified, it gives an idea about the indication and the possible impacts. In the following paragraphs, we give explanations of the decisive factors and categories and substantiate this by examples.

#### **Distance**

The average transportation distance of cargo is determined by the P/D locations and the layout of a case. The classification for distance is divided into long, medium, and short. We substantiate the classifications as follows. Longer distances between P/D locations, based on the chosen route, results in longer travel times for the vehicles. This may decrease the logistical performance significantly. To cope with the decrease, key elements (e.g., the number of vehicles or vehicles type) may be influenced.

#### **Cargo type**

The cargo type defines the method of transportation and packaging. Numerous cargo types can be used, however, for this research we only consider two types. The cargo types are bulk and containers, as these are the most used cargo types at the use cases for this research. Bulk and container cargo come in many different forms. To simplify this, we consider trailers for bulk, and 40 foot containers, as Automated Vehicles (AVs) can handle these types of cargo. The difference between the types is that a trailer needs to be dragged, and a container needs to be placed on top of a chassis.

#### **Product type**

The product type defines what kind of product is being transported. We distinguish four cargo products as follows: general, perishables, dangerous, and priority. The product that is being transported can have an impact on the handling and scheduling of the cargo. To substantiate, a priority product can be the same product as a general product, but has a priority over the other products. This can mean that the schedule has to be changed.

#### **Environment**

The environment is the area in which the smart yard should be implemented. As mentioned before,

the transportation areas can be divided into three environments: confined, hub-to-hub, and open road. Confined area is closed off, no mixed traffic, and can be fully controlled. Hub-to-hub area is partly public, partly mixed traffic, and can be partly controlled. Open road is an open area, mixed traffic, and is not controlled.

### Flow scale

The flow scale is the number of loads that are transported between locations within the system. We propose a classification for the scale of the cargo flow as follows: high, medium, low. The total cargo flow in a smart yard can be calculated by adding up the cargo flow of all individual stakeholders. It is hard to quantify these classifications, but a smart yard with a higher cargo flow may have different key elements than a smart yard with a low cargo flow. For example, if the smart yard should be able to handle 1000 cargo loads per day, the number of vehicles used should probably be higher compared to when only 10 cargo loads per day should be transported.

### Flow timing

The timing of the flow indicates how the cargo flow is distributed in a certain time period. The classification for the cargo timing is as follows: consistent or peaks. A consistent cargo timing indicates that the level of cargo flow is roughly the same in various time periods. Peaks in the cargo timing indicate that there is a clear fluctuation in the cargo flow in certain time periods.

### Secondary factors

The secondary factors will probably influence the decisions that need to be made for the smart yard. However, the categorization and the impact is unknown at this moment and should be researched further. The secondary factors are as follows:

- Handling: how the cargo is handled. For example, reach stackers are used to lift containers and manual decoupling of trailers.
- Job type: how is the cargo picked up / dropped off. For example, a vehicle needs to go to multiple docks/terminals to get a full truckload.

### 3.3.2 Overview key elements

We subdivide key elements into the topics: automation and connection. The elements are classified within three different levels of decisions: strategic, tactical, and operational. Table 3.1 shows an overview of the key elements and the decisions that needs to be taken. We state the topics in the first column, the elements related to to topic in the second, and the factors related to the elements, on which a decision needs to be taken, in the last column.

Table 3.1: Overview of smart yard elements

| Topic              | Element           | Decision                           |
|--------------------|-------------------|------------------------------------|
| <b>Automation</b>  |                   |                                    |
| <i>Strategic</i>   |                   |                                    |
| Vehicle selection  | Vehicle type      | Dimensions<br>Guidance<br>Handling |
| <i>Tactical</i>    |                   |                                    |
| Vehicle selection  | Capacity          | Number of vehicles                 |
| Battery management | Charging capacity | Number of stations                 |

|                    |  |  |
|--------------------|--|--|
| <i>Operational</i> | Charging positioning   | Charging location  |
| Vehicle management | Vehicle scheduling<br>Vehicle routing<br>Vehicle positioning<br>Conflict avoidance | Job assignment<br>Route optimization<br>Dwell point location<br>Collision avoidance<br>Congestion avoidance<br>Livelocks avoidance<br>Deadlock avoidance |
| Battery management | Battery replenishment  | Swapping<br>Charging strategies  |
| <b>Connection</b>  |  |  |
| <i>Strategic</i>   |  |  |
| System             | Control architecture<br>Platform   | Control hierarchy<br>Platform types  |
| Communication      | Environment  | Environment options  |
| <i>Tactical</i>    |  |  |
| System             | Logging  | Logging options  |
| <i>Operational</i> |  |  |
| Communication      | Real time data exchange  | Which information  |

### 3.3.3 Automation elements

#### Vehicle selection

To implement automation in a smart yard, the right type and number of AVs need to be chosen.

- *Type*

A strategic decision that should be made is the type of vehicle. The type of AVs that is used is important and it should suit the characteristics of the case. Three main factors are important for selecting the type of vehicle.

- Dimension

Transportation can be done two-dimensioned or three-dimensioned. Two-dimensioned vehicles can drag trailers or containers that can be placed by other handling vehicles on top of the vehicle or on a chassis that is dragged by the vehicle. Three-dimensioned vehicles can only carry containers and have the ability to lift and stack the container.

- Guidance

There are multiple options to navigate AVs within an environment. The AV can drive in a static or dynamic environment. Le-Anh (2005) provides a classification of vehicle guidance in a static environment. The types are fixed-path, wire guidance, and non-wire guidance. In a dynamic environment, the vehicle is able to detect moving objects. To enable this, the driving system needs sensors (e.g., Light Detection And Ranging (LIDAR), radar, cameras, ultrasonic sensors) to be able to drive safely. In theory, this dynamic environment can be an open road.

- Handling

Depending on the cargo type, the AV should be able to (de)couple a trailer or chassis, or it

should be possible to place a container on top of it.

- *Number of vehicles*

The number of AVs is important for the performance of the system and is a tactical decision. Van der Meer (2000) provides a list of factors that affect the number of AVs required in an internal system. These main factors are as follows:

1. The system layout
2. The number of loads to be transported between transfer points per time unit
3. System reliability
4. Type of vehicle
5. Speed of travel
6. The vehicle dispatching strategy (if the strategy is predetermined, otherwise the vehicle dispatching strategy can be based on, among other things, the number of vehicles)

These factors also affect the number of vehicles in a smart yard. However, as the AVs may be in a mixed traffic situation, other factors may also affect the number of AVs. The number of AVs will be an experimental factor in our simulation model.

### **Vehicle management**

Operational decisions should be made on how to allocate and manage the allocated vehicles. According to Le-Anh (2005), this can be controlled by the following key elements:

- *Vehicle scheduling*

Vehicle scheduling determines which vehicle and when a vehicle should perform a job. The vehicle scheduling can be done offline or online. When all information about the arrival of cargo loads is known in advance and the travel times are deterministic, it is possible to schedule offline. This means that every cargo load is assigned to a specific vehicle and time. In practice, the information about the cargo load arrivals is rarely complete and otherwise unreliable. Online scheduling makes more sense in practice. This can be done by a rolling horizon, where a new schedule is generated after a certain fixed time (short period). Another online scheduling approach is dispatching rules, which schedules new jobs for a vehicle. The assignment is made when a vehicle completed its job, the vehicle reached its destination, or a new job arrived.

- *Vehicle routing*

Given the location and the destination of a vehicle, the travel route must be determined. A route can be predetermined (static) or based on real-time information (dynamic). The vehicle route should be optimized, given the available data and performance indicator. For example, a route can be optimized for the shortest distance, but this is not necessarily the shortest time.

- *Vehicle positioning*

When a vehicle completed its task, dispatching for the vehicle is performed. However, if there are no jobs to perform, the vehicle becomes idle. Then it is necessary to decide where the vehicle should be positioned. This decision can be done by two main strategies, a standard dwell point is determined and an idle vehicle always moves to this location (static), or the dwell point for the idle vehicle is determined based on real-time information (dynamic).

- *Conflict avoidance*

Vehicle conflicts should be avoided as this influences the performance of the logistical process. Qiu and Hsu (1999) provides the following possible conflicts and descriptions that should be avoided:

- Collisions

Collisions occur when more than one vehicle attempts to drive in the same section at the same time. This can be avoided by vehicle routing or collision recognition of the vehicle itself.

– Congestion

Congestion arises when the road capacity can not handle the number of arrivals during a period at a location. This can be avoided by scheduling the vehicles not at the same time at the same place, or by vehicle routing. If the shortest transportation time is driving in the congestion, then the congestion is unavoidable at that time.

– Live locks

When traffic on a horizontal stream is given priority over a vertical stream at a junction, the vertical stream may have to wait indefinitely. This can only happen when the traffic intensity on the horizontal stream is constantly high so that there is no crossing or insertion space for the vertical stream. This can be avoided by using traffic regulations as, e.g., smart traffic lights.

– Deadlock avoidance

A deadlock arises when multiple vehicles are waiting for release. Since there is no possibility to leave this situation, the vehicles are stuck. In a regulated traffic situation, this will never happen.

### **Battery management**

Vehicles need to be recharged because they cannot operate continuously. It should be determined where the charging stations should be located, the charging capacity, and when the vehicles should move to the charging station. Consequently, the vehicle becomes idle when it is being recharged and influences the number of vehicles needed and the performance of the system. Other green fuel alternatives, like biofuels or hydrogen, can also be used. In that case, the term fueling should be used instead of charging.

- *Charging capacity*

A tactical decision needs to be made that determines the required number of charging positions and batteries. Ebben (2001) studies the number of batteries required and showed that it largely depends on the chosen battery type.

- *Charging location*

Charging stations have to be located somewhere in the area. Therefore, a tactical decision should determine where the charging stations will be located. The location should be selected to minimize the effects on the performance of the system. When the charging stations are located far from the hot spots of the vehicles, it takes a long time to go to the charging stations and will have a negative impact on the performance.

- *Battery replenishment*

To replenish the batteries of the vehicles an operational decision needs to be taken when the vehicle is sent to the charging station. The vehicles can either swap the battery or recharge for a certain amount of time. When the battery is swapped, the battery is replaced with a full battery. In the case of fueling, swapping of a fuel tank is not an option and a fueling strategy should be used. Schmidt et al. (2015) studies the impact on the profitability of an automated vehicle fleet. They concluded that the ratio of batteries to vehicles has a significant impact on the profitability and determined that a minimum battery-to-vehicle ratio will not impact the fleet's performance while reducing the costs.

When the decision is made to charge the vehicle's battery, it should be determined for how long

the battery will be charged. McHaney (1995) presents the following charging strategies:

- Opportunity charging: an idle vehicle is always sent to a charging station.
- Automatic charging: a vehicle performs jobs until the battery is almost empty and then scheduled for recharging.
- Combination charging: a combination of opportunity and automatic charging.

### 3.3.4 Connection elements

#### System

We focus on a high abstract level of system elements on the decisions that need to be made. Implementations and the design of the system elements is related to computer science and is outside the scope of this research.

#### Control architectures

A strategic decision is needed for the control architecture, which defines how the elements within the system are controlled. Dilts et al. (1991) provides a description of four control architectures. These are described below and shown in Figure 3.3:

- **Centralized form**  
A centralized control unit that performs all planning and control functions. A global database is used that contains information on the activities of the whole system.
- **Proper hierarchical form**  
A proper hierarchical form contains multiple control units with multiple levels. The activities of the subordinate (slave) level are dictated by the supervisor (master) level. The levels have their purpose and functions. At the highest level, the control unit is responsible for the decision on the whole system while the subordinate levels make detailed decisions for their actions. A top-down control decision is used and a bottom-up for status reporting.
- **Modified hierarchical form**  
The modified hierarchical form contains multiple control units, multiple levels, and subordinate-supervisor relations. The distinction between the proper and modified form is the degree of autonomy of the subordinates. In the modified form there is some degree of coordination among the subordinates that are on the same hierarchical level.
- **Heterarchical form**  
The heterarchical form can be seen as a most decentralized control. The control structures have distributed locally autonomous entities that communicate with other entities without the subordinate-supervisor relation. This means that the entities make their own decision in cooperation with other entities. An example of such a form is a multi-agent system.

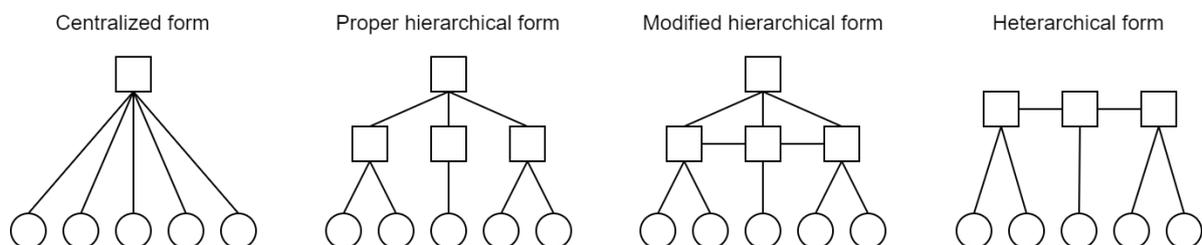


Figure 3.3: Overview control architectures, taken from Dilts et al. (1991)

### *Platform*

Data and information need to be shared between various sources within a system. In order to share the information, a strategic decision is needed for a platform. This platform enables the possibility to share the information. Numerous types of platforms can be used (e.g., clouds, client/server, and operating systems). Further research on what platforms can be used best needs to be conducted.

### *Logging*

A tactical decision needs to be taken on how events in the system are logged. A log file contains information about, e.g., software, hardware, and system processes. Further information on how logging can be done needs to be conducted.

### **Communication**

When a connection is established in a system, communication is needed within the environment of the system.

### *Environment*

Shladover (2018) provides an overview of the connected environment elements. A tactical decision needs to be made on which information is exchanged between these elements. A visualization of the connected environment elements is shown in Figure 3.4. The elements are infrastructure, vehicles, and user elements. Within these options, information can be exchanged.

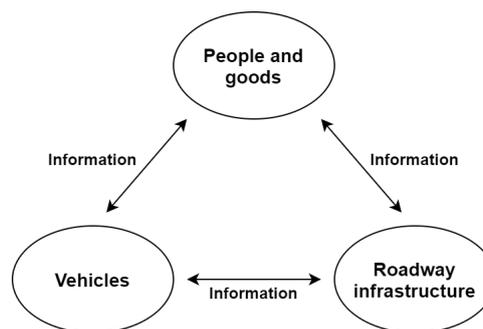


Figure 3.4: Connected vehicles environment, taken from Shladover (2018)

### *Real time data exchange*

An operational decision needs to be made, which information is exchanged in real-time. This means that the data is continuously available to make real-time decisions.

## **3.4 Conclusion**

This chapter has discussed two different frameworks. We provided a framework for CAT concepts, where different CAT concepts can be categorized based on distance and number of unit loads. Furthermore, we provided a framework for smart yards that provides several decisive factors that determine the characteristics of a case. And finally, key elements in a smart yard have been provided. These key elements have been classified into three levels: strategical, tactical, and operational, in the topics: automation and connection. Regarding the differences between the frameworks, the first framework shows how the smart yard concept can be positioned and is connected to other CAT concepts and applications, while the second framework provides a detailed description of the characteristics of a smart yard.

## 4. Smart yard processes

*In this chapter, we describe the general processes of a smart yard. We use the conceptual framework from the previous chapter and the case study, described in the next chapter. The smart yard processes will be used in the simulation model. An introduction is given in Section 4.1. Section 4.2 describes the current process of cargo. In Section 4.3 the physical smart yard is described. Section 4.4 describes the digital smart yard. In Section 4.5 we describe the potential impacts of the smart yard. A summary is given in Section 4.6.*

### 4.1 Smart yard introduction

We described the concept of smart yards briefly in Section 1.1 and provided a conceptual smart yard framework in Section 3.3. In this chapter, we define the smart yard processes in detail. The following elements are implemented in a smart yard:

- Automated Vehicles (AVs);
- Decoupling Point (DP);
- Connectivity through a seamlessly integrated network system.

The smart yard is explained by the processes of the physical smart yard and by the information flows within the digital smart yard. When the smart yard processes are defined, the potential impacts of the smart yard are given.

### 4.2 Current process

To define the current process at various Logistics Service Providers (LSPs), we introduce some general terms that are marked **boldly** in the generic cargo flow in Figure 4.2. The content of these terms differs at LSPs, as the content is case-specific. For example, the modality in a seaport can be a vessel, while the modality in an airport can be an aircraft. The meaning of these terms are as follows:

- **Modality**: various transportation modes to transport the cargo. Modalities considered: truck, barge, aircraft, and train;
- **Cargo**: loads of products that are transported. Cargo types considered: trailers, containers;
- **Dock**: various areas where the cargo of the modalities are loaded and/or unloaded;
- **Buffer**: temporary storage areas. This can be a parking area for modalities or a storage area for cargo.

Figure 4.1 visualizes the generic process flow of cargo in the current yards. Three process areas are depicted by the rectangles: modality inbound (dotted line), modality outbound (dotted line), and cargo flow (solid line). An arrow indicates the flow of the process and a dotted arrow indicates a transition in the process. These processes are discussed in the following paragraphs.

#### Modality inbound

The inbound process starts when a loaded modality arrives at the LSP. The modality is either sent to a buffer (e.g., a truck parking area in case of a truck), or it is sent immediately to the dock for unloading. At the dock (e.g., a quay in case of a barge), the cargo is unloaded from the modality and the emptied modality leaves the LSP. This empty modality can be used in the modality outbound, where it arrives as an empty modality. The cargo process starts when the cargo is unloaded from the modality.

#### Cargo process

When the cargo arrives at the LSP, the cargo is either transported to a buffer or a warehouse. Within

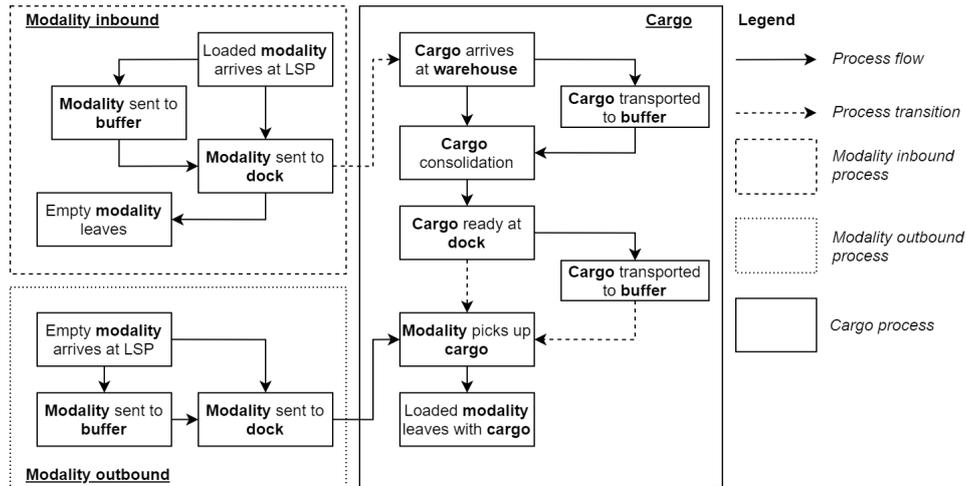


Figure 4.1: Generic cargo flow current yards

the warehouse, the cargo is consolidated and can be seen as an internal process. Consolidation of cargo means that value adding services are performed. This can either be something with the products itself, or the product is loaded into another form of cargo (e.g., from containers into a trailer). When the cargo is ready at the dock, a modality picks up the cargo directly at the dock, or the cargo is transported to a buffer and a modality picks up the cargo from here.

### Modality outbound

The outflow process starts when an empty modality arrives at the LSP. When the cargo is not ready at the loading dock, the modality is sent to a buffer. When the cargo is ready at the loading dock, the modality is sent to the loading dock. At the loading dock, the modality picks up the cargo and the loaded modality leaves the LSP.

## 4.3 Physical smart yard

To describe the intended generic process of the physical smart yard, the same terms as introduced before are used and the following terms with their meanings are added:

- **Decoupling point:** External area for (de)coupling of the cargo, including a buffer for trucks.
- **P/D point:** Pick up / Drop off (P/D) point. Points considered: DP, dock, and buffer.
- **Other task:** Tasks considered for AV besides transporting cargo. These tasks are idle vehicle positioning and recharging.

### 4.3.1 Process

In the smart yard, the process flow of an AV (blue rectangle) is added. Figure 4.2 visualizes the generic process flow of modalities, AVs, and cargo in a smart yard.

The process areas are demarcated by a rectangle as follows: modality inbound (dotted line), modality outbound (dotted line), AV (blue and striped line), and cargo (dashed line). An arrow indicates the flow of the process and a dotted arrow indicates a transition in the process. The processes are discussed in the following paragraphs.

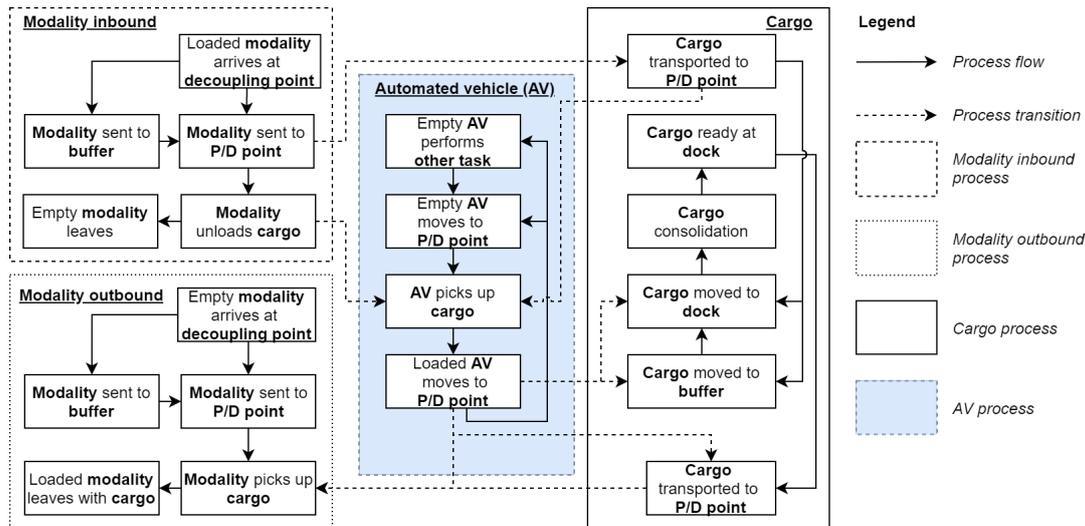


Figure 4.2: Generic cargo flow smart yards

### Modality inbound

A loaded modality arrives at the DP of the LSP. If the unloading point is available, the modality moves to the P/D point, or else it is sent to a buffer. At the P/D point, the modality decouples the cargo and the empty modality leaves the LSP.

### AV process

The AV process starts with an empty AV that it is available for a job. A job is scheduled for the AV and the empty AV moves to the P/D point. At the P/D point, the cargo is coupled with the AV and the cargo is picked up. The loaded AV moves to the scheduled P/D point, where the cargo is dropped and the AV becomes empty. This drop off point can be the buffer at the warehouse, dock at the warehouse, or the P/D point at the DP. The empty AV has four possible tasks: new loading job, idle positioning, recharging. Idle positioning means that there are no more transportation jobs that can be performed by the empty AV, and the AV moves to the optimal idle position. Based on the battery strategy, the AV should move to a recharging station. A vehicle should only start a job when the battery level is sufficient to finish the job. When the AV completed the other tasks, it becomes available for a new transportation job.

### Cargo process

A loaded modality transports the cargo to a P/D point at the DP. From a P/D point, if the warehouse is ready the cargo is transported to a dock at a warehouse, or else it is transported to a buffer at the warehouse. The cargo is consolidated in the warehouse and made ready at a dock. The cargo is then transported to a P/D point at the DP and picked up by a modality.

### Modality outbound

An empty modality arrives at the DP of the LSP. If the cargo is available to be picked up, the modality moves to the P/D point, otherwise, it is sent to a buffer. At the P/D point, the modality couples the cargo, and the loaded modality leaves the LSP.

### **Decoupling point**

The DP is an important part of the smart yard. The DP functions as a buffer for road modalities, buffer for the cargo, and the (de)coupling between trucks and AVs. At the truck buffer, the trucks can wait until called to decouple the cargo. The cargo buffer stores the cargo until it is picked up by an AV or truck. The (de)coupling will transfer the cargo from a truck to an AV, or vice versa.

The potential impacts that result from these physical processes are discussed later on.

## **4.4 Digital smart yard**

A Digital Smart Yard (DSY) is a seamlessly integrated network system in which data is exchanged. As demarcated in Figure 1.3 in Section 1.1, the scope of the DSY is the physical smart yard and additionally reaches all incoming and outgoing modalities. Although the terms digital and smart are related as data plays an important role, we use the term digital smart yard to clearly demarcate the boundaries from the physical smart yard. In the DSY, all data is exchanged, stored, and used as inputs to make decisions. For example, data can be used to make real-time optimizations such as optimal scheduling and routing. The data that is needed for that should all be available in real-time. For example, continuously updated arrival times, positioning, and status of the modalities and loads. The design of a DSY system is outside the scope of this research.

The concept of sharing all necessary data is idealistic and limitations could occur. Companies are reluctant when sharing their data, as they do not want to lose the advantage that they have created. Furthermore, data can present substantial privacy concerns. These limitations should be included in further research.

### **4.4.1 Connected environment**

As concluded before, the information can be exchanged between people, vehicles, and infrastructure. Therefore, we need to define the entities from these elements within the DSY environment.

#### **People**

- *Shipper*  
Responsible for the sending of the cargo. This can be any production company or forwarder.
- *Carrier*  
Responsible for the transportation of the cargo. This can be any trucking company.
- *Forwarder*  
Responsible for the consolidation of the cargo such, e.g., within warehouses.
- *Smart yard operator*  
Responsible for the operations at the smart yard.
- *Logistic service provider*  
An overarching organization such as a seaport or airport. Can be seen as fourth logistics party and is looking for the best solutions for the whole supply chain that the LSP is responsible for.
- *Terminal operator*  
Responsible for the operations at the terminal.
- *Consignee*  
Customer who receives the cargo.

The people, or stakeholders, involved is very case depended. In some cases, a stakeholder can have multiple roles. For example, a distribution center can be shipper, forwarder, and LSP. Besides, stake-

holders (as generally described above) can consist of multiple stakeholders. For example, in a seaport (a LSP), the cargo can go within a terminal from terminal operations to customs, and from customs to a warehouse. All these steps have an impact on the supply chain and should be involved in the DSY. All stakeholders have interests in an efficient process and will benefit from the potential impacts. Later in this section, the information exchange between the stakeholders is discussed.

## **Vehicles**

- *Handling vehicles*  
Vehicles that transport the cargo internal in the smart yard. These vehicles should be connected to the system to enable data-sharing and improve the operational process such as routing and peak-shaving.
- *Transport modalities*  
Any modality that transports the cargo externally to the smart yard. These modalities should be connected to the system to enable data-sharing and improve operational planning.
- *External vehicles*  
External vehicles that are inside the smart yard and can provide information. These vehicles are not part of the smart yard, but influences the process and can provide information such as traffic jams.

## **Roadway infrastructure**

- *Decoupling point*  
DP inside the smart yard where the cargo can be (de)coupled. The DP should provide information on the available capacity, to improve the operational process.
- *Intelligent transport systems*  
Any intelligent transport system (e.g., intelligent traffic light, geo-fence, and traffic sensors), that can collect data and provide information for the traffic situation.
- *Parking places*  
Buffer or handling zones that can be used within the smart yard, such as parking areas and docks. These places should provide information on the available capacity to improve the operational process.

### **4.4.2 Information**

To complete the processes of the digital smart yard, we need to define what information or data should be exchanged. The following information should be shared with the stakeholders:

- *Expected arrival time*  
Every carrier should share the expected arrival time to the consignee. The arrival time should be known at least a fixed time in advanced, since it is not helpful if the arrival time is shared 10 minutes before the arrival. The receiver can not anticipate on the arrival, in terms of scheduling processes.
- *Load order*  
All information about the load order should be shared. This load order can be a CMR, which is a document for the international carriage of goods. In this (digital) document, information is provided about, among others, truck, truck driver, product information, and product volumes.
- *Order time window*  
A time window, or deadline, in which the modality can drop off or pick up the cargo.

- *Parking data*  
The parking areas within the smart yard (e.g., docks, DP, and truck parking) should provide information about the status, such as the available parking spots and the number of waiting vehicles.
- *Traffic data*  
Traffic data needs to be collected and shared in order to determine optimal routes, planning, and scheduling.

Figure 4.3 visualizes the information flow between stakeholders. All these data should preferably be shared in real-time.

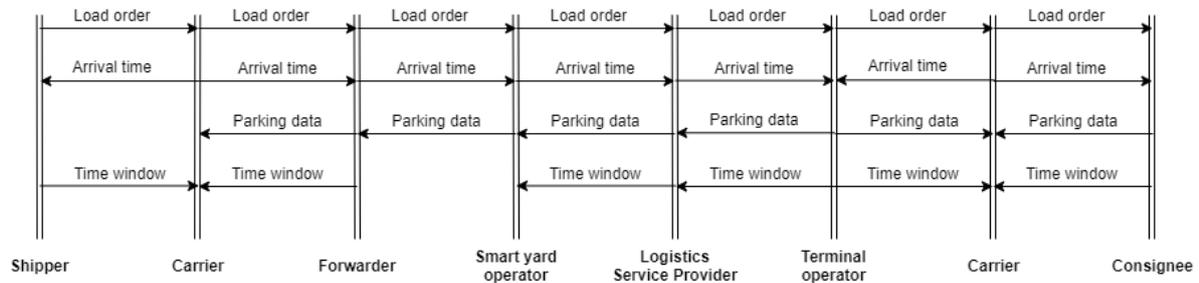


Figure 4.3: Information flow between stakeholders

As can be seen, the data should be shared between all stakeholders as for example, the load order should be known by every stakeholder. If the load order is changed, for example, the load is consolidated and placed in different loads, then the new load order should be shared with the following stakeholder in the supply chain. Furthermore, the time window and arrival time are related to each other, as the arrival should be within the time window, or before a certain deadline. However, if the time window cannot be met in time, the arrival time provides this information and should be used to change the planning. A carrier is a special case from all stakeholders, since they pick up and drop off the cargo. Therefore, they have to share the data backward in the supply chain (e.g., share the arrival time at a shipper), but also forward in the supply chain (e.g., the arrival time at the forwarder).

The potential impacts that result from these digital processes are discussed in the following section.

## 4.5 Impact smart yard

Now that the general processes of a smart yard are defined, we can elaborate on the potential impacts that a smart yard might have. In Section 1.1, we briefly discussed the potential impacts of connected and automated transport. In this section, we elaborate more in detail on the potential impacts of a smart yard. Since we focus on logistics operations for a smart yard in this research, impacts on, for example, the environment and society are not discussed. The potential impacts on logistics operations are the following:

- *Increased process efficiency*  
The process of arrivals and departures of trucks can be better coordinated by using a DP. This process can be improved due to a seamlessly integrated network system (connectivity) and AVs (automation). Therefore, the predictability of the arrival times can be increased and this may result in better planning and scheduling due to constant optimization. Consequently, the waiting times and the total throughput time may be reduced and the total flow can be increased. Furthermore, by being able to store the trailers at the DP, the trucks can arrive and depart at any time.

- *Peak shaving*  
Peak shaving can be achieved for several reasons. First, due to increased connectivity and thus predictability, a better schedule can be made which may decrease the peaks in the demand. Besides, in theory, the internal vehicles are able to operate 24 hours per day which means that the workload can be spread out over the day. Finally, as a more efficient process may reduce the waiting times and total throughput time, the peaks of the demand may be much smaller.
- *Increased safety*  
Safety is an important issue in logistics and AVs can take over human tasks to prevail crashes and other risks such as speeding, aggressive driving, and inexperience. Fagnant and Kockelman (2015) studies the potential impacts of AVs and concludes that AVs may reduce the crash and injury rates by 50% due to taking over human tasks. Besides, the implementation of internal vehicles may reduce the number of vehicles in the area and thus increase safety. First, the number of vehicles can be reduced as arriving trucks are able to go to the truck parking and wait until the trucks are called. Second, the arriving trucks are able to decouple the cargo at the DP and thus do not have to go in the area. Finally, in an ultimate situation, the smart yard area becomes a confined environment where only AVs are able to drive, thus not a mixed traffic situation. The DP will function as the connection between the confined environment (no humans involved) and the open area (humans involved).
- *Reduced congestion*  
The implementation of a smart yard can reduce congestion. Chan (2017) concludes that congestion can be reduced by using AVs to reduce incidents and improve traffic flow. Also, by using effective real-time data the congestion can be reduced due to better trip assignments and dynamic routing. Furthermore, Fagnant and Kockelman (2015) concludes that AVs improve the traffic flows by seeking to minimize accelerations and braking in freeway traffic. However, the traffic flow will not happen automatically, as the AVs should also have the capability to communicate with other vehicles and the infrastructure. So, to improve the congestion, the combination of automation and connectivity is needed.

## 4.6 Summary

This chapter has provided the generic processes of a smart yard. The current process at various LSPs is described and with the implementations for a smart yard, we described the physical process. Furthermore, we stated the stakeholders, the information flow, and the impacts of the smart yard. Having described the conceptual smart yard framework and the smart yard processes, we can research the use cases in the following chapter.

## 5. Case description

*This chapter describes the use case for this research. We use the case study as input for the conceptual smart yard framework, the smart yard processes, and the conceptual model. In Section 5.1 we introduce the cases. Section 5.2 describes the Schiphol case. In Section 5.3 we describe the Schiphol specifications. Finally, we give a summary in Section 5.4.*

### 5.1 Case approach

The CATALYST living lab includes four cases for the smart yard concept. For each case, we describe the following: case problems, the motives for establishing a smart yard, the smart yard scenarios, and a smart yard concept. In this chapter, we only describe the Schiphol case, as this case is the focus of the simulation study. We have chosen the Schiphol case from the CATALYST living lab as our focus, as this case has the most aspects included in the smart yard concept. The other case descriptions are given in Appendix B. The case descriptions have been validated with experts from the cases. Per case, a taxonomy is given that describes the characteristics of the case, based on the decisive factors from the conceptual smart yard framework.

A questionnaire is sent to all cases and can be found in Appendix A. This questionnaire contains questions about the processes, infrastructure, cargo loads, transportation means, and load volumes. Furthermore, the questionnaire contains various data topics. The data of these data topics should be provided by the cases. These topics are: trip-, order-, cargo-, maintenance-, and geographical data. The answers to this questionnaire should give an impression of the characteristics of the case.

### 5.2 Schiphol introduction

Schiphol is the main airport in the Netherlands. Besides passenger flights, Schiphol transports air cargo. In 2018, Schiphol transported roughly 1.7 million tons cargo, in almost 16,000 full cargo trips. In total Schiphol has 159 cargo destinations in 83 countries (23 destinations only cargo). 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 the CATALYST living lab, research has been started to improve the cargo handling process at the landside of Schiphol by using a smart yard.

#### 5.2.1 Process Schiphol

To elaborate on the process at the cargo side, we describe the following important stakeholders in the air cargo supply chain:

- *Airlines*: transport the cargo by air.
- *Ground handlers (GHs)*: service the cargo in and out of the aircraft.
- *Forwarders*: organize the transport of cargo from shipper to GHs and vice versa.
- *Logistics service providers or trucking companies*: transport the cargo, commissioned by forwarders.
- *Shippers*: supplier of the cargo that is transported.

The process flow of Schiphol air cargo is shown in Figure 5.1.

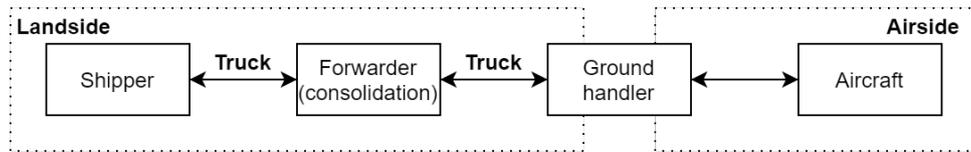


Figure 5.1: Current process Schiphol

This process flow shows the import and export process of cargo. For the import, on the airside, the cargo is taken out of the aircraft and transported to a GH. From the GH on the landside, the cargo needs to be transported to multiple forwarders. To have a more efficient transport between GHs and forwarders, the milk run concept is designed for the import process. Meyer (2016) provides definitions and concepts for the milk run design. By combining multiple cargo loads into a trailer or container, fewer truck movements are necessary. Cargo from a GH is transported to multiple forwarders. The GHs and forwarders are implementing the milk run concept. Another occurrence is that forwarders organize transport via multiple GHs towards their warehouse. From the forwarders, the cargo is picked up to be transported to the customers.

For the export, the cargo is transported from the shipper to a forwarder. From a forwarder, the cargo needs to be transported to multiple GHs. The transportation between the forwarders and GHs can be handled by freight forwarders, logistics service providers, or third-party trucking companies. A GH can also organize a milk run, from multiple forwarders to the GH. Another occurrence is direct transportation between GHs from other airports, most of the time this is an international transport and is called international road feeder. The cargo needs to be delivered at the GH before a fixed predetermined time so that the aircraft can leave on schedule with the correct cargo on board.

### 5.2.2 Taxonomy Schiphol

The characteristics of the current process at Schiphol are shown in Table 5.1.

Table 5.1: Taxonomy Schiphol

| Type         | Characteristics   |
|--------------|---|
| Modalities   | aircraft, truck   |
| Distance     | medium  |
| Cargo type   | trailer   |
| Product type | general, perishables, dangerous                                       |
| Environment  | hub-to-hub  |
| Flow scale   | shipments on average at a forwarder: 30 (normal day), 110 (busy days) |
| Flow timing  | peak on Tuesday and Friday  |
| Handling     | manual  |
| Job type     | pick up, drop off, routing  |

### 5.2.3 Smart yard motives Schiphol

At this moment, there is a lot of congestion within the Schiphol area. The Schiphol environment is an open road, so it is public and the traffic is not controlled. The congestion is caused by the following two reasons:

- **Limited space at GHs**

There is not enough parking space at the GHs for the trucks that come to collect or drop the cargo. Therefore, the trucks have to park alongside the road where they are waiting until they can proceed to the GH parking places. This results in an unsafe traffic situation and congestion.

- **Cargo deliveries are not regulated**

The GH has no full information about the incoming cargo or the arrival time because most trucks arrive unannounced. The GH does receive a loading list for the aircraft and knows which cargo should arrive at the GHs. In general, cargo should be at the GH at least 8-12 hours before flight departure. In practice, the cargo from all forwarders arrives at the same time right before the deadline. When multiple trucks arrive at the same time, the GHs do not have enough handling capacity or storage space, which results in waiting times. This is a problem, as driver-costs are most costly for transport companies and therefore, the waiting times for truck drivers should be minimized. Controlling the logistic flow can result in peak shaving and reduced waiting times for truck drivers at the airport.

## Scenarios

In multiple meetings with the stakeholders at Schiphol, an agreement on four scenarios is reached. The proposed scenarios are as follows:

1. **Current situation**

The current situation needs to be modeled, this will set the benchmark to compare to the other scenarios.

2. **External truck parking with calling system**

An external Truck Parking (TP) area that is used as a buffer. Trucks can park at the external parking until they are called to their destination. This may resolve traffic issues within the Schiphol area and capacity problems at the GHs.

3. **External decoupling point to decouple cargo, handled by traditional trucks**

An external TP area is used as a Decoupling Point (DP), where cargo is decoupled from the forwarders to GHs. The cargo is transported between the DP and GH by traditional trucks. This may resolve traffic issues, capacity problems, and waiting times for truck drivers.

4. **External decoupling point where cargo is handled by Automated Vehicles (AVs)**

An external TP area is used as a DP, where cargo is decoupled from the forwarders and GHs. Transportation between the DP and GHs is handled by AVs. This may resolve traffic issues, capacity problems, waiting times, and increases the predictability of processes.

### 5.2.4 Smart yard concept Schiphol

The concept for the smart yard in Schiphol is shown in Figure 5.2. The striped line square shows the demarcation of the physical smart yard area. For the export process, the smart yard begins when the cargo is consolidated at the forwarder. From here, the cargo can be transported to various forwarders, go to the DP, or go directly to the GHs. The transport of cargo between the DP and GH is handled by AVs. The cargo is handled automatically at the DP, where the cargo is temporarily stored. It is also possible that the cargo goes directly from the forwarder to the GH if the GH is ready to receive the cargo. The physical smart yard ends when the GH received the cargo. For the import process, the smart yard begins when the cargo is ready to be transported at the GH. The cargo can be transported to the DP, to be temporarily stored or it can directly go to various forwarders. Milk runs are possible that allow the cargo from multiple GHs to be delivered to one forwarder. The transportation of cargo between the GH

and the DP is handled by AVs.

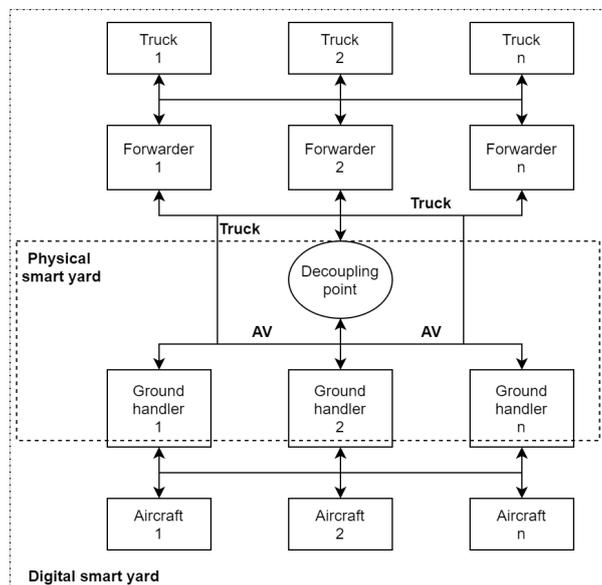


Figure 5.2: Smart yard concept Schiphol

### Impacts

The implementation of a smart yard may result in multiple impacts. First, as the trucks do not need to go to the area of the GHs, the congestion is reduced and traffic safety is increased as the trucks do not need to park alongside the road and the AVs drive safer. Second, peak shaving at the GHs occurs as the DP will function as a buffer and via the connectivity, the arrivals can be regulated. The AVs can pick-up and drop-off the cargo, when the cargo is ready at the GHs or the GHs are ready to receive cargo. Last, the waiting times for truck drivers may be reduced, as the truck can drop their cargo and leave.

### Limitations

The described smart yard concept for Schiphol is idealistic and has limitations that should be researched further. These limitations are outside the scope for this research, but should be known nevertheless. First of all, it may not be feasible to decouple the cargo load at the decoupling point. Since the truck drivers are responsible for the cargo load, they need to be present at the moment of inspection. Besides, when something happens to the cargo load (e.g., damaged or stolen), it should be known who is responsible. So, the legal aspects should be researched. This also includes the responsibilities for the AVs, as it should be known who is the owner of the smart yard. Furthermore, as companies do not want to lose their competitive advantage, research on the costs and benefits should be conducted. Besides economical benefits, other benefits as safety and environmental should be researched.

### 5.3 Schiphol specifications

In this section, we describe the Schiphol case specifications that can be used as input for the simulation study.

#### 5.3.1 Schiphol area

At Schiphol, five GHs - Menzies (MZ), WFS, Swissport (SP), Dnata, and KLM Cargo - are located. Figure 5.3 shows the locations of the GHs. These GHs services the cargo in and out of the aircraft. The GHs are supplied by over 300 forwarder companies, which are located near the Schiphol area. Furthermore, Truckparking 3 is depicted in Figure 5.3.



Figure 5.3: Schiphol cargo area

As can be seen, the GHs are located near the airside. Three GHs and Truckparking 3 are located on the south side and two GHs are located at the north side of a landing strip.

#### Ground handlers

The data gathering for the input of GH specifications is twofold: i) input from experts that are working at various companies at Schiphol and ii) input from Romero-Silva and Mujica Mota (2019). We assume that we can match the GHs by the known probability distribution of GH arrivals to compare the number of docks. Table 5.2 gives the specifications of the GHs at Schiphol.

Table 5.2: Schiphol ground handlers specifications

| Specifications                 | MZ   | WFS  | SP   | KLM | Dnata |
|--------------------------------|------|------|------|-----|-------|
| <i>Experts</i>                 |      |      |      |     |       |
| Probability of arrival at a GH | 0.20 | 0.10 | 0.15 | 0.5 | 0.05  |
| Number of docks                | 25   | 9    | 39   | -   | -     |
| Buffer places                  | 17   | 5    | 12   | -   | -     |

| <i>Paper</i>                   |      |      |      |      |      |
|--------------------------------|------|------|------|------|------|
| Probability of arrival at a GH | 0.15 | 0.10 | 0.14 | 0.53 | 0.08 |
| Number of docks                | 16   | 14   | 17   | 24   | 11   |

The input from the subject experts from Schiphol for the number of docks deviate from the input from the paper. This can be substantiated as the number of docks given by the experts is the total number of docks that the GHs have. The number of docks given by the paper is the assumed number of docks, which are always available, used in the simulation in Romero-Silva and Mujica Mota (2019).

### **Truck parking**

Within the Schiphol area, three TP areas are located. Two of these TP areas can be used by members that pay a monthly rate, while the third TP area can be used by paying an hourly rate. These TP areas have been built to improve traffic safety and flow within the Schiphol area. However, at this moment there is no obligation to use these TP areas and the benefits to use a TP are only marginal: it serves as a safer waiting area, but for most trucks, this is not worth the costs. Truckparking 3 can function as a TP and DP, as described in the four scenarios from the Schiphol case. At the TP, the trucks will wait until they are called when a dock at the GH is available. The capacity of TP3 is 80 trucks. At the DP, the truck can (de)couple, and drop off or pick up the trailer. There can be an area for the internal handling vehicles (manual yard tractors or AVs), that can function as the idle positioning place.

### **Truck arrivals**

To enter the Schiphol cargo area, two entrances can be used. To enter the south side of the landing strip, the exit on the N201 road (depicted in the bottom of Figure 5.3) is used. The north side of the landing strip can be entered by using the exit on the E19 road (depicted in the top left of Figure 5.3). Schiphol has two busy export days. On a Tuesday, the arrivals are twice as high and on a Friday the arrivals are three times as high compared to the other days. An indication for the arrival rate of trucks is provided by the subject experts of Schiphol. Table C.1 in Appendix C provides an overview of the arrival rates at Schiphol.

## **5.4 Summary**

As stated in this chapter, the Schiphol use case is the focus of the simulation study. Furthermore, we described the Schiphol processes, taxonomy, the smart yard motive, concept, and impacts. Besides, we provided specifications of the Schiphol area. These specifications can be used as input for the simulation model. From here, we can start with the simulation study.

## 6. Conceptual model

This chapter describes the conceptual model for this research. We use the case study, described in the previous chapter, as input. The conceptual model will be used in the next chapter namely the simulation model. In Section 6.1 we discuss the simulation literature. The conceptual model is provided in Section 6.2. Section 6.3 describes the model content. Finally, we give a summary in Section 6.4.

### 6.1 Simulation literature

As concluded before, a simulation model is the preferred option to gain insights in the smart yard system. As the focus of the literature study was on connected and automated transport, we discuss briefly the literature on simulation in this section. A simulation model is a mathematical representation of a system, that can be used for experimentation. Law (2014) classifies simulation models along three dimensions:

- **Static vs. dynamic simulation models**

A static model represents a system at a particular moment in time, while a dynamic model represents a system that evolves;

- **Deterministic vs. stochastic simulation models**

A model is deterministic, if the systems' output is determined once the input is specified. When a system includes random input components resulting in variable outcomes, it is considered as a stochastic model;

- **Continuous vs. discrete simulation models**

A model is continuous, if the state of a system changes continuously with respect to time. When only an event changes the state of a system, it is considered as a discrete model.

In this research, we consider a discrete-event simulation model. Law (2014) defines discrete-event simulation as modeling of a system as it evolves, where state variables change instantaneously at separate points in time. So, the systems state can only change when an event occurs.

#### 6.1.1 Simulation Process

Robinson (2014) proposes a simulation framework that includes the process steps, verification, and validation for simulation modeling. The key steps in the simulation framework are visualized in Figure 6.1.

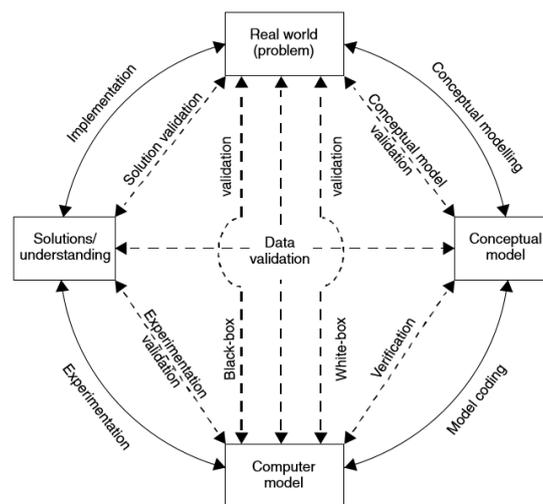


Figure 6.1: Simulation process, verification, and validation, taken from Robinson (2014)

Robinson (2014) defines the following steps in a simulation process:

1. *Conceptual model*: a description of the model;
2. *Computer model*: the simulation model implemented on a computer;
3. *Improvements and/or understanding*: derived from the results of the experimentation;
4. *Real world (problem)*: An improvement in the real world, obtained from implementing the improvements and/or understanding gained.

We follow these steps to develop the simulation model.

## 6.2 Conceptual model

We use a structured approach to develop the conceptual model. Robinson (2008) provides a framework for conceptual modeling with the following steps:

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

These steps are discussed in the following subsections.

### 6.2.1 Problem situation

We develop various scenarios, resulting from the Schiphol case description. We implement the following interventions in the current situation at Schiphol:

- Truck Parking (TP) as a buffer, where trucks are called whenever a dock is available.
- Decoupling Point (DP) including internal manual vehicles, where trailers are decoupled.
- DP including internal Automated Vehicles (AVs), where trailers are decoupled.

We model these interventions in the environment of Schiphol. Therefore, we have a total of four options for the path that a trailer can follow. Scenario 1 is the base scenario and from there, we include extra paths for the trailer. This means that in the other interventions, more path options are added. In scenario 2, the trailer has two path options:

- i) go directly to the Ground Handler (GH);
- ii) go to the TP.

In scenario 3, the trailer has three path options:

- i) go directly to the GHs;
- ii) go to the TP;
- iii) go to the DP to decouple and the trailer handled by internal manual vehicles.

We consider only manual vehicles or only AVs as Internal Vehicles (IVs), and not the combination of manual vehicles and AVs at the same time.

In scenario 4, which is the smart yard scenario, the trailer has three path options:

- i) go directly to the GHs;
- ii) go to the TP;
- iii) go to the DP to decouple and the trailer is handled by internal AVs.

The distribution between the optional paths are probabilities and used as an experimental factor.

Furthermore, we assess the number of internal vehicles in scenarios 3 and 4. Finally, we assess what happens in a calm and busy scenario, where the number of truck arrivals is decreased or increased. The experimental factors are explained later on.

### 6.2.2 Model objectives

The objective of the simulation model is to provide insight into the impact and effectiveness of a smart yard. The model should provide insight into the logistical performance of the system. We research the following key performance indicators:

- Throughput times
- Travel times
- Waiting times
- Truck times
- Utilizations

This involves assessing the impact on the throughput time for trucks in the interventions. More specifically, assessing the impact on travel-, and waiting times for trailers. Furthermore, the utilization of the GHs, the TP, and the DP should be assessed.

The simulation model should be: *flexible* by being able to change the model inputs, *feasible* to build, *credible* to have trust, and be *valid* to show that the model is an accurate representation.

### 6.2.3 Output variables

To assess the operational performance of the system, the following output variables are identified:

- **Throughput times**

The throughput time is the time between the arrival of a trailer into the system until it leaves the system. We use the times of the trailers in the system, so that the times can be compared in every intervention. The times of the trucks cannot be used, since the trucks leave the system after decoupling the trailers. The total throughput time consist of the following duration's:

- The total traveling time required for moving towards the Pick up and Drop off (P/D) locations of the trailers.
- The total waiting time at the P/D locations of the trailers.
- The total processing time at the P/D locations of the trailers.

- **Travel times**

The travel time is the time the trailer is being transported by a vehicle. The travel time of the trailers is assessed.

- **Waiting times**

The waiting time is the time when a trailer arrives at a P/D location until the start of processing. The following waiting times of the trailers are assessed:

- The waiting time at the GHs of the trailers
- The waiting time at the TP of the trailers
- The waiting time at the DP of the trailers

- **Truck times**

The truck time is the time the trailer is on a truck. Since an advantage of using the DP is that the truck driver no longer needs to go through the standard process, we want to assess the truck times.

- **Utilization rates**

The utilization rate is a fraction of the time that a resource is occupied. The following utilization rates are assessed:

- Fraction of the relative number of places occupied at the P/D locations.
- Fraction of IVs operational time compared to the total time. Operational time consists of (de)coupling time and travel time that the IV is loaded.

### 6.2.4 Input variables

Table 8.1 provides an overview of the input variables that are used per scenario and the typical values of the input variables. In Section 5.3, we described Schiphol specifications, which we use to determine the typical values of some input variables. Furthermore, we use input from experts to determine the typical values of the variables. The typical values are used as input for the simulation model.

Table 6.1: Input variables per scenario with typical values

| Input variables                               | Scenario |   |   |   | Typical value<br>[min, max] (unit) |
|---|----------|---|---|---|------------------------------------|
|   | 1        | 2 | 3 | 4 |                                    |
| Number of docks at GHs                        | X        | X | X | X | [1,50]                             |
| Processing time at GH                         | X        | X | X | X | [15:00, 02:00:00] (hour:min:sec)   |
| Distances between P/D locations (fixed)       | X        | X | X | X | [100,2000] (meter)                 |
| Arriving truck characteristic (speed)         | X        | X | X | X | [1,20] (meter/second)              |
| Arriving trailer characteristic (destination) | X        | X | X | X | GH 1, GH 2, GH 3                   |
| TP location                                   |          | X | X | X | (x, y) coordinates                 |
| Capacity at TP                                |          | X | X | X | [1,80]                             |
| DP location                                   |          |   | X | X | (x, y) coordinates                 |
| Capacity at DP                                |          |   | X | X | [1,80]                             |
| (De)coupling time internal manual trucks      |          |   | X |   | [1:00, 10:00] (minutes)            |
| Internal manual trucks characteristic (speed) |          |   | X |   | [1, 20] (meter/second)             |
| (De)coupling time AV                          |          |   |   | X | [1:00, 10:00] (minutes)            |
| AV characteristic (speed)                     |          |   |   | X | [1,10] (meter/second)              |

### 6.2.5 Scope, assumptions, and level of detail

We model the export process of trailers, which means that trucks, with a trailer, arrive from forwarders (or other logistic service providers) to go to a ground handler. From the five GHs, we only model three GHs as a destination, since these three ground handlers are on the south side of a landing strip and closest to the intended location of the TP and DP. Furthermore, we do not include a time window for the arriving trucks at the ground handler. The delivery performance is not an output variable for our model, because our focus is on the impact and effectiveness of the smart yard. In further research, the delivery performance can be assessed when planning and scheduling algorithms have been implemented. As specified in Table 5.1, Schiphol is only making use of trailers. Although the trailers are property of the forwarder companies, we do not take into account that the trailer needs to be returned to the owner. This can be taken into consideration in further research, if planning and scheduling algorithms are researched. Moreover, we do not model the export milkrun, which means that the trailers visit only one GH. In further research, this can be taken into consideration to study the effects of an export milkrun.

The following assumptions are made:

- We assume arriving trailers have the same characteristics (no differentiation in cargo types).
- We assume each arriving trailer equals one full truckload.
- We assume trailers can always be received by a GH.
- We assume arriving trucks have the same characteristics (e.g., speed and maneuvering).
- We assume inter-arrival times of trucks follow a Poisson distribution
- We assume (de)coupling operations have a predetermined duration.
- We assume unloading operations have a predetermined duration.
- We assume IV fleet is homogeneous (e.g., speed, maneuvering, and (de)coupling).
- We assume AVs and trucks to always be available, so no downtime.
- We assume vehicles to always take the shortest route.
- We assume GHs docks to be always open.
- We assume trailers can be internally moved at the GHs.

Appendix D provides a detailed description of the model scope and assumptions. We substantiate if various components, i.e., resources, entities, activities, and queues, are included or not. Furthermore, Appendix E provides a description of the level of detail. We state the components and describe the details, data type, and the explanation of these components.

### 6.3 Model content

The last part of the conceptual model is to determine the model content. First, we have to describe two important process rules of the model.

#### Speed reduction rule

When more trailers are waiting at the GHs, the road becomes more occupied, which results in traffic congestion. To account for this, we reduce the speed of all vehicles based on the number of trailers waiting at the GHs. We used four categories for the congestion level: no, low, medium, and high congestion. For these categories, we used a speed reduction of 0%, 10%, 30%, and 80% respectively, based on the buffer capacity used. These speed reductions are implemented when 0%, 25%, 75%, and 100% (or higher) respectively, of the total buffer capacity (34 places) at the GHs is used. The speed reduction is implemented to assess the impacts and effectiveness of the TP and DP in various conditions.

#### Dock prioritization rule

Whenever a dock becomes available, a prioritization rule, as depicted in Figure 6.2, determines which trailer is next to be processed. We use the following prioritization rule:

1. **Trailer is available in the GH buffer.**

Since the buffer capacity at the GHs is very limited and it is costly to wait at the GH, the trailers and trucks waiting have first priority. The order of the next trailer or truck from the buffer is on a first-in, first-out basis.

2. **Truck is available at the TP.**

When the buffer at the GH is empty, the trucks waiting at the TP have second priority. If the truck at the TP is called to the GH, a dock reservation is made. The available dock at the GH is claimed for the waiting truck at the TP. When other trucks arrive at the GH before the truck (from the TP) reached the GH, the dock is reserved and cannot be assigned to the new arriving truck. Consequently, the truck that was waiting at the TP does not have to wait again at the GH.

### 3. Trailer is available at the DP.

The trailers at the DP have the lowest priority, as these trailers are transported by IVs. Therefore, planning can be made when the trailers from the DP should be transported to the GH.

Having explained the two important rules, we now can describe the high-level process of the model. Figure 6.2 shows a high-level flowchart for the complete simulation flow. This flowchart consists of individual events, important processes, and decisions. The individual events are depicted by the gray ovals and are described later in this section.

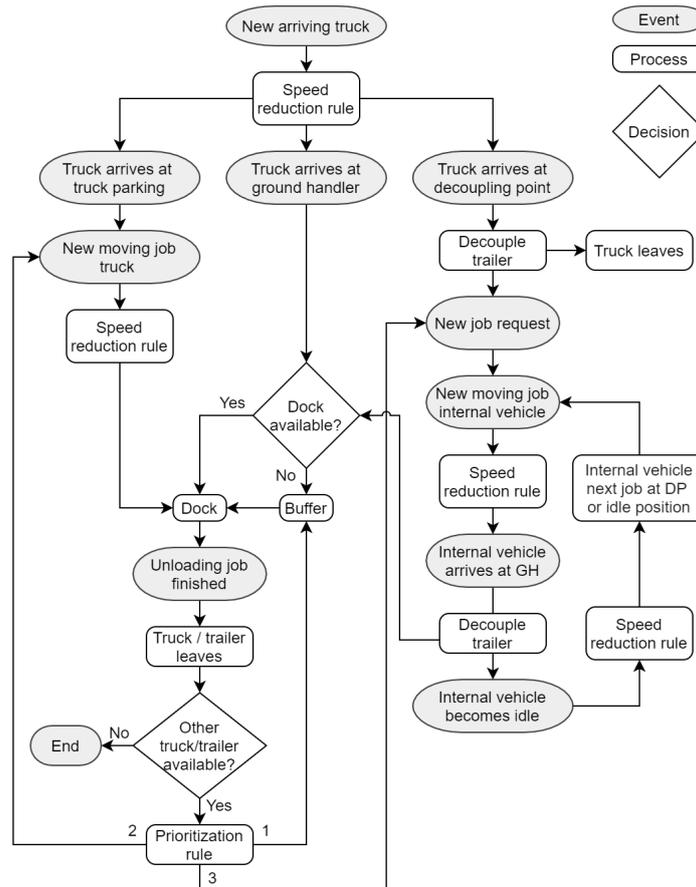


Figure 6.2: High-level flowchart of the complete simulation flow

We see, from the high-level flowchart, that there are in total three optional paths for the new arriving truck. The truck can go to the TP, GH, or DP. The truck from the TP can always go directly to a dock at the GH. For the other two paths, when a vehicle arrives at the GH, the dock is checked on its availability. If the dock is not available, the truck or trailer moves to the buffer. Furthermore, when an IV arrives at the GH, the trailer decouples and moves to the dock or buffer, and the IV becomes idle. The idle IV either moves to the DP, if there is a trailer waiting at the DP, or moves to the idle position if there are no trailers at the DP.

In the following subsections, we discuss the most interesting individual events from the high-level

flowchart. We visualize the events by flowcharts. Appendix F provides the other events with flowcharts.

### 6.3.1 New arriving trucks

Figure 6.3 shows the flowchart in the event of the arrival of a new truck. The arrivals of trucks follow a Poisson distribution and the intensity differs based on the hour and day. The truck and the trailer are created and the attributes such as the destinations (GH1, GH2, or GH3) and decoupling (true/false) are defined. The trailer and truck combine and a unique ID is assigned to the trailer. The creation time is logged, which is used later on to determine the total throughput time. Based on the attributes, the truck moves to its destination.

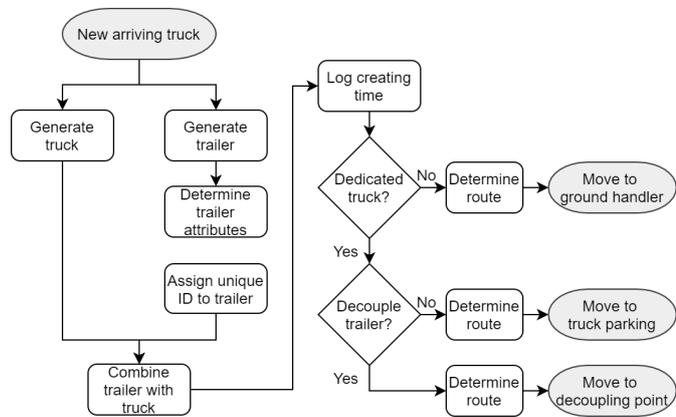


Figure 6.3: Flowchart new arriving trucks

### 6.3.2 Truck arrival at truck parking

When a truck arrives at the TP, the flowchart in Figure 6.4 shows the actions that are triggered in the model. First, we log the arrival time, so the travel time and waiting time are calculated later on. If there is no dock available at the GH destination, the truck enters the TP. If there is a dock available, the truck claims a dock at the GH. When another truck arrives before the truck, the dock is already reserved and the newly arriving truck cannot enter this dock. We determine the route and log the departure time, so that the waiting time and the travel time is calculated later on.

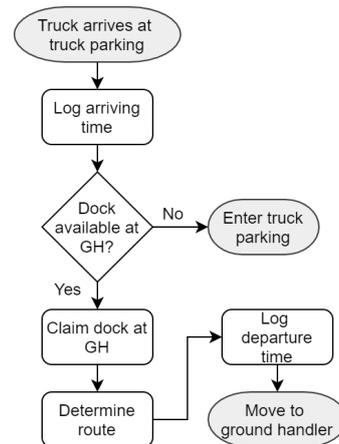


Figure 6.4: Flowchart truck arrival at TP

### 6.3.3 Truck arrival at decoupling point

Figure 6.5 shows the flowchart in the event of the arrival of a truck at the DP. First, we log the arrival time and the start of processing, so the travel time and waiting time are calculated later on. The trailer moves to the DP buffer when the decoupling process is finished and the event "new job request" is triggered. Furthermore, the empty truck moves towards the exit and leaves the system.

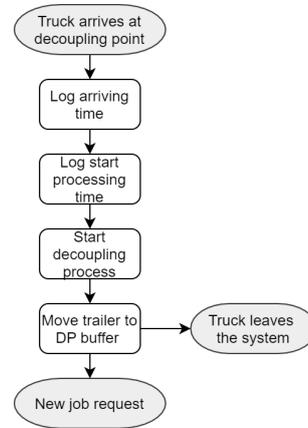


Figure 6.5: Flowchart truck arrival at DP

### 6.3.4 Internal vehicle arrives at ground handler

We log the arrival time when an IV arrives at a GH, to determine the travel time, see Figure 6.6. First, we check if there is a dock available. If no dock is available, the trailer moves to the buffer at the GH. We assume that these trailers can be internally moved to a dock. Therefore, the IV becomes idle and this event is triggered. However, if there is a dock available, the trailer moves to the dock and we log the start of the processing time. The IV becomes idle when the unloading job starts and the event "IV becomes idle" is triggered. The event "unloading job finished" is triggered when the unloading job is finished.

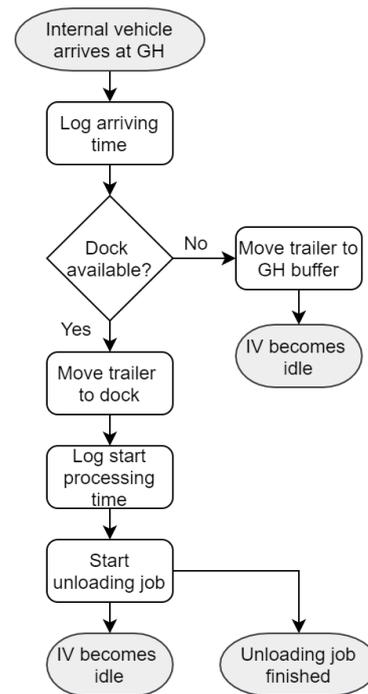


Figure 6.6: Flowchart IV arrives at ground handler

### 6.3.5 Unloading job finished

Figure 6.7 depicts the flowchart that shows how the model reacts when an unloading job is finished. First, we log the finishing time of the job, so that the total throughput time is calculated and the trailer leaves the system. Next, we use the prioritization rule, as described in this section before. First, we check if there is a trailer waiting in the buffer. The trailer moves to a dock, if there is a trailer waiting in the buffer, and the unloading job starts. This event is triggered again when the unloading job is finished. If there is no trailer in the buffer, we check if there is a truck waiting at the TP. The event "New moving job truck" is triggered if there is a truck waiting at the TP. If there is no truck at the external parking, we check whether there is a trailer waiting at the DP, that needs to be transported to a dock. The event "New moving job internal vehicle" is triggered if there is a trailer waiting at the DP. Nothing is done and the dock stays empty if there is no trailer at the DP.

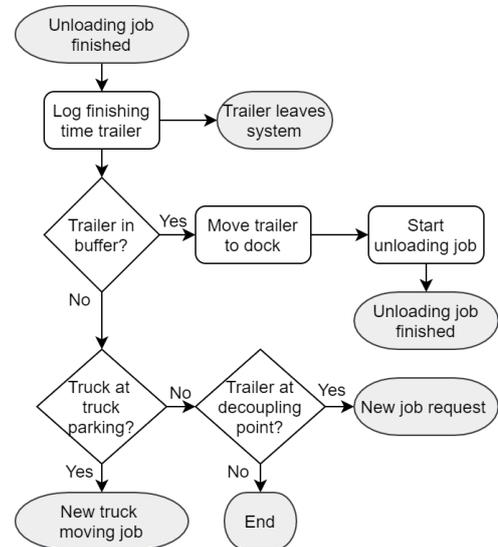


Figure 6.7: Flowchart unloading job finished

### 6.3.6 New moving job internal vehicle

Figure 6.8 shows the processes that happen in the model when a new moving job is assigned to an IV. First, we check if the IV is already loaded or not. If the IV is not loaded, the IV is available to pick up a trailer at the DP. We then determine the route and the IV moves to the DP. If the IV is already loaded, it means that the IV is at the DP and it should move to a GH. We determine the route, log the start of the moving time, and the IV moves to the GH.

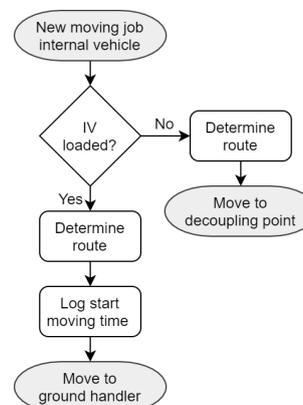


Figure 6.8: Flowchart new moving job IV

## 6.4 Summary

In this chapter, we provided the first step of the simulation process, namely the conceptual model. We described the problems, objectives, outputs, inputs, scope, assumptions, and level of detail. Furthermore, we described the model content by depicting a high-level flowchart of the simulation flow and describing the events. From here, we can implement the computer model, verify, and validate the simulation model.

## 7. Simulation model

*This chapter describes the simulation model of the research. We use the smart yard processes and the conceptual model, described in the previous chapters, as input. The simulation model is used to determine the impact and effectiveness of a smart yard. In Section 7.1 we describe the computer model. Section 7.2 gives the verification and validation. Finally, in Section 7.3 we give a summary.*

### 7.1 Computer model

To implement the conceptual model in a computer model, we use the licensed discrete-event simulation software Tecnomatix Plant Simulation from Siemens. This software package features object-oriented programming and 3D modeling capabilities. Object-oriented programming is used to create a flexible and feasible model. we use the 3D animations to build a credible and valid model. Figure 7.1 displays a 3D visualization of the Schiphol simulation model. The simulation model is based on the Schiphol case description and the conceptual model, as described in the previous chapters.

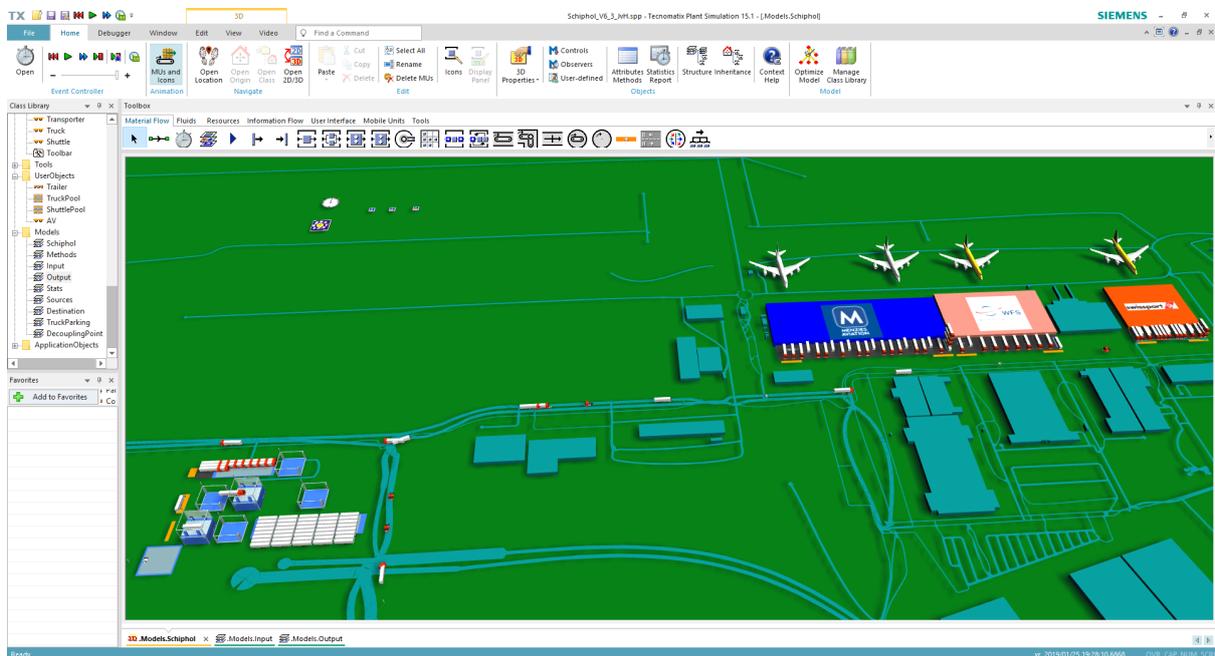


Figure 7.1: Screen capture of the Schiphol simulation model

We implement the infrastructure of the Schiphol area by using a 3D modeling software package called ArcGIS CityEngine. The infrastructure is shown in Figure 7.1 as the dark cyan color. We use the infrastructure to lay down markers in the model. The vehicles follow these markers based on a preset route. Since we have to deal with a scale of the simulation dimensions compared to the real-life dimensions, we calculate a ratio. This ratio is a fraction of the traveled distance in the computer program compared to the actual distance in real-life. We adjust the speed of the vehicles by this ratio so that the travel times of the vehicles are correct.

Furthermore, the three Ground Handlers (GHs) have a color: Menzies (blue), WFS (pink), and Swissport (orange). As can be seen in Figure 7.1, all docks are occupied at the moment of the screen capture. Since all docks at the GHs are occupied, a queue developed at all GHs. Figure 7.2 shows that a queue

developed at Menzies, since the trucks and trailers are stacked on each other. This indicates that the trucks and trailers are waiting in the buffer area of Menzies. Furthermore, since all docks are occupied, there are also trucks waiting at the Truck Parking (TP). Besides, since no internal vehicles are available, there are trailers waiting at the Decoupling Point (DP) to be transported to the GHs.

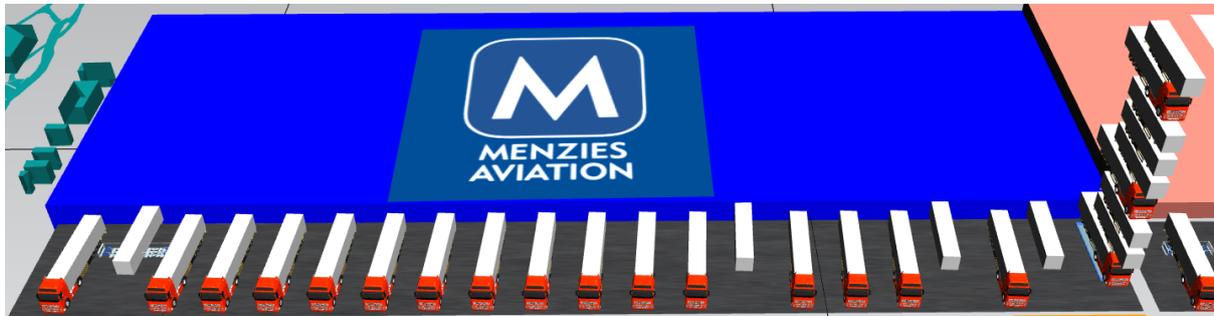


Figure 7.2: Screen capture of the Schiphol simulation model

The input variables for the simulation model are designed flexible, so that the parameters can easily be changed. For example, we can adjust the path parameters to create a scenario. When we adjust a path parameter (for the fraction that goes directly to the ground handlers) to 1 (so the fraction to the TP and DP to 0), we can recreate scenario 1 (as defined in Subsection 6.2.1). Besides, the input parameters can be used as experimental factors. For example, the number of deployed internal vehicles (IVs) is modeled flexibly, and experiments can assess the impact of the number of IVs on the system. Figure 7.3 shows the input frame from the Schiphol simulation model. The input variables and the values are defined as described in Table 8.1.

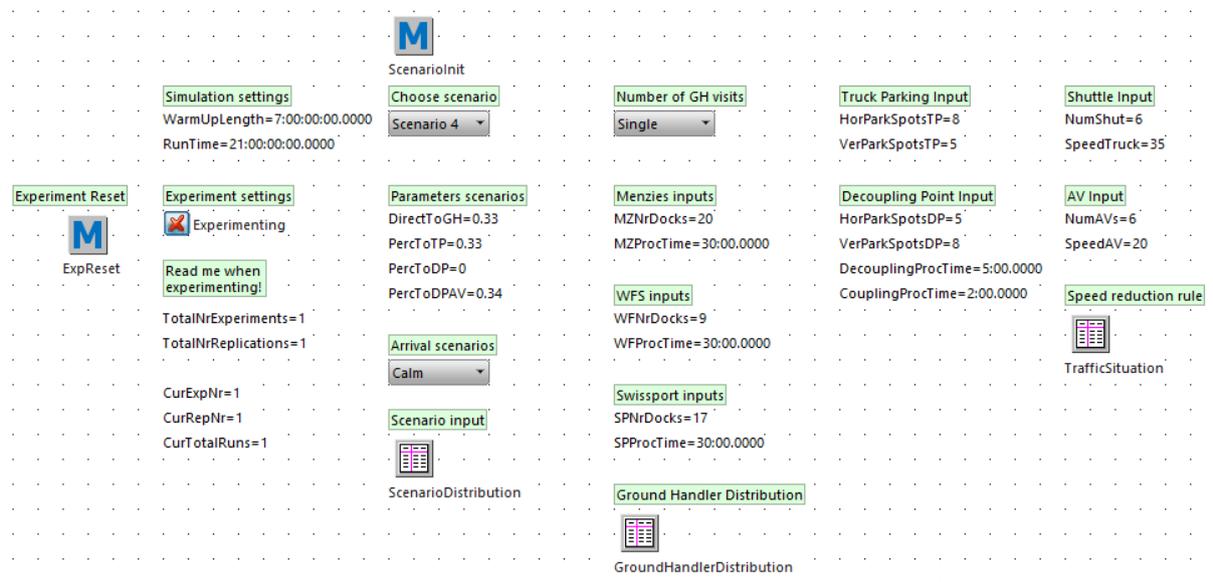


Figure 7.3: Screen capture of the input frame

The simulation run time consists of a warm-up period and a run length, both can easily be adjusted. The substantiation of the simulation settings is given later on. After the predefined simulation end time, we calculate statistics of the smart yard performances.

## 7.2 Verifiication and validation

Having described the computer model, we now can verify and validate the simulation model. It is impossible to prove that a model is valid, so verification and validation is a process until the model is convincing enough to be used for decision-making. The verification of the model ensures that the conceptual model is transformed correctly in the computer model. Validation ensures that the model is sufficiently accurate for the purpose of the study. The framework in Figure 6.1 shows the verification and validation activities that should be performed.

### 7.2.1 General verification steps

Law (2014) provides eight verification techniques. To verify our simulation model, we use the following techniques:

- **Write and debug in modules or subprograms**

We use frames in our program that can be implemented multiple times. For example, we create a frame for the GH destination, which can be implemented multiple times in the main model. This makes sure that when something is changed in the main module, all the implemented destinations are changed as well. Furthermore, the sub-modules can be debugged separately to make sure that the module is correct. After the frame is implemented in the main model, we debug the entire model to make sure the modele is incorporated correctly.

- **Run the simulation under a variety of settings of the input parameters**

We use a variety of input settings to test and verify the model. For example, we change the processing time inputs from 0 seconds to a few hours, to check what happens. With a processing time of 0 seconds, we see that no queues develop, which should be the case. On the other hand, when we change the processing time to a few hours, we see that large queues are created, which should also be the case. We use this technique on all input parameters (e.g., number of docks, (de)coupling times, number of arriving trucks, and capacity at TP and DP). In all the various settings, the model responds logically.

- **Traces**

We use a variety of traces in the model. For example, we use tables to keep track of the reserved docks at the GHs. We check this table when the event of a reservatio occurs, and check the table again in the event when the reserved dock is entered by the correct truck. Furthermore, we use state variables to keep track of, for example, the number of trailers. Another thing that we implement, is a list of all trucks, with their destination, that are waiting at the TP. We see that when the TP is occupied by trucks, and the docks at only one destination (a GH) are full, all the trucks waiting at the TP have this destination. This confirms that the waiting trucks at the TP are at the correct place.

- **Run under simplified assumptions**

We run simplified scenarios to verify the paths that the trailers should take. Instead of having three possible paths, we test each path separately. When we set the path for each truck to decouple the trailer, we conclude that the model does the right thing. After that, we test this with two paths and later on with three paths. In all scenarios, the model behaves as expected.

- **Animations**

We create a 3D environment of the Schiphol area with moving units, which we use to verify if the model behaves as expected. We verify if the vehicles follow the correct route, if the trailers (de)couple correctly, and if the trailers process correctly. Furthermore, we model waiting areas in front of the processing stations, so that the queue lengths can be seen.

- **Use a commercial simulation package**

We use the software package Tecnomatix Plant Simulation. This reduces the amount of programming, as the software package provides certain tools. A tool that we use is the AGVPool, which creates the IVs. The IVs are not bounded to a permanent routing network. Instead, we place markers where the IVs can drive along. Another feature that we use are the statistics that are included in e.g., the processing stations, stores, and AGVPool.

## 7.2.2 Verification input simulation model

We have to verify parts of the computer model to check if the simulation model provides the correct results. For every verification test, we do ten observations and calculate average counts, totals, proportions, and differences. In the following paragraphs, we discuss the verification of three inputs.

### Arriving transport

Appendix G provides the data for the verification of the arrival rate. We model a varying arrival rate per hour based on the arrival rates at schiphol. Table C.1 in Appendix C provides these arrival rates per hour. Table G.1 provides an overview of the average arrivals per hour over multiple days gathered from ten runs in the simulation model. On average, two trucks less than the total actual arrivals per day arrived, which is 0.2% less than actual. Furthermore, the absolute difference between the actual arrival rate per hour and the average arrival rate per hour, vary from 0 to 4.3. The percentual absolute difference vary from 0% to 22.6%. We see that there is a small deviation from the actual arrival rate. However, on a daily basis the deviation is very small and we conclude that the arrival input is verified.

### Destinations distribution

We model flexible input parameters for the proportional distribution of the destinations. Table 7.1 shows the assignment of destinations among the trailers. The maximum absolute difference is 0.60%, and we conclude that the proportion distribution works properly and is verified.

Table 7.1: Destination validation

| Destination  | Count  | Proportion | Actual proportion | Absolute difference |
|--------------|--------|------------|-------------------|---------------------|
| Menzies      | 596.4  | 46.86%     | 47.00%            | 0.14%               |
| WFS          | 452.2  | 35.54%     | 36.00%            | 0.46%               |
| Swissport    | 223.8  | 17.60%     | 17.00%            | 0.60%               |
| <b>Total</b> | 1272.4 | 100.00%    | 100.00%           |                     |

### Path distribution

We model flexible input parameters for the path distribution. Table 7.2 shows the assignment of the paths among the trailers. We conclude that the path distribution performs as expected, as the maximum absolute difference is 0.5%.

Table 7.2: Path proportion validation

| Path         | Count  | Proportion | Actual proportion | Absolute difference |
|--------------|--------|------------|-------------------|---------------------|
| 1            | 430.5  | 33.83%     | 33.33%            | 0.50%               |
| 2            | 420.7  | 33.06%     | 33.33%            | 0.27%               |
| 3            | 0      | 0.00%      | 0.00%             | 0.00%               |
| 4            | 421.2  | 33.10%     | 33.33%            | 0.23%               |
| <b>Total</b> | 1272.4 | 100.00%    | 100.00%           |                     |

### 7.2.3 Validation

Robinson (2014) provides various techniques to validate a simulation model. The lack of a real world system makes it hard to compare our simulation model to real data. However, we use the following validation techniques to make sure the model is sufficiently accurate for the purpose.

#### Conceptual model validation

We base our simulation model on the conceptual model stated in Chapter 6, which is an abstraction from the real world. We described the scope, assumptions, and level of detail and have to show that all necessary details are included to meet the simulation study objectives. In multiple meetings with subject experts from Schiphol, we discussed the scope, assumptions, and details to validate the conceptual model. Furthermore, we showed the simulation model to the subject experts from Schiphol and conclude that the simulation model is not sufficiently accurate at this moment to represent the actual real world of Schiphol, but is accurate enough to study the impact and effectiveness of a smart yard within the Schiphol environment. To actually construct a simulation model that represents the real world within the Schiphol environment sufficiently accurate, the whole community of Schiphol needs to be involved to make agreements and accurate data should be collected.

#### Data validation

One of the issues is the lack of acquired data, to compare the model to. However, the provided data is sufficiently accurate for the purpose, to show the first analyses on the performance of the smart yard system. We are not providing clear answers to solve a problem, but are showing the impact and effectiveness of a smart yard. The simulation study can show the effects of various experiments, to provide the first analysis.

#### Black-box validation

Finally, we use the black-box validation to check the overall behavior of the simulation model. We check if the input parameters give logical and realistic outputs. We perform two different tests to validate the model. We assess the outputs described in Subsection 6.2.3. For the first test, we perform three experiments with ten replications each. We run scenario 4 and set the path parameter of path iii to 100%, as described in Subsection 6.2.1. This means that all arriving trucks are going to the DP. We vary the number of deployed Automated Vehicles (AVs) from 4 to 6 and 8. Furthermore, we use the other inputs as depicted in Figure 7.3. Table 7.3 shows the results of these experiments.

Table 7.3: Results of validation test (number of AVs)

| Experiment | Number of AVs | Avg. throughput time (day:hour:min:sec) | Avg. travel time (min:sec) | Avg. total waiting time (day:hour:min:sec) |
|------------|---------------|---|----------------------------|--|
|------------|---------------|---|----------------------------|--|

|   |    |             |       |             |
|---|----|-------------|-------|-------------|
| 1 | 6  | 08:23:57:31 | 09:38 | 08:23:10:53 |
| 2 | 8  | 04:22:14:04 | 09:38 | 04:21:27:26 |
| 3 | 10 | 01:17:19:34 | 09:38 | 01:16:32:56 |

As we see, the average throughput time and average total waiting time decreases when the number of AVs is increased. The transportation by AVs is a bottleneck when the number of deployed AVs is too low. Therefore, it is logically that the the throughput time and waiting times are very high. Furthermore, we see that the average travel time stays the same. This makes sense, since the supply of the trailers to the GHs depends on the supply by the AVs. The speed of the AVs is reduced when a sufficient number of trailers is waiting in the queue at the GHs. Since the average travel time of the three experiments are the same, we conclude that no queue developed at the GHs in the experiments, and therefore the speed of the AVs has not been reduced.

For the second test, we perform three experiments with ten replications each. We run scenario 1, as described in Subsection 6.2.1. This means that all arriving trucks are directly going to GHs. We vary between the normal, a calm, and a busy scenario, where the number of arriving trucks per hour differs. For the normal scenario, we use the arrival rates as described in Table C.1. For the calm scenario, we multiply the arrival rates from the normal scenario by 0.75, and for the busy scenario by 1.5. Table 7.4 shows the results of these experiments.

Table 7.4: Results of validation test (normal/calm/busy scenario)

| Experiment | Scenario | Avg. throughput time (hour:min:sec) | Avg. travel time (min:sec) | Avg. total waiting time (hour:min:sec) |
|------------|----------|-------------------------------------|----------------------------|--|
| 1          | Normal   | 00:43:10                            | 05:21                      | 00:07:50                               |
| 2          | Calm     | 00:35:44                            | 04:00                      | 00:01:44                               |
| 3          | Busy     | 01:19:46                            | 08:32                      | 00:41:14                               |

As we see, the average throughput-, travel-, and total waiting time decreases in the calm scenario and increases in the busy scenario. In the calm scenario, less trucks arrive, which results in less queues at the GHs. Consequently, the speed of the truck reduces less frequently compared to the normal situation. Therefore, the average travel- and total waiting time decreases. The number of arriving trucks increases in the busy scenario, which results in queues at the GHs. This also results in longer average travel times, since the speed of the truck reduces if there are queues at the GHs.

We conclude that the simulation model behaves as expected for all experiments on the two performed tests. Furthermore, with the approval from the subject experts from Schiphol on the conceptual model, we assume that the simulation model is validated.

### 7.3 Summary

In this chapter, we described the implemented simulation model, and the verification and validation of this model. We showed the Schiphol simulation model and described some modeling techniques used. Furthermore, we used six verification techniques and verified three inputs for the computer model. Finally, we validated the simulation model by using three different validation techniques. From here, we can use the simulation model to experiment and analyze the results.

## 8. Experimental settings and analysis of results

*This chapter describes the experiments and the analysis of the results. We use the simulation model as described in the previous chapter. In Section 8.1, we describe the experimental objectives. Section 8.2 describes the experimental factors. The experimental settings are provided in Section 8.3. Next, in Section 8.4 we discuss the analysis of the experimental results. In Section 8.5, we discuss a sensitivity analysis. Finally, we give a conclusion in Section 8.6.*

### 8.1 Experimental objectives

The goal of the simulation study is to gain insight into the impact and effectiveness of a smart yard. In order to achieve this, we use the validated simulation model to show the effects on the defined Key Performance Indicators (KPIs). To show the effects on the KPIs, we define experiments with various experimental factors. In the following section, we discuss the experimental factors.

### 8.2 Experimental factors

We subdivide the experimental factors into three classes and construct in total nine experimental factors. We focus on the impacts and effectiveness of the interventions for the smart yard. Therefore, the experimental factors are as follows:

#### 1. Path proportions

Based on the scenarios described in Subsection 6.2.1, experiments with the path proportions can be performed. We experiment with the percentages of which path the arriving trucks are following. This percentage indicates the probability of which path is assigned to the truck. Within a scenario, the experimental factors are used in combination, except for the decoupling point (DP) intervention, as either manual vehicles or Automated Vehicles (AVs) are used as Internal Vehicles (IVs). The sum of the path proportions within an experiment should be equal to 1, or 100%. We use path proportions as an experimental factor to assess the effects of the interventions.

#### 2. Internal vehicles

In the intervention of the DP, a number of IVs should be deployed. We use the number of internal vehicles as an experimental factor to assess the effects of the DP intervention. We conduct a sensitivity analysis to show the effects on the KPIs.

#### 3. Truck arrival intensity

The number of arriving trucks is uncertain, as the provided data is not conclusive and in the future, the business can increase or decline. Therefore, the number of arriving trucks can be lower or higher and we want to assess what happens in these situations. We use the arrival rate based on the hour and the day as input, provided in Table C.1. We consider the following three settings for the truck arrival intensity:

- Calm;
- Normal;
- Busy.

The following table provides an overview of the experimental factors per scenario:

Table 8.1: Input variables per scenario with typical values

| Experimental factor | Scenario |   |   |   |
|---------------------|----------|---|---|---|
|                     | 1        | 2 | 3 | 4 |

|                                     |   |   |   |   |
|-------------------------------------|---|---|---|---|
| <b>1. Path proportions</b>          |   |   |   |   |
| (a) Proportion direct to GH         | X | X | X | X |
| (b) Proportion to TP                |   | X | X | X |
| (c) Proportion to DP, manual IVs    |   |   | X |   |
| (d) Proportion to DP, internal AVs  |   |   |   | X |
| <b>2. Internal vehicles</b>         |   |   |   |   |
| (a) Number of manual IV             |   |   | X |   |
| (b) Number of internal AV           |   |   |   | X |
| <b>3. Arriving trucks intensity</b> |   |   |   |   |
| (a) Calm (boolean)                  | * | * | * | * |
| (b) Normal (boolean)                | * | * | * | * |
| (c) Busy (boolean)                  | * | * | * | * |

The "X" indicates if the experimental factor applies to the scenario. The "\*" indicates that only one of all the experimental factors with a "\*" can be used in an experiment, and not in combination. Therefore, we model these experimental factors as a Boolean. So, when one of the arriving truck intensity experimental factors is true, the other two experimental factors of the arriving truck intensity class are false. Having described the experimental factors, we can now determine the experimental settings.

## 8.3 Experimental settings

To use the simulation model, we have to determine experimental settings as the warm-up period, the number of replications, and the configurations of the experiments. In Subsection 6.2.2, we defined four key performance indicators to study the effects of the smart yard. We use the throughput time for the calculations of the experimental settings, as the travel- and waiting times are included in the throughput time. The utilizations are calculated at the end of the simulation run and can therefore not be used to determine the warm-up period.

### 8.3.1 Warm-up period

To access the steady-state behavior of the model, an estimation of a warm-up period is necessary to avoid any bias due to an initial empty system. We have a non-terminating simulation with steady-state cycles, as the number of arriving trucks depends on the hour and day of the week. To determine the warm-up period, a number of replications with a large run length should be performed to get averaged observations of an output variable. We use the Welch's procedure suggested in Law (2014) and perform five replications with a simulation run time of ten weeks.

Figure 8.1 shows the results of Welch's method. Moving averages with different windows (i.e., 1/5, 1/10, 1/25, and 1/50 of the total number of trailers) are calculated over the simulation run. As indicated by the black arrow, around the 6000th trailer, the lines of the two largest windows stabilize. This number is equal to one week of simulation time. We test the warm-up period for all interventions described in Subsection 6.2.1, and conclude that for all four experiments, the model has the same behavior and warm-up period. Therefore, we use a warm-up period of one week. The run length of the simulation should be much larger than the warm-up period. We use three times the warm-up period as the run length, so the total run length of the simulation is four weeks or one month.

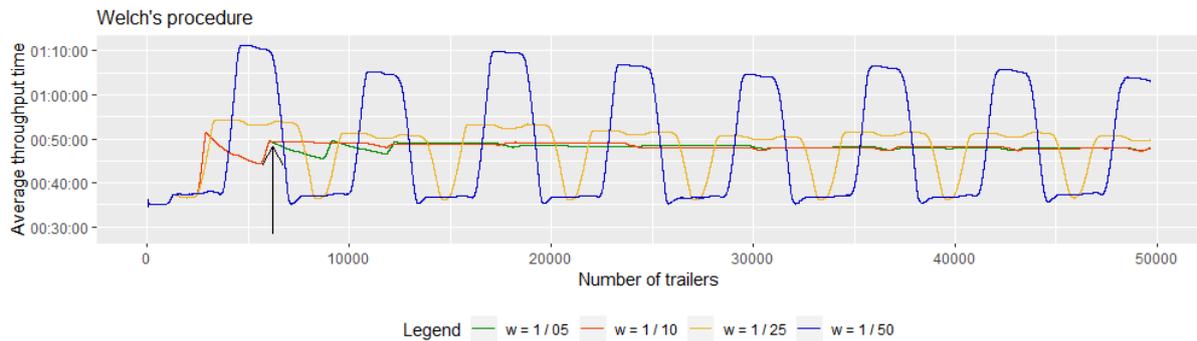


Figure 8.1: Welch's procedure for the warm-up period

### 8.3.2 Replications

To obtain reliable results, multiple replications are required so a certain confidence interval with a relative error can be calculated. Commonly used value of the significance level is 95% with a relative error of 5%. We perform the same four experiments as in the warm-up period calculation and use ten replications. Table H.1 in Appendix H provides the calculations for the number of replications for one experiment. After three replications, the relative error is below the threshold of the required relative error. This is the same for all experiments. Therefore, we conclude that the number of replications per experiment is three.

### 8.3.3 Experiment configurations

As the path proportions factors can take any number between 0 and 1, there are infinite experimental possibilities. Therefore, we choose to have one experiment for every possible combination for the path proportions. The distribution of the path proportions within an experiment is equally distributed among the available paths in the corresponding experiment. For example, in the experiment where we consider a path direct to the GH in combination with a path to the TP, 50% of the trucks should go directly to the GH and 50% should go first to the TP. Table 8.2 shows the experiments for all possible path combinations and configurations.

Table 8.2: Path proportions experiment configurations

| Exp <sup>1</sup> | Experimental factor |      |      |      |
|------------------|---------------------|------|------|------|
|                  | 1(a)                | 1(b) | 1(c) | 1(d) |
| 1                | 1                   | 0    | 0    | 0    |
| 2                | 0                   | 1    | 0    | 0    |
| 3                | 0                   | 0    | 1    | 0    |
| 4                | 0                   | 0    | 0    | 1    |
| 5                | 0.5                 | 0.5  | 0    | 0    |
| 6                | 0.5                 | 0    | 0.5  | 0    |
| 7                | 0.5                 | 0    | 0    | 0.5  |
| 8                | 0                   | 0.5  | 0.5  | 0    |
| 9                | 0                   | 0.5  | 0    | 0.5  |
| 10               | 0.33                | 0.33 | 0.34 | 0    |

<sup>1</sup>Due to space limitations we use the acronym Experiment (Exp) in all tables.

|    |      |      |   |      |
|----|------|------|---|------|
| 11 | 0.33 | 0.33 | 0 | 0.34 |
|----|------|------|---|------|

In total, we conduct 11 experiments for every intensity. Since we defined three possible intensities, we conduct in total 33 experiments. Per intensity, a number of vehicles is used which is based on the black-box validation in Subsection 7.2.3, and the percentage per intensity. Table 8.3 shows the input for the three intensities.

Table 8.3: Intensity input

| Input           | Intensity |        |      |
|-----------------|-----------|--------|------|
|                 | Calm      | Normal | Busy |
| Truck intensity | 75%       | 100%   | 150% |
| Number of IVs   | 6         | 8      | 12   |

## 8.4 Analysis of experimental results

The results of the experiments of the output variables, defined in Subsection 6.2.3, are given in Appendix I. Per KPI, we provided the average, the standard deviation, the minimum, and the maximum. The results for the throughput time, travel time, waiting time, and truck time output variables are provided in Table I.1, Table I.2, Table I.3, and Table I.4 respectively. In the following subsections, we show and discuss the most interesting results.

### 8.4.1 Throughput times

The throughput times of the trailers is the total time between the time of arrival and time of departure. First, we see that the average throughput time of experiments 3 (almost five hours) and experiment 4 (more than 5 days), where all trucks go to the decoupling point, increased extremely. In addition, we see that the average utilization rate of the IVs is high (66% in experiment 3 and 72% in experiment 4). Therefore, we conclude that the number of IVs is not sufficient to handle the intensity. Therefore, we conduct a sensitivity analysis to provide more details about the number of IVs.

Next, we analyze the results of the experiments 7, 9, and 11, that all include the decoupling point with internal AVs (experimental factor 1d). Table 8.4 provides the average throughput times<sup>2</sup> of these experiments and the percentage difference<sup>3</sup> compared to experiment 1.

Table 8.4: Results from experiments including decoupling with internal AVs

| Intensity | Experiments |          |        |          |        |          |       |
|-----------|-------------|----------|--------|----------|--------|----------|-------|
|           | 1           |          | 7      |          | 9      |          | 11    |
|           | Avg ThrT    | Avg ThrT | Diff   | Avg ThrT | Diff   | Avg ThrT | Diff  |
| Calm      | 00:35:53    | 01:26:29 | 141.0% | 01:27:36 | 144.2% | 00:46:35 | 29.8% |
| Normal    | 00:43:41    | 01:29:52 | 105.7% | 01:27:30 | 100.3% | 00:54:31 | 24.8% |
| Busy      | 01:21:42    | 02:37:18 | 92.5%  | 02:14:30 | 64.6%  | 01:54:52 | 40.6% |

<sup>2</sup>We use the acronym Average Throughput Times (Avg ThrT) in all tables, due to space limitations.

<sup>3</sup>We use the acronym Difference (Diff) in all tables, due to space limitations.

We see that the implementation of the decoupling point with AVs increases the average throughput time. The increase of the percentage differences varies from 24.8 % to 144.2%. This can be explained as there is an additional processing time for the (de)coupling process, a limited number of available AVs, and the speed of the AVs is lower compared to traditional trucks.

Next, we analyze the effects of the manual internal vehicles compared to the internal AVs. These are experiments 6, 7, 8, 9, 10, and 11, that all include internal vehicles. Table 8.5 provides the average throughput times and the difference between these experiments.

Table 8.5: Results from experiments including decoupling point

| Intensity | Experiments |          |       |          |          |       |          |          |       |
|-----------|-------------|----------|-------|----------|----------|-------|----------|----------|-------|
|           | 6           | 7        |       | 8        | 9        |       | 10       | 11       |       |
|           | Avg ThrT    |          | Diff  | Avg ThrT |          | Diff  | Avg ThrT |          | Diff  |
| Calm      | 00:45:28    | 01:26:29 | 47.4% | 00:46:37 | 01:27:36 | 46.8% | 00:40:31 | 00:46:35 | 13.0% |
| Normal    | 00:55:57    | 01:29:52 | 37.7% | 00:56:04 | 01:27:30 | 35.9% | 00:51:25 | 00:54:31 | 5.7%  |
| Busy      | 01:29:52    | 02:37:18 | 42.9% | 02:03:57 | 02:14:30 | 7.8%  | 01:51:08 | 01:54:52 | 3.2%  |

We see multiple impacts of using manual IVs compared to internal AVs. First, we see that the average throughput time increases when AVs are used compared to manual IVs. This makes sense since the speed of the manual IVs is higher than the AVs.

Second, we see the the percentage differences decreases when the intensity is increased, except for experiment 6 & 7 in the busy intensity. It is expected that the percentage difference would be even larger when the intensity is increased. However, the number of IVs is increased when the intensity is increased (as stated in Table 8.3). Therefore, the percentage difference for experiment 8 & 9, and 10 & 11, is decreasing when the intensity is increased. This shows that the number of IV has a big impact on the average throughput time.

Last, we see that percentage difference in experiment 6 & 7 for the busy intensity increases. Table 8.6 provides the average travel time and average waiting time at the DP.

Table 8.6: Results from experiments including

| Intensity | Experiments     |          |                        |          |
|-----------|-----------------|----------|------------------------|----------|
|           | 6               | 7        | 6                      | 7        |
|           | Avg travel time |          | Avg waiting time at DP |          |
| Calm      | 00:05:07        | 00:06:44 | 00:06:18               | 00:46:09 |
| Normal    | 00:05:28        | 00:06:49 | 00:14:40               | 00:48:32 |
| Busy      | 00:07:51        | 00:08:26 | 00:55:21               | 01:49:49 |

In these experiments, half of the arriving trucks go directly to the GH. We see that in the busy scenario, the average travel time increases in the busy scenario compared to the other intensities. Therefore, the speed of the internal vehicles decreases, which results in queues at the GH. Furthermore, the average waiting time at the DP is in the busy scenario higher compared to the other intensities. This indicates that the capacity of IVs impacts the average throughput time in experiment 6 & 7. This also explains way the percentage difference between experiment 6 and 7 is high. As we concluded before, the throughput

time increases when AVs are used compared to manual IVs. Since the capacity of IV is important in experiment 6 and 7, the percentage difference in time is just as high in the busy scenario compared to the other intensities.

So, we conclude the following from the throughput times results:

- Base scenario has the lowest average throughput time;
- Average throughput time increases extremely when sending all arriving trucks to the decoupling point;
- Every implemented intervention increases the average throughput time;
- Average throughput time increases when using AVs compared to manual IVs;
- Number of IVs have a big impact on the average throughput time.

### 8.4.2 Travel times

Figure 8.2 depicts the average travel times for every experiment. We see that the average travel time is the lowest in experiment 1 with a calm intensity. This makes sense since the travel distance to go directly to the GH is the shortest. Furthermore, we see that when the intensity is increased, the average travel time is also increased. Due to the speed reduction rule, the speed of the vehicles is reduced, and therefore, congestion occurred within the hub.

Furthermore, we see that for every intervention, the average travel times decrease in the busy intensity compared to the base scenario. Experiment 5 has the lowest average travel time of the three intensities. The trucks are waiting at the TP until a dock is free at the GH, consequently, fewer trucks are waiting at the GH and therefore the speed is reduced fewer times.

Last, the DP intervention also reduces the average travel times, even though the travel distance is increased and the speed of the AVs is lower. As there is a limited number of IVs available, the supply to the GH is reduced and therefore, the number of trailers at the GH is reduced, so there is less congestion within the hub. Consequently, the speed of the vehicles is reduced fewer times.

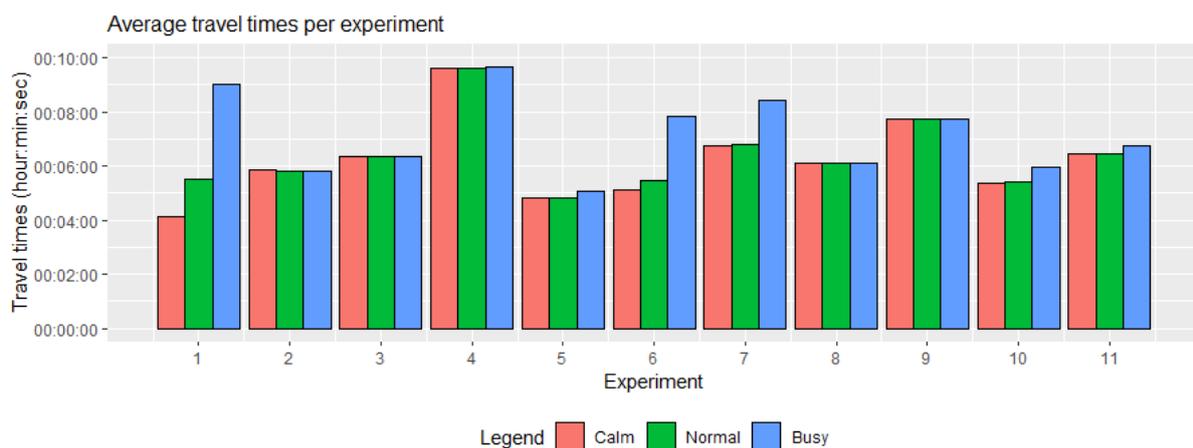


Figure 8.2: Average travel times per experiment

We conclude the following from the travel times results:

- Intensity has a big impact on the average travel times;
- The implemented interventions increase the travel distance;
- The implemented interventions reduce the travel times and congestion within the hubs.

### 8.4.3 Waiting times

To analyze the waiting times<sup>4</sup>, we use the results from the average waiting times at the GH, TP, and DP from the experiments with normal intensity. The results of these experiments are given in Table tab:WaitingTimesExp.

Table 8.7: Waiting time results from experiments

| Exp | Avg WaiT GH | Avg WaiT TP | Avg WaiT DP | Avg total WaiT <sup>5</sup> |
|-----|-------------|-------------|-------------|-----------------------------|
| 1   | 00:08:10    | 00:00:00    | 00:00:00    | 00:08:10                    |
| 2   | 00:00:00    | 00:20:39    | 00:00:00    | 00:20:39                    |
| 3   | 00:00:01    | 00:00:00    | 04:11:46    | 04:11:47                    |
| 4   | 00:00:00    | 00:00:00    | 04:23:13    | 04:23:13                    |
| 5   | 00:00:29    | 00:14:42    | 00:00:00    | 00:15:11                    |
| 6   | 00:02:21    | 00:00:00    | 00:14:40    | 00:17:02                    |
| 7   | 00:01:04    | 00:00:00    | 00:48:32    | 00:49:35                    |
| 8   | 00:00:19    | 00:09:29    | 00:06:42    | 00:16:31                    |
| 9   | 00:00:07    | 00:02:46    | 00:43:25    | 00:46:18                    |
| 10  | 00:01:03    | 00:11:43    | 00:00:53    | 00:13:39                    |
| 11  | 00:00:37    | 00:07:48    | 00:07:17    | 00:15:43                    |

The average total waiting times increase in every implemented intervention. However, the average waiting time at the GHs decreases in every implemented intervention. The waiting times are shifted from the GHs to the TP or DP. This is a positive impact in threefold, since; i) it is safer to wait at the TP, and the truck drivers can take a rest there; ii) truck driver costs are reduced since the trailers are waiting at the DP without a driver, and iii) due to planning and scheduling, the trucks and trailers can be sent to the GHs at the best moment in time.

#### Waiting time at truck parking and decoupling point

To analyze the waiting times at the TP and DP, we calculate the average waiting time per hour for the trucks that left the TP or DP that hour. We choose to show the results of the following experiments, with the reason behind it:

- Experiment 2. Busiest at the TP, since all trucks first have to go to the TP.
- Experiment 3. Busiest at the DP with manual IVs.
- Experiment 4. Busiest at the DP with AVs.
- Experiment 8. Combination of TP and DP with manual IVs.
- Experiment 11. Combination of TP, DP with AVs, and directly to GH.

<sup>4</sup>We use the acronym Waiting Time (WaiT) in tables due to space limitations.

<sup>5</sup>The total waiting time can have a deviation of one second due to rounding off, as all waiting times are calculated individual.

The results of the average waiting time per hour for experiment 2, 3, 4, 8, and 11 are depicted in Figure 8.3, Figure 8.4, Figure 8.5, Figure 8.6, and Figure 8.7 respectively.

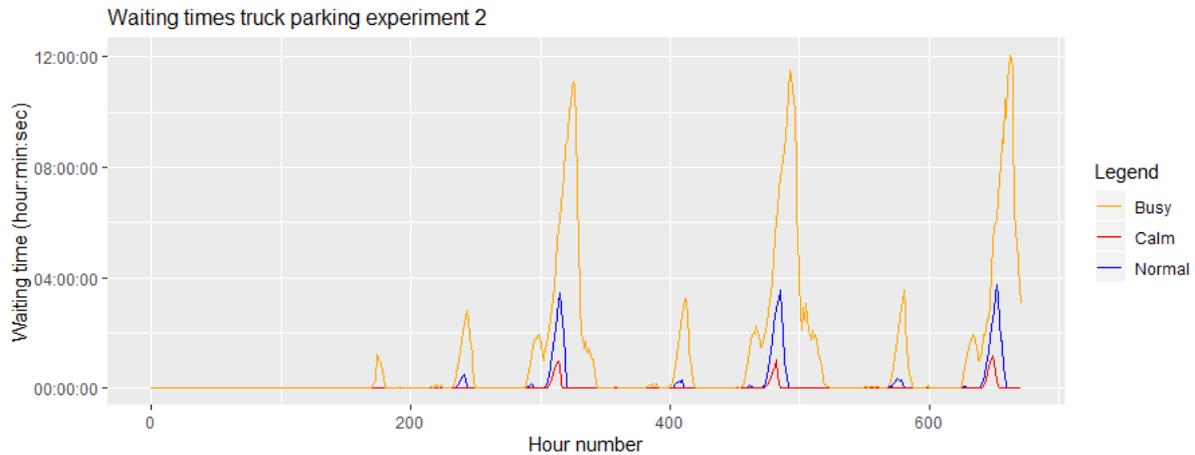


Figure 8.3: Waiting times truck parking per hour experiment 2 (every truck to TP)

We see clear peaks at the TP, especially in the busy intensity, caused by the peak on Friday in the arrival rate. The average waiting time at the TP can increase up to 12 hours for the busy intensity, up to four hours for the normal intensity, and up to an hour for the calm intensity. Furthermore, there are some small peaks caused by the peaks on Tuesday in the arrival rate.

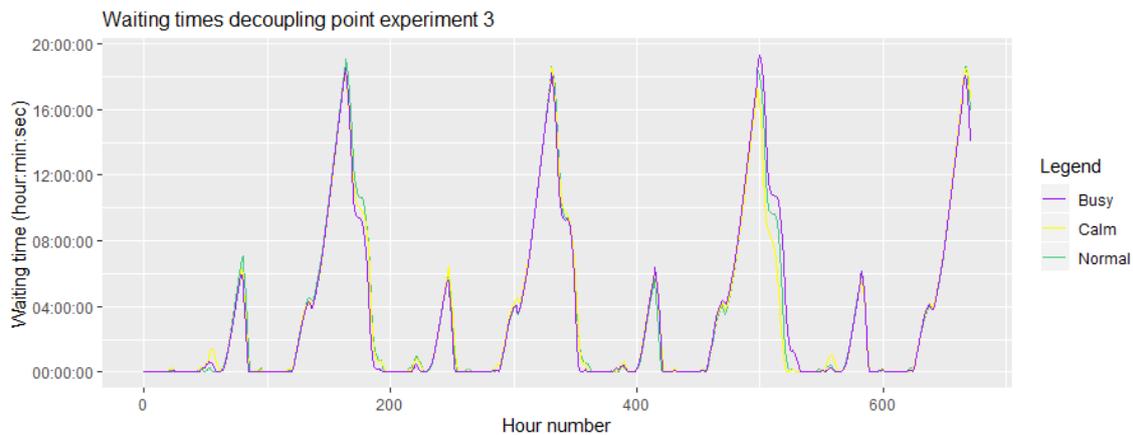


Figure 8.4: Waiting times decoupling point per hour experiment 3 (every truck to DP with manual IVs)

The average waiting time per hour at the DP are very similar for each intensity. The number of vehicles is lower in the calm intensity and increased for the busier intensities. This results in roughly the same average waiting times at the DP. Furthermore, we see two clear peaks each week. A small peak that is caused by the doubled arrival rate on Tuesday, and a big peak caused by the arrival rate that is three times as high on Friday.

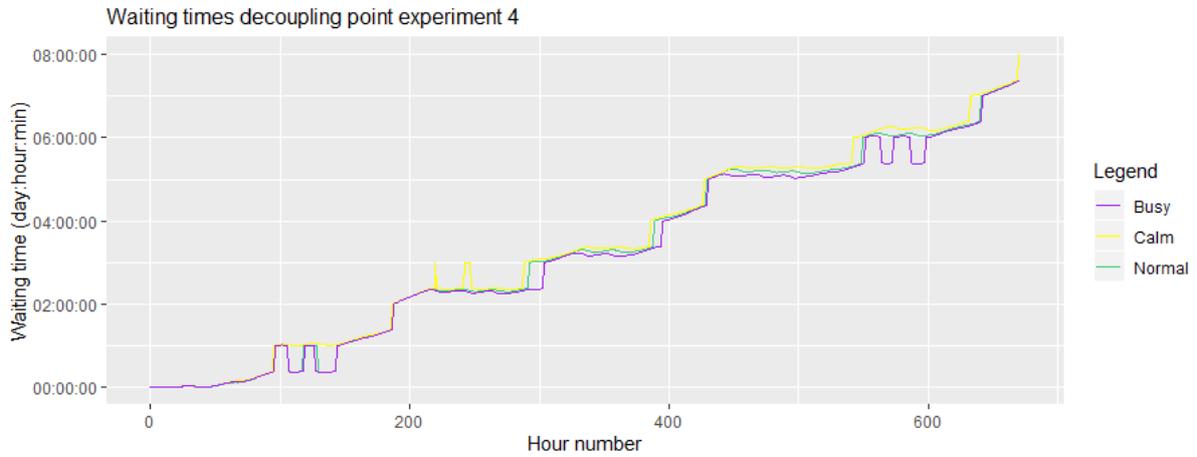


Figure 8.5: Waiting times decoupling point per hour experiment 4 (every truck to DP with internal AVs)

The average waiting time per hour at the DP in experiment 4 increases extremely. This is caused by an insufficient capacity of the AVs, which results in very long waiting times. A sensitivity analysis for the number of vehicles should provide answers about the vehicle utilization and throughput times.

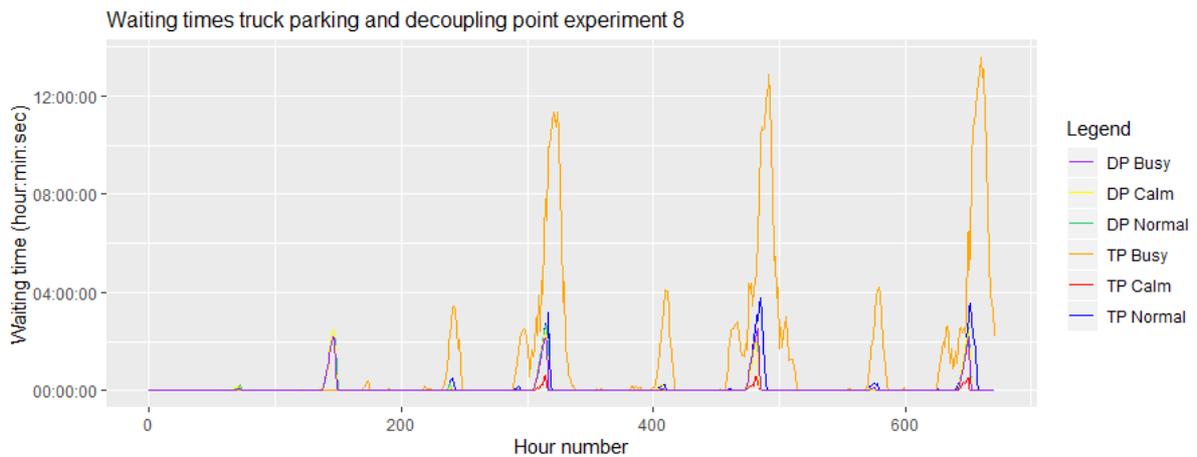


Figure 8.6: Waiting times truck parking and decoupling point per hour experiment 8 (half of trucks to TP and half of truck to DP with manual IVs)

We see that the average waiting times at the TP increases earlier and are on average higher than at the DP. This makes sense since the trucks at the TP have the lowest priority. Therefore, the trucks are waiting longer at the TP. Furthermore, the peaks are much lower on Tuesdays compared to the other experiments. Only at the TP in the busy intensity, long average waiting times developed.

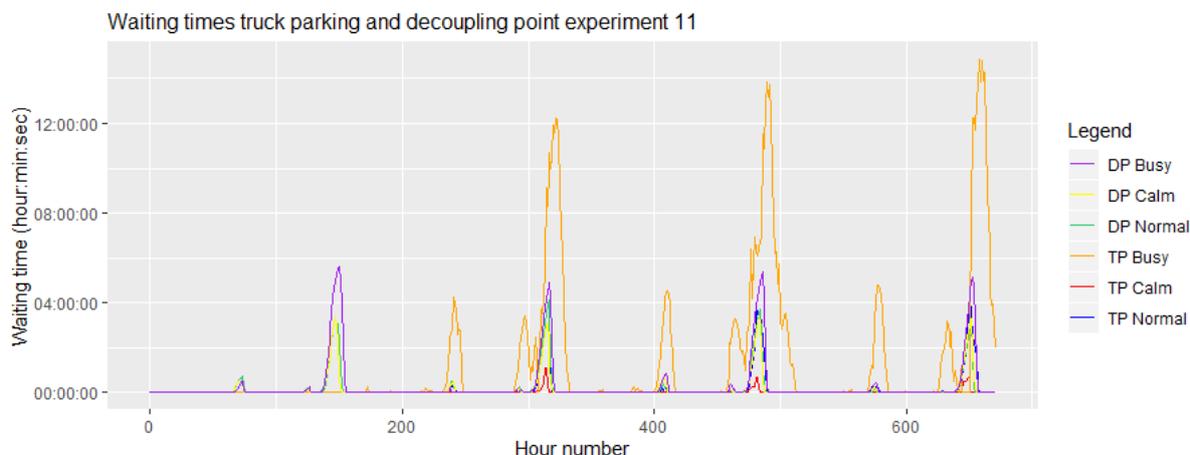


Figure 8.7: Waiting times truck parking and decoupling point per hour experiment 11 (one third of trucks directly to GH, one third of trucks to TP, and one third of truck to DP with internal AVs)

We see almost the same pattern for the average waiting time as in experiment 8. The only difference is that the average waiting times are a bit higher compared to experiment 8. In experiment 11, a proportion of the arriving trucks go directly to the GH, and therefore, the trucks at the TP have to wait longer on average. Furthermore, the speed of the AVs is lower which results in longer waiting times for the trailers at the DP.

We conclude the following from the waiting times results:

- The average waiting times increase with the implemented interventions;
- The waiting time shift from the GHs to the TP and DP;
- Peaks in the arrival rate causes peaks in the average waiting times at the TP and DP;
- The average waiting times are increased earlier at the TP than at the DP;
- The average waiting times are higher at the TP than at the DP;
- Insufficient capacity on the internal handling vehicles causes extreme waiting times at the DP;
- AVs increases the average waiting times compared to manual IVs.

#### 8.4.4 Truck times

The truck time<sup>6</sup> is the time that a trailer is on a truck. Table 8.8 provides the average throughput time, the average truck time, and the percentage difference of all experiments.

Table 8.8: Results average truck time compared to average throughput time

| Exp | Calm     |          |         | Normal   |          |         | Busy     |          |         |
|-----|----------|----------|---------|----------|----------|---------|----------|----------|---------|
|     | Avg ThrT | Avg TrcT | Diff    | Avg ThrT | Avg TrcT | Diff    | Avg ThrT | Avg TrcT | Diff    |
| 1   | 00:35:53 | 00:35:53 | 0.00%   | 00:43:41 | 00:43:41 | 0.00%   | 01:21:42 | 01:21:42 | 0.00%   |
| 2   | 00:40:30 | 00:40:30 | 0.00%   | 00:56:29 | 00:56:29 | 0.00%   | 02:36:23 | 02:36:23 | 0.00%   |
| 3   | 04:51:20 | 00:07:01 | -97.59% | 04:55:09 | 00:08:25 | -97.15% | 04:59:46 | 00:24:07 | -91.96% |

<sup>6</sup>Due to space limitations, we use the acronym Truck Time (TrcT) in the table

|                |          |          |         |          |          |         |          |          |         |
|----------------|----------|----------|---------|----------|----------|---------|----------|----------|---------|
| 4 <sup>7</sup> | 5:04:35  | 00:07:00 | -       | 5:00:00  | 00:08:27 | -       | 4:20:28  | 00:23:56 | -       |
| 5              | 00:37:52 | 00:37:52 | 0.00%   | 00:50:01 | 00:50:01 | 0.00%   | 01:59:06 | 01:59:06 | 0.00%   |
| 6              | 00:45:28 | 00:20:44 | -54.39% | 00:55:57 | 00:22:17 | -60.17% | 01:45:56 | 00:28:05 | -73.49% |
| 7              | 01:26:29 | 00:20:29 | -76.32% | 01:29:52 | 00:21:23 | -76.20% | 02:37:18 | 00:25:43 | -83.65% |
| 8              | 00:46:37 | 00:22:26 | -51.86% | 00:56:04 | 00:31:03 | -44.64% | 02:03:57 | 01:39:08 | -20.01% |
| 9              | 01:27:36 | 00:21:37 | -75.33% | 01:27:30 | 00:24:20 | -72.20% | 02:14:30 | 01:07:41 | -49.68% |
| 10             | 00:40:31 | 00:27:40 | -31.71% | 00:51:25 | 00:37:49 | -26.46% | 01:51:08 | 01:31:35 | -17.59% |
| 11             | 00:46:35 | 00:26:26 | -43.26% | 00:54:31 | 00:33:39 | -38.26% | 01:54:52 | 01:29:25 | -22.17% |

The average truck time is lower in every experiment where the decoupling point is used, while the average truck time stays the same in the experiments where the decoupling point is not used. In experiment 4, the truck time is low compared to the average throughput time of more than four days, so we do not calculate the percentage difference. In the smart yard scenario (experiment 11), we see that the percentage difference varies from -22.17% to -43.26%. These results show that the implementations towards a smart yard can decrease the total time that a truck driver needs to be within a hub. From the truck times results, we conclude that the decoupling point intervention decreases the time that a trailer is on a truck within the hub. Therefore, the waiting time and the total time that a truck driver is within a hub are decreased.

#### 8.4.5 Utilization rates

The utilization rate of the TP and DP is the fraction of relative number of places occupied. This means that the utilization rate is the average over the utilization rates for every available spot. Figure 8.8 and Figure 8.9 show the utilization rate per experiment for the three intensities of the TP and DP respectively. Although some experiments do not include the use of the TP or DP, we include every experiment to show the effects.

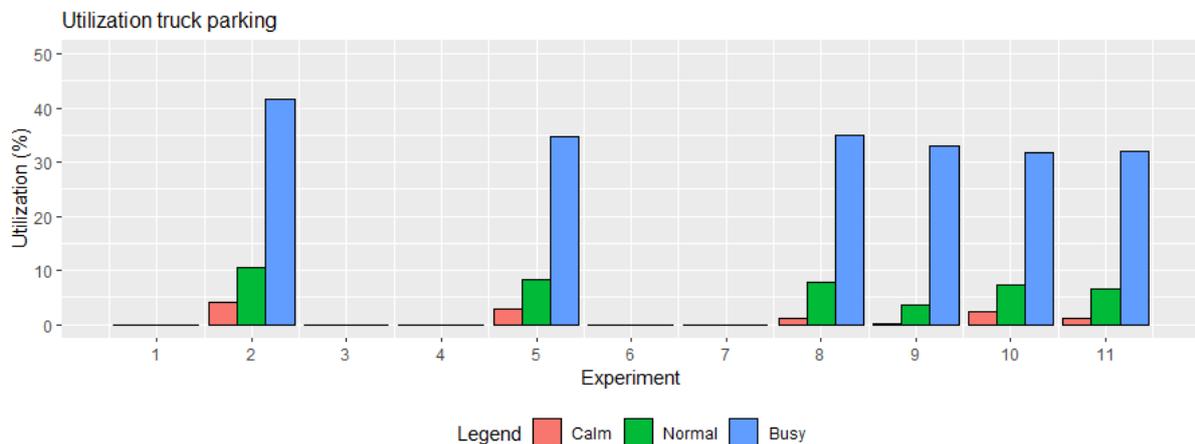


Figure 8.8: Utilization truck parking per experiment

We see that the utilization of every experiment per intensity slightly decreases when the proportion to the TP is decreased. This makes sense since the number of total arriving trucks is lower. Furthermore, in

<sup>7</sup>The average throughput times of experiment 4 are given in (day:hour:minute).

every experiment, we see a big increase in the utilization rate when the intensity is increased. In the busy intensity, the utilization rates are very high and result in long waiting times as shown in Subsection 8.4.3.

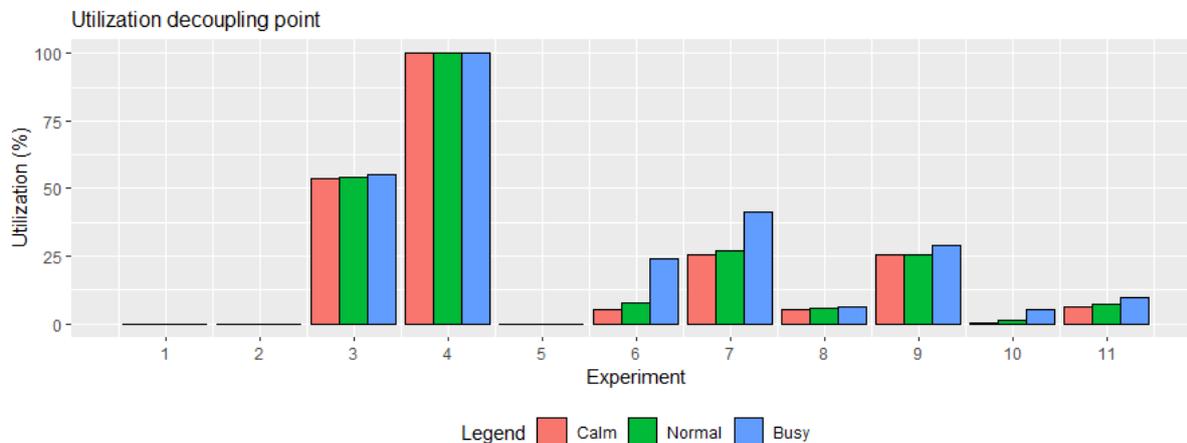


Figure 8.9: Utilization decoupling point per experiment

The utilization rates in experiment 3 & 4 are extremely high, which results in long waiting times and thus in long total throughput times. Furthermore, the utilization rates only increase slightly when the intensity is increased, as the utilization rates are roughly the same per experiment.

Although the utilization rates are lower than 50% for every experiment (except experiment 3 & 4), there is more to it. The effects of the peaks in the arrival rate are not shown in the average utilization. As we discussed in Subsection 8.4.3, the peak moments cause peaks in the waiting times at the TP and DP. Table J.1 in Appendix J provides the number of trailers for every experiment that could not enter the TP or DP directly. This means that at the moment of the arrival of a trailer at the TP or DP, the TP or DP was full at that moment and was sent to a buffer.

Increasing the capacity at the TP or DP will not have any effect, since this will not decrease the throughput times. Instead, the capacity of the IVs should be increased or the arrivals should be regulated to not have peak moments. This can be accomplished by introducing connectivity, so that the trucks arrive on the exact time at the smart yard that is needed.

## 8.5 Sensitivity analysis

We conduct a sensitivity analysis for the number of internal vehicles. We experiment with a range of 1 to 20 internal vehicles in the normal, calm, and busy arriving truck intensity. We use the path proportions stated in experiment 10 (for internal manual vehicles) and experiment 11 (for internal AVs), as describe in Table 8.2. The other experimental settings are depicted in Figure 7.3. The following two figures show the effects on the average throughput time from the experiments of the sensitivity analysis:

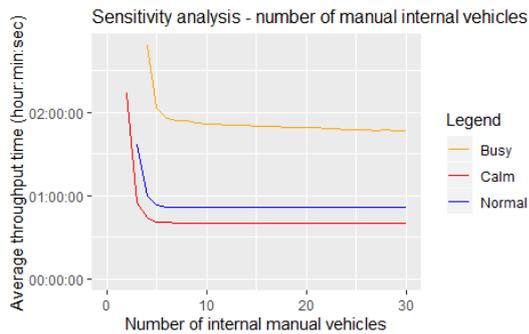


Figure 8.10: Sensitivity analysis - Throughput time - Number of manual IVs

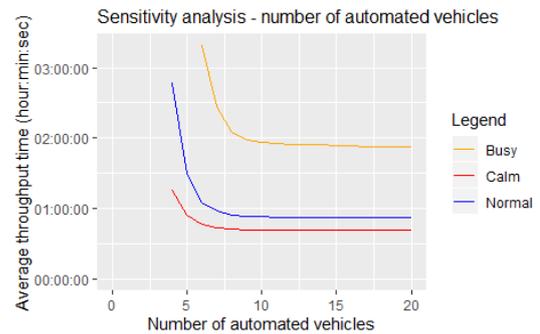


Figure 8.11: Sensitivity analysis - Throughput time - Number of AVs

Figure 8.10 shows that at least two manual IVs are needed for the calm intensity, three for the normal intensity, and four for the busy intensity, to have an average throughput time below three hours. The average throughput times drastically increases when the number of vehicles is decreased. Furthermore, the average throughput time decreases when the number of vehicles is increased. In the calm and normal intensity, the average throughput time stabilizes when the number of internal manual vehicles is six or more. For the busy intensity, the average throughput time does not stabilize but decreases with a few seconds when the number of internal manual vehicles is seven or more.

Figure 8.11 shows that the number of AVs should be higher compared to the number of manual vehicles, if the average throughput time should be smaller than three hours. This makes sense as the speed of the AV is lower than the speed of the manual vehicle. Therefore, the average throughput time also decreases less when the number of AVs is increased. Furthermore, around eight AVs the average throughput time stabilizes in the calm and normal intensity. The average throughput time still decreases with a few seconds for the busy intensity, after the number of AVs is ten or more.

The effects of the average utilization from the same experiments of the sensitivity analysis are shown in the following two figures:

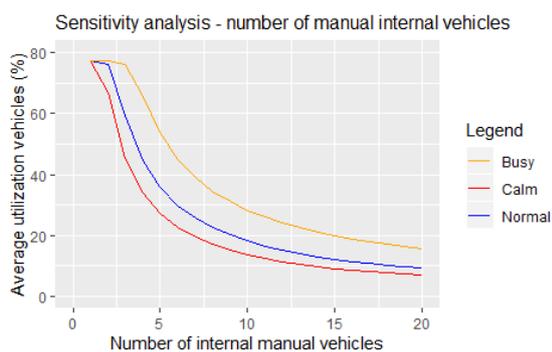


Figure 8.12: Sensitivity analysis - Utilization - Number of manual IVs

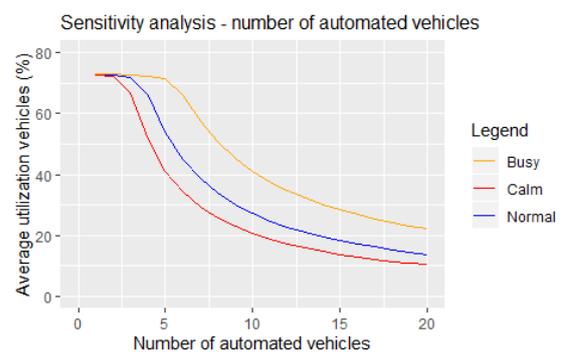


Figure 8.13: Sensitivity analysis - Utilization - Number of AVs

Figure 8.12 and 8.13 shows that the average utilization for both the manual IVs and AVs is high when the number of vehicles is low. This also explains why the average throughput times in some experiments are extremely high. The average utilization is not higher than 80 %, since the time that the AVs are driving empty is not included in the utilization. An increase in the number of vehicles results in a lower average utilization for both the IVs. Furthermore, the average utilization of the AVs is on average higher than of the manual IVs. This makes sense since the speed of the AVs is lower and consequently, the AVs are occupied for a longer period.

## **8.6 Conclusion**

This chapter provided an analysis of the experimental configurations and results. For the experimental settings, we use a warm-up period of one week, a run time of four weeks, and three replications should be conducted to acquire a significance level of 95%. In total, 33 experiments are conducted and the results of five output variables are analyzed.

The results of the throughput times revealed that the interventions increase the average throughput and waiting times. However, the waiting times shifted from the GHs to the TP and the DP. Moreover, the analysis on the results of the travel times revealed that implemented interventions decrease the travel times when the intensity is increased. This means that the congestion within the hub is decreased. Also, the results of the truck times revealed that when implementing the DP intervention, the waiting time and total time that a truck driver needs to be present at the hub are decreased. Last, the number of vehicles used at the DP has a big impact on the average waiting times and thus the average throughput times.

Although we provided the impacts and effectiveness of a smart yard, we did not provide any quantitative answers on the impacts and effectiveness in the ideal situation for the use case.

## 9. Conclusions and recommendations

This chapter gives the conclusions and recommendations of the research. In Section 9.1 we present the main conclusions. We discuss the limitations in Section 9.2. Next, in Section 9.3 we describe the contributions. Finally, we present the recommendations in Section 9.4.

### 9.1 Conclusions

In this research, the following main research question is addressed:

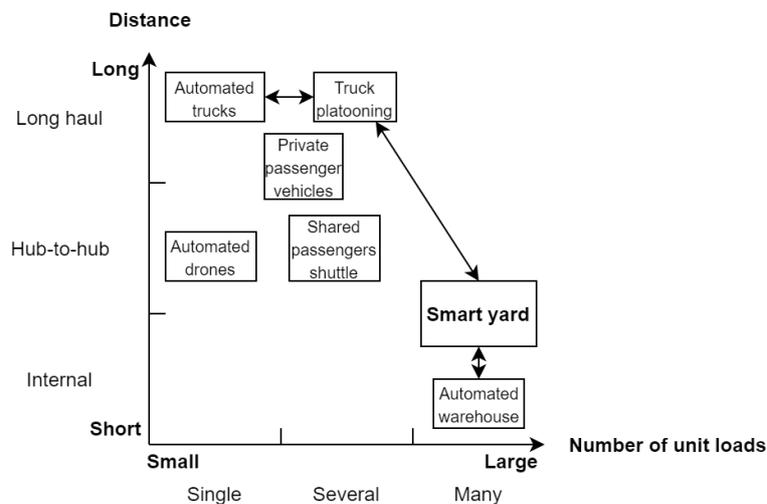
***How to define the characteristics of Connected Automated Transport (CAT) and smart yard processes, and how to analyze their potential impact and effectiveness using simulation?***

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

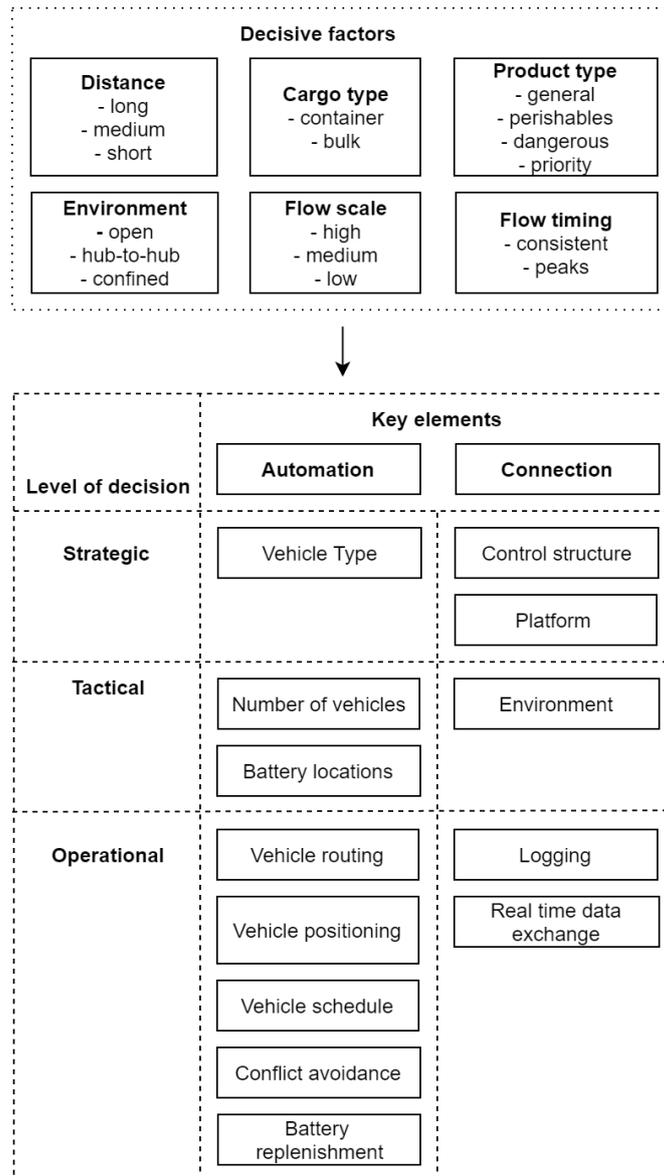
#### 1. How should CAT be defined?

We discussed the terms for self-driving cars and concluded that we refer to the vehicles used in a smart yard as automated vehicles. Furthermore, we discussed the literature of CAT logistics and smart logistics and stated the developments of CAT in the literature study. CAT concepts are used to make the transition from regular yards to smart yards. From here, we concluded that a theoretical framework for CAT and smart yards is necessary. This resulted in two frameworks, namely a framework for CAT concepts and applications, and a conceptual framework for smart yards.

The framework for CAT concepts and applications visualizes the positions and connections of the smart yard and other CAT concepts and applications. This framework is shown in the figure below.



Furthermore, the conceptual framework for smart yards can be used to determine the characteristics of a smart yard. In this framework, we defined key elements and decisive factors. The key elements of a smart yard and the decisions that need to be taken are provided. The decisive factors, that can be determined based on the characteristics of a case, should substantiate the decisions on the key elements. The framework is shown in the figure below.

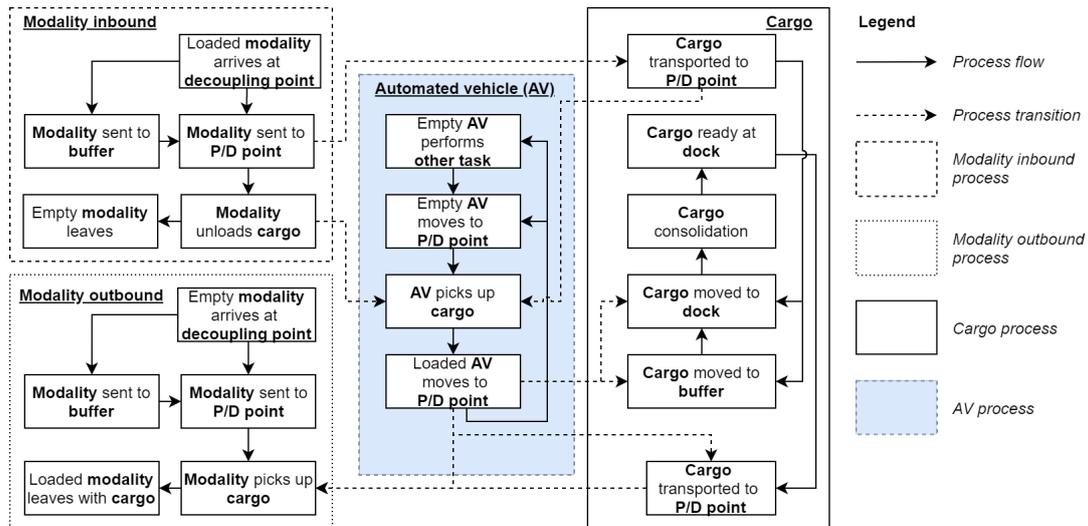


## 2. How should the generic smart yard processes be defined?

We defined the generic smart yard processes by first describing the current process at various logistics service providers and stating the elements that are implemented in a smart yard. The elements that should be implemented in a smart yard are the following:

- Automated vehicles;
- Decoupling point;
- Connectivity through a seamlessly integrated network system.

The generic processes of the physical smart yard are depicted in the figure below.



Furthermore, we defined the digital smart yard as a seamlessly integrated network system in which information or data is exchanged. Information flows between stakeholders, which is also defined. We applied the generic smart yard processes to the various use cases included in the CATALYST living lab project and defined a smart yard concept for each use case.

### 3. How to construct a simulation model for a smart yard?

To construct the simulation model, we first constructed a conceptual model based on the smart yard processes and the case description of Schiphol. In the conceptual model, we described multiple aspects, such as the scope, the assumptions, and the level of detail. Furthermore, we described the process of the simulation model by a high-level flowchart and described individual events. This conceptual model is implemented in the discrete-event simulation software Tecnomatix Plant Simulation from Siemens. We described the computer model and used several verification and validation techniques to ensure that the model is correct and sufficiently accurate. We concluded that the simulation model behaved as expected. With the approval from the subject experts from Schiphol, we assumed that the simulation is validated.

### 4. What is the potential impact and effectiveness of a smart yard?

From a theoretical point of view, we defined four potential impacts. These potential impacts are the following:

- Increased process efficiency;
- Peak shaving;
- Increased safety;
- Reduced congestion.

Moreover, we conducted a simulation study to show the impact and effectiveness of a smart yard of various output measurements. We showed the results on the throughput-, waiting-, travel-, truck times, and utilization rates output variables. The analysis of the results of the simulation model revealed that the implemented interventions increase the throughput time of trailers. Also, the waiting time of the trailers is increased when implementing an intervention. However, the waiting time shifts from the ground handlers to the truck parking and the decoupling point. The trailers that are waiting at the decoupling point are waiting without any driver, which is also shown in the results of the truck times. In

addition, we showed that the congestion within the hub can be reduced with the interventions. Also, the implementation of the decoupling point intervention decreases the total time that a truck driver is within a hub and the total waiting time of a truck driver. Last, we showed that the number of internal vehicles has a big impact on the total throughput time.

## **9.2 Limitations**

This research contains limitations that need to be addressed. First, the lack of acquired data limited the validation of the simulation model. Second, unfortunately, due to circumstances it was not possible to visit the Schiphol area and see the processes from up close. This limited and delayed the research, as it was inconvenient to get in contact with the people involved. Third, the defined smart yard concept is idealistic and limitations on legal aspects could occur. Also, the companies do not want to lose their competitive advantage and need to be convinced that the smart yard concept is beneficial. Fourth, we assumed that the arriving trailers have the same characteristics, the trailers equals one full truckload, and the unloading operations have a predetermined duration. Making these processes stochastic may influence the results. Last, we assumed road obstacles and vehicle maneuvering and conflicts to be included in the travel speed of the vehicles. All these assumptions should be incorporated in the simulation model in further research, to make the model more accurate. Thus, the outcome of this research should be used as an indication for the first insights in smart yards.

## **9.3 Contributions**

### **Theoretical**

Our research contributes to the theory by defining the characteristics of CAT and providing a conceptual framework for smart yards. Other researchers can use this to further extend the concept of smart yards and research the impact and effectiveness. Also, we suggest to other researchers to work on the simulation model. First, the Schiphol simulation model should be extended to provide answers for the Schiphol case. Afterward, a simulation model can be developed for a generic smart yard. This generic smart yard simulation model could be used to show the impacts and effectiveness of new use cases.

### **Practical**

For the CATALYST living lab, our research contributes to understanding the smart yard concept better. The characteristics of CAT are defined and we provided the generic process of a smart yard. Furthermore, the simulation model is shown to all stakeholders of the smart yard working group from the CATALYST living lab. Although the simulation model does not provide answers for the Schiphol case, the stakeholders at Schiphol were triggered to continue working on the smart yard concept. Also, stakeholders from the other use cases saw the potential of a simulation study and the smart yard concept.

## **9.4 Recommendations**

Based on this research, we provide the following recommendations for further research. First, we recommend providing more details and make the factors quantitative in the conceptual framework for smart yards, so that the characteristics of a case can be easier related to this framework. Furthermore, in the conceptual smart yard framework the handling and job type factors should be research further, so that these factors can be categorized and the impact of these factors is known. Eventually, the conceptual model should be able to provide answers for the characteristics of the smart yard, based on the characteristics of the decisive factors. The conceptual framework should first be tested at multiple logistics service providers.

Second, we recommend to develop similar simulation models for the other use cases included in the CATALYST living lab and assess the potential impacts and effectiveness of their smart yard concepts. Since the other use cases are a different type of logistics service provider (two seaports and a distribution center), other impacts and effectiveness can be revealed. Also, it may be possible that other implementations are needed for a smart yard at different types of logistics service providers.

Third, we suggest further research on the connectivity part of CAT. It should be researched what the effects of connectivity will be and what that will mean for smart yards. Potentially, if the arrivals of trucks can be regulated by the seamlessly integrated network, a truck parking or a decoupling point are no longer necessary. Furthermore, planning and scheduling algorithms based on real-time information through connectivity might influence the potential impacts and effectiveness.

Fourth, we recommend further research on the impact on aspects such as, e.g., the legal, economic, and environmental.

Also, we recommend to find the ideal situation for the use case. This means that the optimal values for the experimental factors needs to be found. From there, we also recommend to provide quantitative answers on the impacts and effectiveness of a smart yard. For example, provide an answer on how much the average throughput time can increase when a smart yard is implemented.

Last, further research is needed to provide answers from the simulation model for the Schiphol use case. First, accurate data should be collected that can be used as input for the simulation model. Furthermore, the whole community of Schiphol needs to be involved to make agreements on the smart yard concept and the conceptual model. We recommend to further extend the simulation model and implement the following.

First, we recommend to increase the recreation of the real life situation of Schiphol in the simulation model further, by implementing the other two ground handlers. This should also provide an answer if one decoupling point is feasible. Second, include the import process, so that cargo from the aircraft are stored at the ground handler and cargo is picked up by trucks. Furthermore, include stochastic processes such as truckloads, unloading operations, and (de)coupling operations. Also, included ultimate delivery times for the export, since the aircraft have a tight schedule and cannot be delayed. The performance of the on time deliveries can be measured when the latest delivery times are included. Next, we recommend including a milkrun export, so that this process can be researched further. All these processes can be improved by planning and scheduling algorithms. For example, when ultimate delivery times are included, the order of which cargo should be delivered to the ground handler should be changed, so that the cargo is always on time and not waiting too long at the ground handler. Therefore, we also recommend including planning and scheduling algorithms.

Besides the implementations to recreate the Schiphol scenario, we recommend the following to increase the real life situation of smart yards in the simulation model. We recommend to include road obstacles, e.g., passenger vehicles, pedestrians, and roundabouts. Furthermore, conflict avoidance and maneuvering of the internal vehicles should be included. At last, the automatic vehicles should be charged. Therefore, we recommend including charging stations and charging strategies.

The impact and effectiveness of all these recommendations should be further researched.

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# Appendices

## A. General questionnaire smart yards

### Description questionnaire

The purpose of this questionnaire is to define the factors that classify a smart yard (taxonomy) at logistics service providers. A smart yard functions as a coupling point area for cargo between modalities. The questions do not have to be answered in detail. Therefore, try to describe the answers as generally as possible.

### Questions

1. What does the process flow of cargo look like?
2. What does the infrastructure within the company area look like?
3. Which parties are involved in the transport of cargo?
4. What kind of freight types are transported?
5. What kind of product types are transported?
6. What does the coupling of cargo between two parties look like?
7. Which means of transport are used within the process?
8. How much loading on average is transported each day?
9. How many loads on average are done each day?
10. What does the demand pattern look like?

### Data

The purpose of this section, is to provide values for the data as detailed as possible for the topics below.

- *Trip data*
  - Arrival times modalities (amount per period)
  - Processing times (duration)
  - loading times (duration)
- *Order data*
  - Time windows modalities
- *Cargo data*
  - Volumes (amount)
  - Cargo dimensions (weight / length)
- *Maintenance data*
  - Planned maintenance handling vehicles (duration / frequency)
  - Failure handling vehicles (duration / frequency)
- *Geographical data*
  - Docks
  - Parking places
  - Map / drawings / 3D models

## B. Case descriptions CATALYST living lab

### Zeeland case

North Sea Port (NSP) is a merger between two ports authorities, consisting of the ports of Flushing, Terneuzen, and Ghent. The multimodal port is ranked fifth in the Hamburg - Le Havre range, ranked eighth in European seaports and ranked third regarding added value. The total transshipped cargo volume was 131.4 million tons in 2019, consisting of breakbulk, dry bulk, and container transshipment. The total amount of transshipped containers in 2019 was approximately 330.000 TEU. In collaboration with the CATALYST living lab and NSP, the Zeeland case has been started for the deployment of AVs and a central gate in the Port of Flushing, to optimize the transport and terminal operations. The central gate functions as a central parking and a facility center for trucks, in combination with pre-gate facilities to optimize the transport between the central gate and terminals. The Zeeland case is the research of autonomous transport at a central gate of NSP. We use the term NSP to describe the seaport area.

### Process NSP

There are multiple terminals located at NSP, which all have value-added services. This means that the cargo is not only transshipped, but extra services are carried out at the warehouses. For example, bananas are unpacked at a warehouse, to start the ripening process. The bananas end up with the exact number of ripening days in the supermarket, which is a value-added service. The process flow at NSP, which applies to all terminals, is shown in Figure B.1.

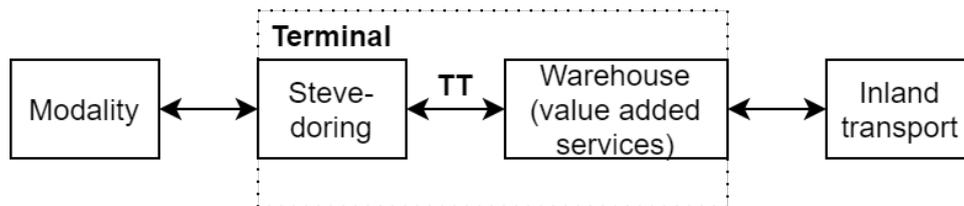


Figure B.1: Current process NSP

For the import, a modality (e.g., barges, sea vessels) arrives at a terminal and stevedore operations are carried out at a quay. In the warehouse, the cargo is consolidated (value-added services) and made ready for hinterland transport. Most of the time, the transportation is done by trucks, but other modalities (e.g., train and inland barges) are used as well. The transportation of cargo at the terminal is either done with trailers or containers on a chassis by a Terminal Tractor (TT). When a trailer is used, the truck driver keeps their trailer. Therefore, the truck drives to a warehouse where the cargo is (un)loaded, and when the cargo in the trailer is ready the truck drives away. A container can be consolidated before the arrival of a truck and stored temporarily. When the truck arrives at the terminal, the container can be placed on a chassis by using a reach stacker and the truck transports the cargo inland.

For the export, a truck arrives at the terminal and two general cargo types are used (trailer and container). The trailers are docked at a warehouse and containers are decoupled by using a reach stacker. In the warehouse, the cargo is consolidated and made ready for transport by various modalities.

### Taxonomy NSP

The characteristics of the current process at NSP are shown in Table B.1.

Table B.1: Taxonomy NSP

| Type         | Characteristics  |
|--------------|--|
| Modalities   | Vessel, truck, train   |
| Distance     | long   |
| Cargo type   | trailer, containers on chassis   |
| Product type | general, reefer, dangerous good  |
| Environment  | open road, mixed traffic   |
| Flow scale   | 200 trucks/day (big terminal), 100 trucks/day (average terminal), 40 trucks/day (small terminal) |
| Flow timing  | peaks around 7-9 h (morning) and 13-14 h (afternoon)   |
| Handling     | reach stacker for containers on chassis, decoupling trailer/chassis                              |
| Job type     | pick up, drop off, fill own trailer  |

### Smart yard motives NSP

There are multiple motives for a smart yard, that will improve the processes at NSP. First of all, the terminals are not able to handle the peaks at the busiest time, and in quiet times the capacity is too high. So, the terminal capacity is not utilized optimally, and therefore peak shaving needs to be done. Furthermore, the traffic situation at NSP is unsafe, as there is not enough parking space within the NSP area or at the terminals, and trucks have to park alongside the road. In addition, other safety issues as, e.g., cargo protection and illegal or unwanted transportation of passengers are also issues that needs to be dealt with. Finally, the whole pre-terminal process for truck drivers is not optimized as the administrative tasks take a lot of time. Implementation of a central gate with a smart yard might result in the following benefits:

- Increased safety in the NSP area
- Better use of the capacity at the terminal
- Reduced waiting times for truck drivers
- Reduced throughput times for cargo
- Increased efficiency throughout the NSP processes

### Scenarios

Four scenarios have been developed to research the deployment of AVs and the central gate. The scenarios are as follows:

#### 1. Current situation

The current situation will set a benchmark, to compare to the other scenarios.

#### 2. Central gate as decoupling point, traditional truck connection with terminals

Incoming and outgoing transportation can (de)couple cargo at the central gate. Yard tractors will pick up and drop cargo from the central gate and the terminals. This may resolve traffic issues, capacity problems, and waiting times for truck drivers.

#### 3. Central gate as decoupling point, AV connection with terminals

Incoming and outgoing transportation can (de)couple cargo at the central gate. AVs will pick up and drop cargo from the central gate and terminals. This scenario can be seen as a smart yard.

This may resolve traffic issues, capacity problems, waiting times, and increases the predictability of processes.

#### 4. **Completely autonomous transportation system**

Smart yard scenario with pick up and delivery of cargo at the central gate by AVs from the hinterland. This may resolve traffic issues, capacity problems, waiting times, and increases the predictability of the whole supply chain processes.

### **Smart yard concept NSP**

Figure B.2 shows the concept for the smart yard in NSP. The physical smart yard is demarcated by the striped square and the digital smart yard by the dotted line. When the truck driver arrives at the central gate, it is checked-in digitally and it drives to the designated parking spot to decouple the cargo. The cargo is decoupled and transported to the terminal. At the terminal, the cargo is loaded and/or unloaded. Then the cargo is transported by AVs back to the central gate, where it is decoupled. The truck then picks up the cargo and checks out.

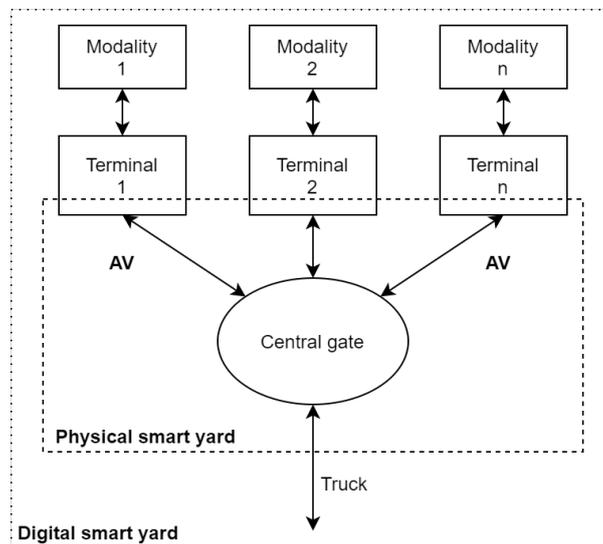


Figure B.2: Smart yard concept NSP

### **Impacts**

The first impact of the implementation of a smart yard is peak shaving. Since the central gate will function as a buffer and the arrivals can be regulated, as the AVs can pickup and drop-off the cargo when the terminal is ready. Consequently, the deliveries at the terminals will be distributed over the day. Second, by dropping and picking up the cargo in the central gate area by AVs, fewer trucks need to go to the NSP area and AVs drive safer. This may increase traffic safety as the trucks no longer need to park alongside the road. Furthermore, the throughput time of the trucks may decrease as the waiting times may reduce and the truck drivers can take their rest while the trailer is being filled. Also, the efficiency of the NSP process may increase due to a more predictable process, therefore the planning can be optimized. Last, the registration procedure in the pre-terminal process will be done digitally, which may result in increased efficiency.

### **Central gate concept**

The central gate is a centralized facility that initially will function as a truck parking (buffer) with extra value added services. A decoupling point at the central gate will follow where cargo can be (de)coupled. The coupling between trucks and AVs is made, to transport the cargo between the terminals and the central gate by AVs. Besides a decoupling point, the central gate functions as temporary storage for cargo. The central gate concept is developed for scenario five and six (as described in the scenarios paragraph above). This central gate concept is a concrete plan to implement this within the NSP area. This plan consists of a location, layout, and extra services. Different layouts for the traffic and decoupling between AVs and traditional trucks at the central gate are considered and is going to be researched. The following central gate concepts are considered:

1. **Mixed traffic**

The traditional and autonomous flows are mixed in the central gate area. Decoupling is done by traditional trucks and AVs.

2. **Separated traffic**

Two separated areas for traditional - and autonomous flow. Traditional trucks and AVs will drop off and pick-up the cargo in a dedicated area. A specialized driver transports the cargo between the two dedicated areas. This transportation is done by a yard tractor or an automated yard tractor with human guidance. Decoupling is handled by the specialized chauffeur.

3. **Dynamic traffic with time frames**

Two dynamic parking areas to separate the manual and automated vehicle traffic flow. Traditional trucks drop off and pick-up cargo in the assigned parking area (in that time frame) and AVs in their assigned parking area. After a certain time, the assignment of the parking areas is swapped around. After the swap, the AVs can pick-up the dropped cargo from the truck, and vice versa. In this way, the traffic flows stay separated and the cargo does not have to be transported between the two parking areas, as it stays in the assigned parking area.

The central gate will include a service area, where facilities as truck maintenance and cleaning, fuel station, overnight stays, and restaurants/shops are included. The central gate and the extra facilities should make it more attractive to use NSP as a transportation route.

## Port of Moerdijk

The Port of Moerdijk (PoM) is a multimodal (rail, water, road, and pipelines) port located in Moerdijk. In 2018, the total handled cargo volume was 18.2 million tons, consisting mostly of wet bulk, dry bulk, and containers. Over 400 companies are located in the port area. In collaboration with the CATALYST living lab and PoM, research has been started for the deployment of automated vehicles (AVs) and an external parking place in the PoM, to optimize the efficiency at reasonable costs within the port.

### Process PoM

Multiple terminals and warehouses are located at PoM. Figure B.3 shows the process flow of cargo at PoM. The terminals and warehouses are independent companies. The warehouses are supplied by the terminals and the cargo needs to be transported over the open road within the PoM area.

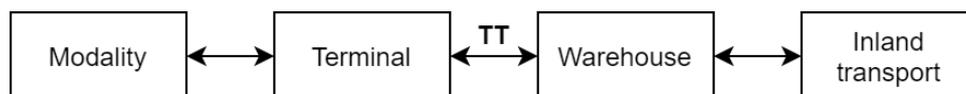


Figure B.3: Current process PoM

The cargo arrives by a modality and is unloaded at the quay of a terminal. The cargo is temporarily stored at the terminal or directly transported to an external warehouse. The transportation to the warehouse is handled by a terminal tractor (TT). In the warehouse, the cargo is consolidated and made ready for hinterland transport. When the cargo is ready, a truck picks up the cargo within a predefined time window.

### Taxonomy PoM

The characteristics of the current process at PoM are shown in Table B.2.

Table B.2: Taxonomy PoM

| Type         | Characteristics  |
|--------------|--|
| Modalities   | vessel, truck, train   |
| Distance     | medium   |
| Cargo type   | trailer, containers on chassis                                     |
| Product type | general, reefer, dangerous good                                    |
| Environment  | hub-to-hub   |
| Flow scale   | 600 full truck loads per day                                       |
| Flow timing  | peaks in morning (waiting before opening time)                     |
| Handling     | reach stacker for container on chassis, decoupling trailer/chassis |
| Job type     | pick up, drop off, fill own trailer                                |

### Smart yard motives PoM

The PoM area is a hub-to-hub environment with four entry points to the port. The two main entries monitor all incoming and outgoing traffic and the other two entries do not monitor the traffic and are closed off during the night and weekend. Due to the gate and pre-gate processes at the warehouses (e.g., registration, ID controls, and CMR control), a lot of congestion occurs at the warehouses. This also causes congestion within the port area and ultimately can result in long waiting times for truck drivers or even missed time windows at the warehouses. In addition, due to the limited parking space, the trucks have to park alongside the road, which results in even more congestion and an unsafe traffic situation. The building space within the PoM area is also limited and costly, which makes an external parking area not the preferred option. Therefore, PoM is interested if CAT concepts, besides a decoupling point, can improve the situation.

### Scenarios

The scenarios are developed to research the deployment of AVs and a decoupling point. The scenarios are as follows:

1. **Current situation**

The current situation will set a benchmark, to compare to the other scenarios.

2. **Connected transport**

The transportation trucks will be connected so that the arrival of trucks can be regulated. Based on real-time data, the trucks may be provided with better estimated arrival times, when driving towards the PoM area. This may resolve traffic issues, waiting times, and increased the predictability of the arrival process.

3. **Central parking**

Central parking will function as a buffer, where the incoming trucks can park. This may resolve the traffic issues within the PoM area.

4. **Central parking as decoupling point, AV connection with warehouses**

Central parking that functions as a decoupling point for the cargo. AVs will pick up and drop cargo from the warehouses to the central parking. This may resolve traffic issues, waiting times, and increases the predictability of processes.

5. **AV connection between terminals and warehouses**

A fixed route between terminals and warehouses to transport the cargo by AVs, instead of terminal tractors. This may resolve the traffic issues, waiting times, and increases the predictability of processes.

6. **AV connection between terminals, warehouses, and central parking**

Smart yard scenario with transportation between the terminals, warehouses, and central parking by AVs. This may resolve the traffic issues, waiting times, and increases the predictability of processes.

**Smart yard concept PoM**

The concept for the smart yard in PoM is shown in Figure B.4. The demarcation of the physical smart yard is depicted by the striped square. When the cargo is ready at a terminal, it can be transported to various warehouses within the PoM area. The transport between the terminals and warehouses is handled by AVs. The cargo is consolidated in the warehouse and made ready for transport. When the cargo is ready, it is transported to the decoupling point by AVs. At the decoupling point, the cargo is dropped-off by the AVs and picked-up by the trucks. The trucks then leave with the cargo for hinterland transport.

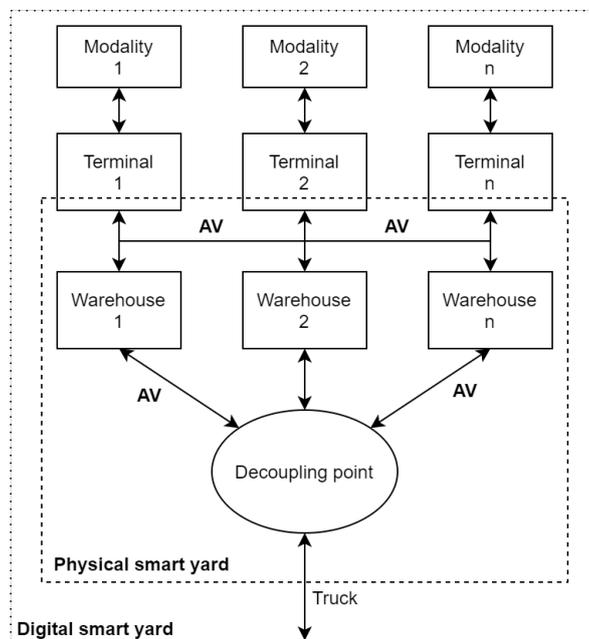


Figure B.4: Smart yard concept PoM

## Impacts

Implementation of CAT might result in the following impacts:

- Decreased throughput time for truck drivers
- Increased traffic safety
- Peak shaving

The impacts of the implementation of a smart yard at PoM are as follows. First, traffic safety may be increased and the congestion may be reduced as the trucks no longer have to be in the PoM area and the AVs drive safer. The trucks can drop-off and pick up the cargo at the decoupling point and the AVs can drop-off and pick up the cargo at any time. This may result in less waiting time for the drivers and peak shaving. If the trucks are connected, the processes may become predictable, as the arrival times of trucks are known. When the arrival times are known, better planning can be done. This means that planning can be made so that the trucks do not arrive at the same time, which may result in peak shaving. Better planning and less waiting times for the truck drivers may result in a decreased total throughput time for truck drivers.

## DPD

DPDgroup is an international parcel delivery service. DPDgroup has multiple warehouses across the world and the Netherlands. In 2019, a new "superhub" of 88.000 square meters opened in Oirschot for sorting and distributing packages. The sorting and distribution center can deal with 800.000 parcels per day. In collaborating with DPD NL and the CATALYST living lab, research has been started for the deployment on autonomous vehicles with the focus on automated docking maneuvering. We use the term DPD to describe the area of DPD NL in Oirschot.

### Process DPD

Figure B.5 shows the current process flow of cargo at DPD. The process is described more in detailed steps since the process is done internally within the DPD area.

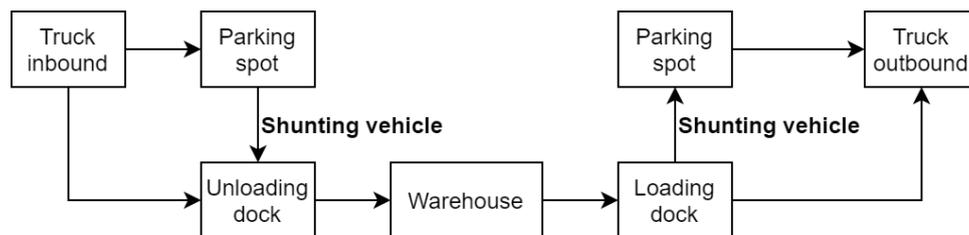


Figure B.5: Current process DPD

For the inbound process, trucks with various cargo types, or empty, arrive at the entrance of the area, where the vehicle is scanned and checked-in. The arrival time of the trucks is known in advance. From here it is determined where the vehicle should move to. In case of a swap body or a semi-trailer cargo type, the truck moves to a parking spot and decouples its cargo. The cargo is picked up by a special shunt vehicle or a tractor and moved to an unloading dock. A semi-trailer can also move directly to an unloading dock. At the docks, the cargo is consolidated and internally handled within the warehouse. For the outbound process, the cargo is consolidated into various cargo types at a loading dock. When the

cargo is ready, it is picked up by a shunting vehicle or tractor to be moved and decoupled at the parking spot. A truck then picks up the cargo directly from the loading dock or the parking spot.

### Taxonomy DPD

The characteristics of the current process at DPD are shown in Table B.3.

Table B.3: Taxonomy DPD

| Type         | Characteristics  |
|--------------|--|
| Modalities   | truck  |
| Distance     | short  |
| Cargo type   | semi-trailer, swap body  |
| Product type | general  |
| Environment  | confined   |
| Flow scale   | 300 trucks per day   |
| Flow timing  | arrivals between 15.00 and 03.00 with peak between 19.00 and 01.00 |
| Handling     | shunting vehicles  |
| Job type     | pick-up, drop-off, fill own trailer                                |

### Smart yard motives DPD

The maneuvering of vehicles and cargo and the rearward docking is a complicated operation within the DPD warehouse area. Although the speed is relatively low (10 - 15 km/ hour), it can lead to dangerous situations and possibly damage. This is because traffic is intense and a mix of shunting vehicles and external trucks is used. External drivers are to follow the one-way directions, while shunting vehicle drivers are allowed to choose their path. Besides, it is important that the (un)loading docks have high utilization and that the processing time is fast. Implementation of AVs might result in the following benefits:

- Reduced costs
- Reducing workload
- Increased efficiency
- Increased safety

### Scenarios

The scenarios are developed to research the implementation of AVs. The scenarios are as follows:

#### 1. Current situation

The current situation will set a benchmark, to compare to the other scenarios.

#### 2. Decoupling point with AVs

Trucks go to the decoupling point or directly to the unloading docks. The cargo from the decoupling point to the docks and vice versa will be transported by AVs. This may improve traffic safety, reduce the workload, and increase efficiency.

#### 3. Decoupling point with AVs for all trucks

All trucks go to the decoupling point to decouple the cargo. The cargo from the decoupling point to the docks and vice versa will be transported by AVs. This may resolve traffic issues, reduce the workload, and increase efficiency.

### Smart yard concept DPD

Figure B.6 shows the smart yard concept for DPD. The physical smart yard is demarcated by the striped square and starts at the decoupling point until the warehouse. When a truck arrives within the DPD area, it is checked-in and given the location for the decoupling. The location for the truck can either be the decoupling point or the unloading dock if the handling process is simple. At the decoupling point, the cargo is decoupled and transported by an AV to the unloading dock. At the warehouse, the cargo is consolidated. When the cargo is ready, it is transported to the decoupling point by an AV, or directly picked-up by a truck. At the decoupling point, the AV is decoupled and the truck picks up the cargo.

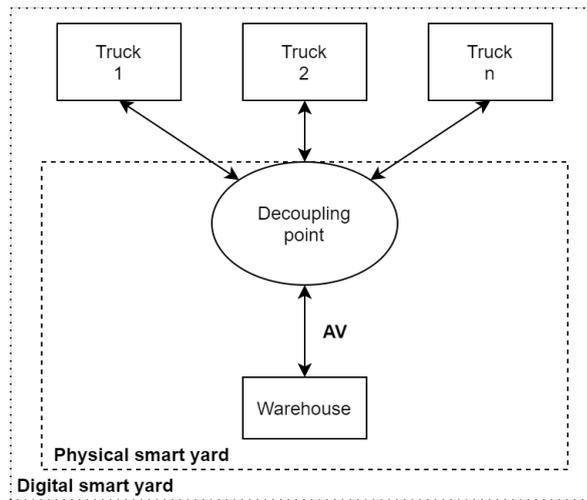


Figure B.6: Smart yard concept DPD

### Impacts

The implementation of AVs in the DPD area can have multiple impacts. First, the costs may be reduced as the AVs drive unmanned and electric. This saves personnel costs and fuel costs. Furthermore, the efficiency of the logistic process may increase. Automatic control takes over the maneuvering of the cargo and vehicle. This may reduce transportation time and docking time. Also, vehicle and cargo planning can be optimized. Last, AVs may increase traffic safety and contribute to damage avoidance.

### Summary cases

This chapter described four different cases. In this section, we give an overview of the case problems, the case scenarios, and the smart yard impacts per case. The most interesting elements are stated and a "X" indicates if the element is applicable to a case. The most interesting case problems are stated in the following table:

Table B.4: Overview of case problems

| Problem               | SH | NSP | PoM | DPD |
|-----------------------|----|-----|-----|-----|
| Peaks in demand       | X  | X   | X   |     |
| Traffic safety        | X  | X   | X   | X   |
| Limited parking space | X  | X   | X   |     |
| Congestion            | X  | X   | X   |     |

|                     |   |   |   |   |
|---------------------|---|---|---|---|
| Inefficient process | X | X | X | X |
|---------------------|---|---|---|---|

Most cases have the same problems which indicate that it is interesting to help and learn from each other. This also can indicate that these cases are not the only cases with these problems and that a smart yard can be a solution for other cases that are not involved in the CATALYST living lab.

An overview of the most interesting impacts per case is stated in the following table:

Table B.5: Overview of smart yard impacts

| Impacts                      | SH | NSP | PoM | DPD |
|------------------------------|----|-----|-----|-----|
| Peak shaving                 | X  | X   | X   |     |
| Increased traffic safety     | X  | X   | X   | X   |
| Reduced congestion           | X  | X   | X   |     |
| Increased process efficiency | X  | X   | X   | X   |

The main focus of the cases are as follows.

#### **Schiphol**

The impact of the scenarios, where the level of CAT is increasing. This research will show the logistical impacts of the smart yard concept, to get a first impression on the effectiveness. The results can be used by the other cases to determine the focus on their researches.

#### **Zeeland case**

Design of an optimal lay-out of the central gate, in combination with different traffic situations with the central gate. This optimal lay-out, where also other services are included, can be an example for other cases how to design their central gate.

#### **Port of Moerdijk**

In the PoM case, we research if a decoupling point is really necessary or that other CAT applications are able to solve the problems. This might also be interesting for the other cases. For example, if the capacity of the decoupling point is at peak hours not sufficient, connected transport can be the solution to regulated the inflow of incoming transport.

#### **DPD**

Automated docking maneuvering of AVs. This research focuses on the technical aspects of AVs. The results of this research can be used as technical inputs for the other cases.

## C. Arrival rate Schiphol

Table C.1: Arrival rate Schiphol

| <b>Begin hour</b> | <b>End hour</b> | <b>Other days</b> | <b>Tuesday</b> | <b>Friday</b> |
|-------------------|-----------------|-------------------|----------------|---------------|
| 0                 | 1               | 26                | 51             | 77            |
| 1                 | 2               | 23                | 45             | 68            |
| 2                 | 3               | 25                | 49             | 74            |
| 3                 | 4               | 25                | 50             | 75            |
| 4                 | 5               | 22                | 43             | 65            |
| 5                 | 6               | 19                | 38             | 57            |
| 6                 | 7               | 20                | 39             | 59            |
| 7                 | 8               | 16                | 32             | 48            |
| 8                 | 9               | 16                | 31             | 47            |
| 9                 | 10              | 13                | 25             | 38            |
| 10                | 11              | 12                | 23             | 35            |
| 11                | 12              | 11                | 22             | 33            |
| 12                | 13              | 19                | 38             | 57            |
| 13                | 14              | 23                | 45             | 68            |
| 14                | 15              | 25                | 49             | 74            |
| 15                | 16              | 25                | 50             | 75            |
| 16                | 17              | 30                | 59             | 89            |
| 17                | 18              | 36                | 71             | 107           |
| 18                | 19              | 40                | 79             | 119           |
| 19                | 20              | 41                | 82             | 123           |
| 20                | 21              | 43                | 85             | 128           |
| 21                | 22              | 44                | 88             | 132           |
| 22                | 23              | 38                | 76             | 114           |
| 23                | 24              | 36                | 71             | 107           |

## D. Scope and assumptions conceptual model

Table D.1: Scope and assumptions

| <b>Component</b>                    | <b>Included?</b> | <b>Substantiation</b>  |
|-------------------------------------|------------------|--|
| <b>Resources</b>                    |                  |  |
| Trucks                              | Yes              | Transports the trailers, output: throughput time                                     |
| Trailers                            | Yes              | Output: throughput and waiting time  |
| Manual shuttle vehicle              | Yes              | Transports the trailers, influences throughput and waiting time, output: utilization |
| Automated Vehicles (AVs)            | Yes              | Transports the trailers, influences throughput and waiting time, output: utilization |
| Cargo in trailers                   | No               | Assumed to be always one full truckload, further research                            |
| AV charging stations                | No               | Assumed to be charged in non-operating time  |
| Handling equipment                  | No               | Handling included in processing times  |
| <b>Entities</b>                     |                  |  |
| Docks                               | Yes              | Output: utilization  |
| Truck parking                       | Yes              | Output: utilization  |
| Decoupling point                    | Yes              | Output: utilization  |
| Road                                | Yes              | Determines the travel route  |
| Dock opening times                  | No               | No sufficient data, further research   |
| Road obstacles                      | No               | Assumed to be included in travel speed vehicles                                      |
| <b>Activities</b>                   |                  |  |
| Export process                      | Yes              | Influences throughput  |
| Import process                      | No               | Further research   |
| Drop-off at ground handler          | Yes              | Influences throughput  |
| Unloading trailer                   | Yes              | Influences throughput  |
| Waiting at truck parking            | Yes              | Influences throughput  |
| Decoupling of trailer from vehicle  | Yes              | Influences throughput  |
| Pick up trailer at decoupling point | Yes              | Influences throughput  |
| Delivery times export               | No               | No influence on KPI's, further research  |
| Milkrun export                      | No               | Only one destination, further research   |
| Maneuvering vehicles                | No               | Assumed to be included in travel speed vehicles                                      |
| AV charging                         | No               | Assumed to be charged in non-operating time  |
| Vehicle conflict avoidance          | No               | Assumed to be included in travel speed vehicles                                      |
| <b>Queues</b>                       |                  |  |
| Dock queues                         | Yes              | Output: throughput and waiting time  |
| Truck parking queues                | Yes              | Output: throughput and waiting time  |
| Decoupling point queues             | Yes              | Output: throughput and waiting time  |

## E. Level of detail conceptual model

Table E.1: Level of detail

| Component              | Detail             | Data type          | Explanation   |   |
|------------------------|--------------------|--------------------|---|---|
| <b>Resources</b>       |                    |                    |   |   |
| Truck                  | Quantity           | Integer            | Total arriving transport (experimental factor)                        |   |
|                        | Arrival pattern    | Integer            | Follows an arrival distribution                                       |   |
|                        | Truck ID           | Attribute: integer | Unique ID   |   |
|                        | CurrentLocation    | Attribute: string  | Used to determine the route to the destination                        |   |
|                        | CurrentDestination | Attribute: string  | Which destination is next, received from trailer                      |   |
|                        | Truck Parking      | Attribute: boolean | Does the truck go to the truck parking                                |   |
| Trailer                | Decouple cargo     | Attribute: boolean | Does the truck go to the decoupling point                             |   |
|                        | Quantity           | Integer            | Total arriving transport, same number as trucks (experimental factor) |   |
|                        | Arrival pattern    | Integer            | Same as truck arrival pattern   |   |
|                        | TrailerID          | Attribute: integer | Unique ID   |   |
|                        | Path               | Attribute: integer | Which path to take (experimental factor)                              |   |
|                        | CurrentLocation    | Attribute: string  | Determine the route to the destination                                |   |
| Manual shuttle vehicle | Schedule           | Attribute: list    | Destinations to visit   |   |
|                        | Truck Parking      | Attribute: boolean | Does the cargo goes to the truck parking                              |   |
|                        | Decouple cargo     | Attribute: boolean | Is the trailer decoupled  |   |
|                        | Quantity           | Integer            | Total used in system (experimental factor)                            |   |
|                        | Schedule           | Attribute: list    | Which jobs to perform   |   |
|                        | CurrentLocation    | Attribute: string  | Used to determine the route to the destination                        |   |
| AV                     | CurrentDestination | Attribute: string  | Which destination is next, received from trailer (or idle position)   |   |
|                        | Occupied           | Attribute: boolean | Is the truck idle or not  |   |
|                        | Quantity           | Integer            | Total used in system (experimental factor)                            |   |
|                        | Schedule           | Attribute: list    | Which jobs to perform   |   |
|                        | CurrentLocation    | Attribute: string  | Used to determine the route to the destination                        |   |
|                        | CurrentDestination | Attribute: string  | Which destination is next, received from trailer (or idle position)   |   |
| <b>Entities</b>        | Occupied           | Attribute: boolean | Is the AV idle or not   |   |
|                        | Docks              | Quantity           | Integer   | Input: number of docks per P/D location   |
|                        |                    | (Un)loading time   | Time  | Input: time to unload trailers            |
|                        |                    | Reserved           | Integer   | Number of docks reserved per P/D location |

|                                      |                  |         |   |
|--------------------------------------|------------------|---------|---|
| Truck parking                        | Buffer capacity  | Integer | Input: number of truck parkings slots               |
| Decoupling point                     | Buffer capacity  | Integer | Input: number of trailer parking slots              |
|                                      | Decoupling time  | Time    | Input: time to decouple trailer of truck            |
|                                      | Coupling time    | Time    | Input: time to couple trailer to shuttle vehicle    |
| Road                                 | Length           | real    | Used to determine distances between P/D locations   |
| <b>Activities</b>                    |                  |         |   |
| Export process                       | Quantity         | Integer | Arriving trucks                                     |
| Drop-off at various GHs              | Distribution     | Real    | Proportional distribution between GH                |
| Unloading trailer                    | Duration (fixed) | Time    | Input: time of unloading at GH of arriving trailers |
| Buffer at truck parking              | Duration         | Time    | Waiting time at truckparking                        |
| Drop off trailer at decoupling point | Duration (fixed) | Time    | Input: time of decoupling                           |
| Pick up trailer at decoupling point  | Duration(fixed)  | Time    | Input: time of coupling                             |
| <b>Queues</b>                        |                  |         |   |
| Dock queues                          | Quantity         | Integer | Total number in dock queue                          |
|                                      | Waiting time     | Time    | Total time in dock queue                            |
| Truck parking queues                 | Quantity         | Integer | Total number in truck parking queue                 |
|                                      | Waiting time     | Time    | Total time in truck parking queue                   |
| Decoupling point queues              | Quantity         | Integer | Total number in decoupling point queue              |
|                                      | Waiting time     | Time    | Total time in truck parking queue                   |

## F. Flowcharts conceptual model

### Truck arrival at ground handler

When a truck arrives at a GH, the following flowchart is triggered and shows what happens. the arriving time is logged so that the travel time can be calculated and later on the waiting time. If no dock is available the truck is moved to a buffer. If a truck is available it moves to the dock and the unloading process is started. The processing time is started so that the waiting time can be determined.

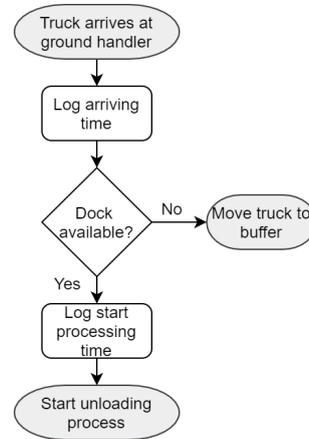


Figure F.1: Flowchart truck arrival at GH

### Internal vehicle arrives at decoupling point

In the event that an IV arrives at the DP, the arriving time is logged. Then the travel time is determined to the DP, so that the total percentage of idle moving time can be calculated. If the IV arrives at the DP, it means that the IV has a job scheduled and the first one from the list is taken. Then the coupling process is started, where the cargo is coupled to the IV. If the cargo is coupled, the event of a new moving job is triggered.

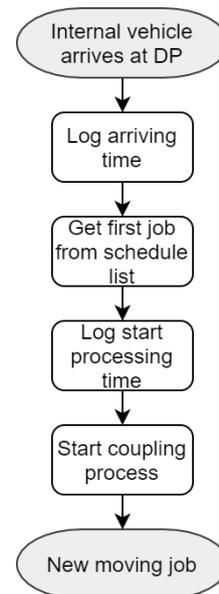


Figure F.2: Flowchart AV arrives at destination

## New moving job truck

When a dock becomes available, the second priority is the truck from the truck parking and a new moving job for the truck is started. In the event when a truck gets a new moving job, the following flowchart shows what actions are performed. First, the dock at the GH is claimed. Then the route is determined and the start time of the move is logged. Then the truck moves towards the GH.

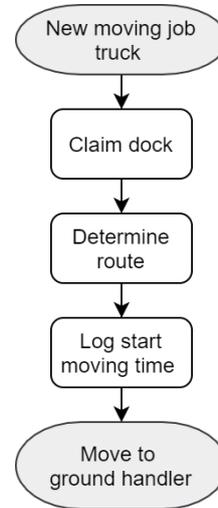


Figure F.3: Flowchart new moving job truck

## Internal vehicle becomes idle

If an IV finished the assigned job, it becomes idle. First, the battery is checked if the AV needs to be recharged. If the battery level is under a certain threshold, the AV is sent to the charging station and recharged. If the battery level is above the threshold, it is checked if the AV has job scheduled. If this is true, the event of a new moving job is triggered. If there are no job in the AV schedule, the AV is move to the idle position.

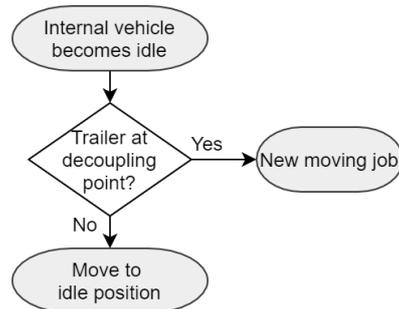


Figure F.4: Flowchart AV becomes idle

## New job request

When a new job request is triggered, it is checked if an IV is idle. If there is not an IV idle, a job is scheduled to an AV. If there is an AV idle, the job is assigned to this AV and the event "New moving job" is triggered.

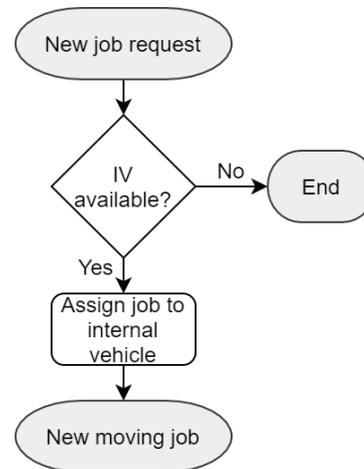


Figure F.5: Flowchart new job request

## G. Arrival rate verification

Table G.1: Arrival rate verification

| <b>Begin hour</b> | <b>End hour</b> | <b>Actual arrival rate</b> | <b>Avg. experiment arrival rate</b> | <b>Absolute difference</b> | <b>Percentual difference</b> |
|-------------------|-----------------|----------------------------|-------------------------------------|----------------------------|------------------------------|
| 00:00:00          | 01:00:00        | 26                         | 24.7                                | 1.4                        | 5.2 %                        |
| 01:00:00          | 02:00:00        | 23                         | 21.7                                | 1.3                        | 5.7 %                        |
| 02:00:00          | 03:00:00        | 25                         | 26.1                                | 1.1                        | 4.4 %                        |
| 03:00:00          | 04:00:00        | 25                         | 25.0                                | 0.0                        | 0.0 %                        |
| 04:00:00          | 05:00:00        | 22                         | 21.1                                | 0.9                        | 4.3 %                        |
| 05:00:00          | 06:00:00        | 19                         | 14.7                                | 4.3                        | 22.6 %                       |
| 06:00:00          | 07:00:00        | 20                         | 19.1                                | 0.9                        | 4.8 %                        |
| 07:00:00          | 08:00:00        | 16                         | 14.4                                | 1.6                        | 10.0 %                       |
| 08:00:00          | 09:00:00        | 16                         | 16.0                                | 0.1                        | 0.3 %                        |
| 09:00:00          | 10:00:00        | 13                         | 11.8                                | 1.2                        | 9.2 %                        |
| 10:00:00          | 11:00:00        | 12                         | 14.3                                | 2.3                        | 19.2 %                       |
| 11:00:00          | 12:00:00        | 11                         | 12.5                                | 1.5                        | 13.2 %                       |
| 12:00:00          | 13:00:00        | 19                         | 20.1                                | 1.1                        | 5.5 %                        |
| 13:00:00          | 14:00:00        | 23                         | 22.5                                | 0.5                        | 2.2 %                        |
| 14:00:00          | 15:00:00        | 25                         | 25.2                                | 0.2                        | 0.8 %                        |
| 15:00:00          | 16:00:00        | 25                         | 25.1                                | 0.1                        | 0.4 %                        |
| 16:00:00          | 17:00:00        | 30                         | 31.3                                | 1.3                        | 4.2 %                        |
| 17:00:00          | 18:00:00        | 36                         | 35.5                                | 0.5                        | 1.4 %                        |
| 18:00:00          | 19:00:00        | 40                         | 37.7                                | 2.4                        | 5.9 %                        |
| 19:00:00          | 20:00:00        | 41                         | 37.4                                | 3.6                        | 8.8 %                        |
| 20:00:00          | 21:00:00        | 43                         | 45.9                                | 2.9                        | 6.6 %                        |
| 21:00:00          | 22:00:00        | 44                         | 48.1                                | 4.1                        | 9.3 %                        |
| 22:00:00          | 23:00:00        | 38                         | 41.7                                | 3.7                        | 9.6 %                        |
| 23:00:00          | 23:59:59        | 36                         | 37.6                                | 1.6                        | 4.4 %                        |
| <b>Total</b>      |                 | 628                        | 629                                 | 1                          | 0.2 %                        |

## H. Calculations for number of replications

Table H.1: Number of replications calculation

| <b>Replication</b> | <b>Avg. through-put time</b> | <b>Avg. experi-ments</b> | <b>Variance</b> | <b>T-value</b> | <b>Error</b> |
|--------------------|------------------------------|--------------------------|-----------------|----------------|--------------|
| 1                  | 00:52:27                     |                          |                 |                |              |
| 2                  | 00:53:30                     | 00:52:59                 | 00:00:00        | 12.70620474    | 0.124450208  |
| 3                  | 00:53:05                     | 00:53:01                 | 00:00:00        | 4.30265273     | 0.024502681  |
| 4                  | 00:51:46                     | 00:52:42                 | 00:00:00        | 3.182446305    | 0.022776484  |
| 5                  | 00:52:24                     | 00:52:38                 | 00:00:00        | 2.776445105    | 0.015738424  |
| 6                  | 00:53:15                     | 00:52:44                 | 00:00:00        | 2.570581836    | 0.012841187  |
| 7                  | 00:55:11                     | 00:53:05                 | 00:00:00        | 2.446911851    | 0.019096376  |
| 8                  | 00:50:14                     | 00:52:44                 | 00:00:00        | 2.364624252    | 0.022687381  |
| 9                  | 00:51:36                     | 00:52:36                 | 00:00:00        | 2.306004135    | 0.020326716  |
| 10                 | 00:49:58                     | 00:52:21                 | 00:00:00        | 2.262157163    | 0.021253485  |

# I. Experimental results

Per KPI, we provided the average, the standard deviation, the minimum, and the maximum<sup>1</sup>.

## Experiment results throughput times

Table I.1: Experiment results throughput times

| Exp            | Output variable                |          |          |          |          |          |          |          |          |          |          |          |
|----------------|--------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|                | Throughput time (hour:min:sec) |          |          |          |          |          |          |          |          |          |          |          |
|                | Calm                           |          |          |          | Normal   |          |          |          | Busy     |          |          |          |
|                | Avg                            | SD       | Min      | Max      | Avg      | SD       | Min      | Max      | Avg      | SD       | Min      | Max      |
| 1              | 00:35:53                       | 00:08:35 | 00:33:21 | 02:03:44 | 00:43:41 | 00:29:50 | 00:33:21 | 04:13:20 | 01:21:42 | 01:34:28 | 00:33:21 | 10:26:07 |
| 2              | 00:40:30                       | 00:16:37 | 00:35:18 | 03:01:59 | 00:56:29 | 00:55:51 | 00:35:17 | 06:34:56 | 02:36:23 | 03:30:19 | 00:35:17 | 17:51:15 |
| 3              | 04:51:20                       | 05:07:05 | 00:42:52 | 20:33:29 | 04:55:09 | 05:16:47 | 00:42:52 | 20:29:07 | 04:59:46 | 05:18:14 | 00:42:52 | 20:23:00 |
| 4 <sup>2</sup> | 5:04:34                        | 1:10:47  | 2:21:01  | 8:02:22  | 5:00:00  | 1:10:13  | 2:17:54  | 8:00:46  | 4:20:28  | 1:10:26  | 2:15:30  | 7:23:41  |
| 5              | 00:37:52                       | 00:16:10 | 00:33:21 | 03:52:26 | 00:50:01 | 00:57:55 | 00:33:21 | 06:59:56 | 01:59:06 | 03:31:12 | 00:33:21 | 19:14:07 |
| 6              | 00:45:28                       | 00:27:32 | 00:33:21 | 03:42:24 | 00:55:57 | 01:01:02 | 00:33:21 | 06:34:56 | 01:45:56 | 02:39:42 | 00:33:21 | 13:18:30 |
| 7              | 01:26:29                       | 02:00:49 | 00:33:21 | 11:49:59 | 01:29:52 | 02:13:40 | 00:33:21 | 13:01:14 | 02:37:18 | 04:11:21 | 00:33:21 | 19:17:18 |
| 8              | 00:46:37                       | 00:25:48 | 00:35:17 | 03:33:07 | 00:56:04 | 00:47:55 | 00:35:17 | 06:57:30 | 02:03:57 | 03:21:14 | 00:35:18 | 19:13:59 |
| 9              | 01:27:36                       | 02:00:19 | 00:35:20 | 11:49:49 | 01:27:30 | 01:59:14 | 00:35:18 | 11:58:22 | 02:14:30 | 02:55:26 | 00:35:19 | 18:55:55 |
| 10             | 00:40:31                       | 00:15:59 | 00:33:21 | 04:05:16 | 00:51:25 | 00:57:21 | 00:33:21 | 08:26:23 | 01:51:08 | 03:24:04 | 00:33:21 | 21:43:40 |
| 11             | 00:46:35                       | 00:32:23 | 00:33:21 | 04:37:38 | 00:54:31 | 00:53:20 | 00:33:21 | 07:06:33 | 01:54:52 | 03:22:34 | 00:33:21 | 20:59:15 |

## Experiment results travel times

Table I.2: Experiment results travel times

| Exp | Output variable                |          |          |          |          |          |          |          |          |          |          |          |
|-----|--------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|     | Throughput time (hour:min:sec) |          |          |          |          |          |          |          |          |          |          |          |
|     | Calm                           |          |          |          | Normal   |          |          |          | Busy     |          |          |          |
|     | Avg                            | SD       | Min      | Max      | Avg      | SD       | Min      | Max      | Avg      | SD       | Min      | Max      |
| 1   | 00:04:07                       | 00:01:47 | 00:03:21 | 00:22:42 | 00:05:31 | 00:04:47 | 00:03:21 | 00:22:42 | 00:09:01 | 00:07:18 | 00:03:21 | 00:22:42 |
| 2   | 00:05:51                       | 00:00:31 | 00:05:16 | 00:06:36 | 00:05:50 | 00:00:31 | 00:05:16 | 00:06:36 | 00:05:49 | 00:00:32 | 00:05:16 | 00:06:36 |
| 3   | 00:06:21                       | 00:00:31 | 00:05:52 | 00:07:05 | 00:06:22 | 00:00:31 | 00:03:16 | 00:07:49 | 00:06:22 | 00:00:31 | 00:03:16 | 00:11:30 |
| 4   | 00:09:38                       | 00:00:54 | 00:08:47 | 00:10:53 | 00:09:38 | 00:00:54 | 00:08:47 | 00:10:53 | 00:09:39 | 00:00:55 | 00:04:14 | 00:11:06 |
| 5   | 00:04:50                       | 00:01:08 | 00:03:21 | 00:06:38 | 00:04:50 | 00:01:08 | 00:03:21 | 00:07:05 | 00:05:03 | 00:01:41 | 00:03:21 | 00:27:25 |
| 6   | 00:05:07                       | 00:01:22 | 00:02:53 | 00:08:24 | 00:05:28 | 00:02:14 | 00:03:21 | 00:30:39 | 00:07:51 | 00:05:34 | 00:02:59 | 00:35:28 |
| 7   | 00:06:44                       | 00:02:59 | 00:03:21 | 00:11:17 | 00:06:49 | 00:03:04 | 00:03:21 | 00:25:26 | 00:08:26 | 00:05:26 | 00:01:58 | 00:47:20 |
| 8   | 00:06:06                       | 00:00:34 | 00:04:10 | 00:07:46 | 00:06:06 | 00:00:35 | 00:05:16 | 00:07:05 | 00:06:05 | 00:00:36 | 00:05:16 | 00:07:50 |
| 9   | 00:07:45                       | 00:02:02 | 00:05:16 | 00:10:53 | 00:07:44 | 00:02:02 | 00:05:16 | 00:10:53 | 00:07:44 | 00:02:03 | 00:05:16 | 00:11:13 |
| 10  | 00:05:21                       | 00:01:12 | 00:03:21 | 00:07:39 | 00:05:25 | 00:01:15 | 00:03:21 | 00:10:05 | 00:05:58 | 00:02:41 | 00:03:21 | 00:35:22 |
| 11  | 00:06:28                       | 00:02:30 | 00:03:21 | 00:11:12 | 00:06:28 | 00:02:30 | 00:03:21 | 00:12:24 | 00:06:45 | 00:02:53 | 00:03:21 | 00:46:55 |

<sup>1</sup>Due to space limitations, we use the acronyms Average (Avg), the Standard Deviation (SD), the Minimum (Min), and the maximum (Max) in every table.

<sup>2</sup>Due to space limitations, this experiment is shown in (day:hour:min).

## Experiment results waiting times GH

Table I.3: Experiment results waiting times at ground handlers

| Exp | Output variable             |          |          |          |          |          |          |          |          |          |          |          |
|-----|-----------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|     | Waiting time (hour:min:sec) |          |          |          |          |          |          |          |          |          |          |          |
|     | Calm                        |          |          |          | Normal   |          |          |          | Busy     |          |          |          |
|     | Avg                         | SD       | Min      | Max      | Avg      | SD       | Min      | Max      | Avg      | SD       | Min      | Max      |
| 1   | 00:01:45                    | 00:07:47 | 00:00:00 | 01:17:59 | 00:08:10 | 00:26:21 | 00:00:00 | 03:24:22 | 00:42:42 | 01:30:04 | 00:00:00 | 09:37:10 |
| 2   | 00:00:00                    | 00:00:00 | 00:00:00 | 00:00:00 | 00:00:00 | 00:00:00 | 00:00:00 | 00:00:00 | 00:00:00 | 00:00:00 | 00:00:00 | 00:00:00 |
| 3   | 00:00:00                    | 00:00:03 | 00:00:00 | 00:05:16 | 00:00:01 | 00:00:21 | 00:00:00 | 00:12:17 | 00:00:34 | 00:02:37 | 00:00:00 | 00:41:55 |
| 4   | 00:00:00                    | 00:00:00 | 00:00:00 | 00:00:00 | 00:00:01 | 00:00:01 | 00:00:00 | 00:01:17 | 00:00:00 | 00:00:17 | 00:00:00 | 00:10:26 |
| 5   | 00:00:12                    | 00:01:04 | 00:00:00 | 00:19:05 | 00:00:29 | 00:01:55 | 00:00:00 | 00:31:40 | 00:01:41 | 00:05:58 | 00:00:00 | 01:12:58 |
| 6   | 00:00:32                    | 00:03:20 | 00:00:00 | 00:43:46 | 00:02:21 | 00:08:56 | 00:00:00 | 01:31:52 | 00:09:14 | 00:23:10 | 00:00:00 | 03:42:39 |
| 7   | 00:00:06                    | 00:00:56 | 00:00:00 | 00:20:09 | 00:01:04 | 00:05:05 | 00:00:00 | 00:59:07 | 00:05:32 | 00:15:34 | 00:00:00 | 02:34:27 |
| 8   | 00:00:06                    | 00:00:42 | 00:00:00 | 00:14:34 | 00:00:19 | 00:01:15 | 00:00:00 | 00:17:29 | 00:00:51 | 00:02:19 | 00:00:00 | 00:31:04 |
| 9   | 00:00:01                    | 00:00:21 | 00:00:00 | 00:13:00 | 00:00:07 | 00:00:47 | 00:00:00 | 00:17:19 | 00:00:39 | 00:01:50 | 00:00:00 | 00:22:21 |
| 10  | 00:00:19                    | 00:01:31 | 00:00:00 | 00:26:21 | 00:01:03 | 00:04:19 | 00:00:00 | 00:59:10 | 00:03:09 | 00:09:29 | 00:00:00 | 01:52:16 |
| 11  | 00:00:10                    | 00:01:01 | 00:00:00 | 00:19:38 | 00:00:37 | 00:02:25 | 00:00:00 | 00:37:36 | 00:02:24 | 00:07:07 | 00:00:00 | 01:29:30 |

## Experiment results truck times

Table I.4: Experiment results truck times

| Exp | Output variable           |          |          |          |          |          |          |          |          |          |          |          |
|-----|---------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|     | Truck time (hour:min:sec) |          |          |          |          |          |          |          |          |          |          |          |
|     | Calm                      |          |          |          | Normal   |          |          |          | Busy     |          |          |          |
|     | Avg                       | SD       | Min      | Max      | Avg      | SD       | Min      | Max      | Avg      | SD       | Min      | Max      |
| 1   | 00:35:53                  | 00:08:35 | 00:33:21 | 02:03:44 | 00:43:41 | 00:29:50 | 00:33:21 | 04:13:20 | 01:21:42 | 01:34:28 | 00:33:21 | 10:26:07 |
| 2   | 00:40:30                  | 00:16:37 | 00:35:18 | 03:01:59 | 00:56:29 | 00:55:51 | 00:35:17 | 06:34:56 | 02:36:23 | 03:30:19 | 00:35:17 | 17:51:15 |
| 3   | 00:07:01                  | 00:00:19 | 00:06:58 | 00:12:39 | 00:08:25 | 00:05:00 | 00:06:58 | 00:42:14 | 00:24:07 | 00:44:30 | 00:06:58 | 03:41:25 |
| 4   | 00:07:00                  | 00:00:16 | 00:06:58 | 00:11:55 | 00:08:27 | 00:05:13 | 00:06:58 | 00:41:47 | 00:23:56 | 00:44:39 | 00:06:58 | 03:37:47 |
| 5   | 00:37:52                  | 00:16:10 | 00:33:21 | 03:52:26 | 00:50:01 | 00:57:55 | 00:33:21 | 06:59:56 | 01:59:06 | 03:31:12 | 00:33:21 | 19:14:07 |
| 6   | 00:20:44                  | 00:14:01 | 00:06:58 | 01:16:38 | 00:22:17 | 00:16:52 | 00:06:58 | 02:14:22 | 00:28:05 | 00:28:20 | 00:06:58 | 04:30:27 |
| 7   | 00:20:29                  | 00:13:32 | 00:06:58 | 00:53:36 | 00:21:23 | 00:14:57 | 00:06:58 | 01:35:40 | 00:25:43 | 00:23:14 | 00:06:58 | 03:22:55 |
| 8   | 00:22:26                  | 00:17:16 | 00:06:58 | 02:28:47 | 00:31:03 | 00:46:36 | 00:06:58 | 06:57:30 | 01:39:08 | 03:29:33 | 00:06:58 | 19:13:59 |
| 9   | 00:21:37                  | 00:14:47 | 00:06:58 | 01:16:05 | 00:24:20 | 00:22:20 | 00:06:58 | 03:29:45 | 01:07:41 | 02:27:13 | 00:06:58 | 18:55:55 |
| 10  | 00:27:40                  | 00:21:27 | 00:06:58 | 04:05:16 | 00:37:49 | 01:00:50 | 00:06:58 | 08:26:23 | 01:31:35 | 03:27:36 | 00:06:58 | 21:43:40 |
| 11  | 00:26:26                  | 00:16:42 | 00:06:58 | 03:07:24 | 00:33:39 | 00:45:23 | 00:06:58 | 07:06:33 | 01:29:25 | 03:24:03 | 00:06:58 | 20:59:15 |

## J. Number of waiting trailers at TP and DP

Table J.1: Experiment results number of waiting trailers at TP and DP

| Experiment | Total number of waiting trailers |        |       |       |        |       |
|------------|----------------------------------|--------|-------|-------|--------|-------|
|            | TP                               |        |       | DP    |        |       |
|            | Calm                             | Normal | Busy  | Calm  | Normal | Busy  |
| 1          | 0                                | 0      | 0     | 0     | 0      | 0     |
| 2          | 840                              | 2460   | 11505 | 0     | 0      | 0     |
| 3          | 0                                | 0      | 0     | 7756  | 10670  | 16456 |
| 4          | 0                                | 0      | 0     | 14148 | 18698  | 27966 |
| 5          | 194                              | 1027   | 5007  | 0     | 0      | 0     |
| 6          | 0                                | 0      | 0     | 535   | 1092   | 4298  |
| 7          | 0                                | 0      | 0     | 1677  | 2575   | 6720  |
| 8          | 0                                | 884    | 4940  | 517   | 922    | 1503  |
| 9          | 0                                | 369    | 4160  | 1677  | 2502   | 4993  |
| 10         | 62                               | 636    | 3066  | 0     | 43     | 871   |
| 11         | 0                                | 521    | 3093  | 343   | 635    | 1221  |