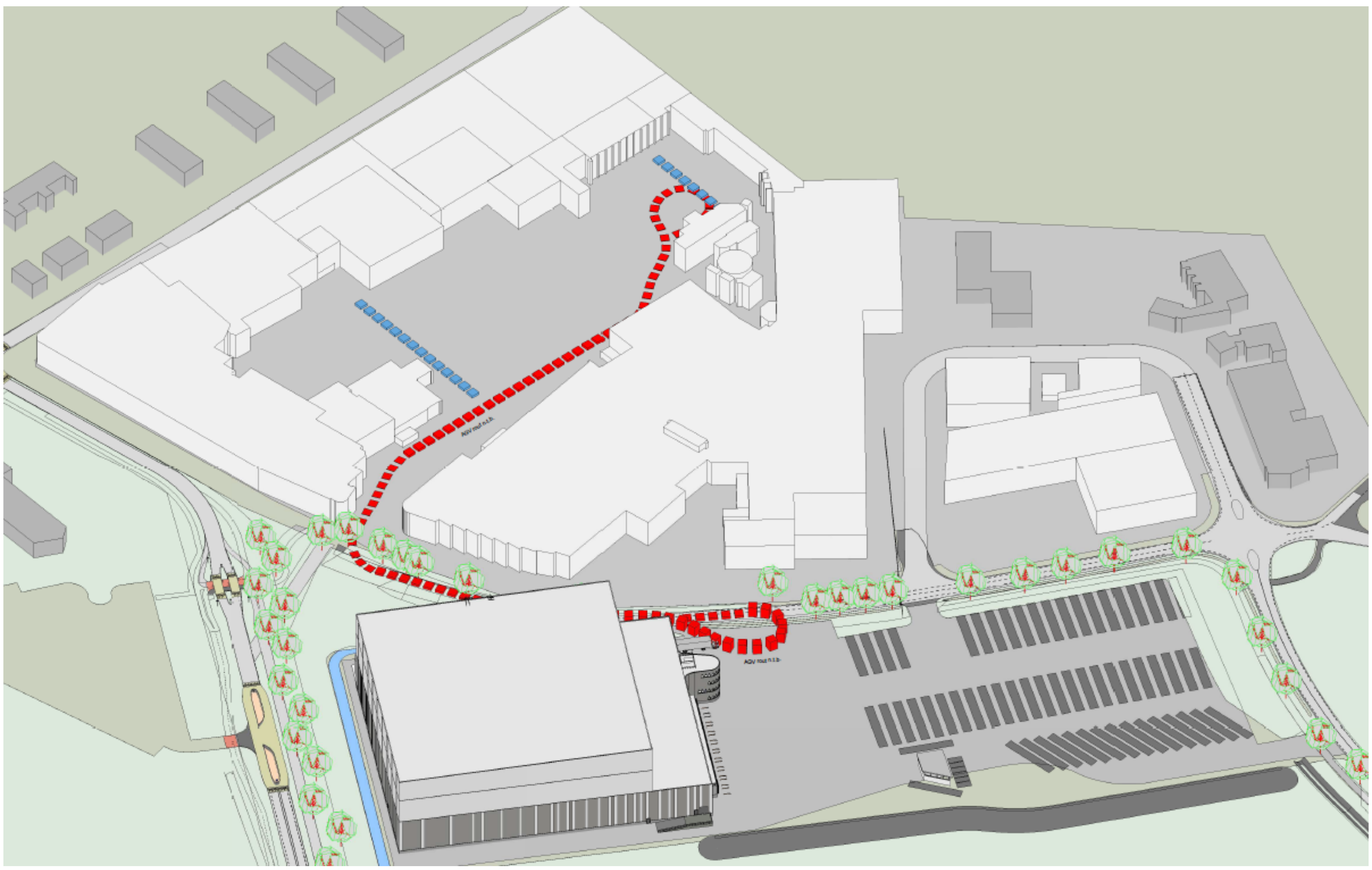
Master Thesis:

Efficient Routing and Planning within the Complex Logistical Network

Based on the Integration of a New Warehouse, AGV Transports and Increased Transportation Rates



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MSc Industrial Engineering & Management
Production & Logistic Management

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Title:	Efficient Planning and Routing within the Complex Logistical Network. Based on the Integration of a New Warehouse, AGV Transports and Increased Transportation Rates.
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Management Summary

Throughout this research, a case study is done at Company X located in Location Y. Company X is one of the major producers of Product Y and other products in the world. Company X's mission is to create value from Product Y and inspire their customers with a wide and diverse range of products.

Research Motivation

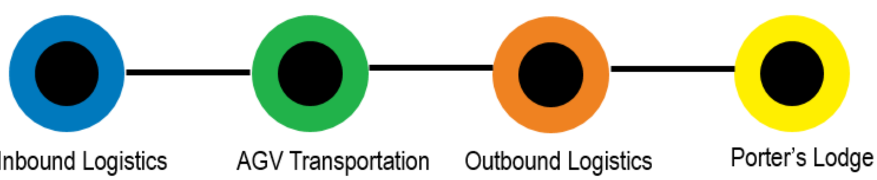
Multiple production lines are producing 24 hours a day for 7 days a week to ensure that customer demand is met. Currently, these finished products are transported to external locations for storage. However, Company X wants to deal with this large number of transportation flows towards the storage locations in an alternative way. Furthermore, they want to store their products more efficiently. To do so, they are building a new warehouse to be able to store 40,700 pallets on their own site. This warehouse is being built to increase capacity and diminish the external transportation flows. The logistical network changes significantly due to the new warehouse. Therefore, research is performed to analyze the impacts upon the logistical network and predict future inconveniences and consequences. To be able to eventually prevent future failures from happening.

Moreover, one of the major challenges within the new logistical network is the introduction of a single Automated Guided Vehicle (AGV). This AGV eventually transports the finished goods from the production area towards the new warehouse. Moreover, a porter's lodge in the future situation incorporating the new warehouse ought to be used. This porter's lodge coordinates and regulates the in- and outgoing transportation flows upon the Company X site. The functioning of this porter's lodge is essential, because all the transportation modes pass this lodge and therefore the logistical network relies upon its performance. To address the future changes for Company X and gain insights in future consequences and impacts, the following research question is designed:

How can the routing and planning, i.e. (1) the incoming supply of raw material, (2) the inter-warehouse transportation, (3) the AGV transportation and (4) the outbound logistics on the site of Company X *be arranged in such a way that the situation incorporating the new warehouse functions efficiently?*

Research Methods

First of all, the current situation is analyzed to be able to indicate deficiencies and derive efficient routing and planning opportunities. All the logistical flows currently present on the Company X site are analyzed. Furthermore, the production at the different facilities is evaluated. Currently, Company X makes use of three production facilities: *Z1*, *Z2* and *Z3*. To be able to transfer the information of the current situation at Company X towards the future situation incorporating the new warehouse, we make a distinction amongst the different logistical processes. The emphasis lies upon the following:



On the one hand, especially the introduction of the AGV and the new porter's lodge are of major importance. On the other hand, the inbound and outbound logistics make up the entire logistical network and effect the processes significantly. For the AGV we identify the different bottlenecks and check their impact upon the functioning of the AGV. The four major bottlenecks that are analyzed are: (1) *Z5 Supply*, (2) *Company Y Activities*, (3) *Pallet Supplementing* and (4) *Expedition X Transports*. The supply of Product X for production facility Z5 is partly done manually. These trucks might hinder the AGV in the future since they maneuver on the AGV-track to be able to dock the truck and unload the Product X meant for processing at Z5. Furthermore, Company Y processes all the waste material arising from production. The gathering of this waste material is performed alongside the future AGV track. Therefore, the activities from the Company Y trucks can be considered as a bottleneck for the AGV functioning as well. Besides that, pallets need to be supplemented within production. This is done by internal forklift trucks whom replenish the pallets at the different facilities. These forklift trucks cross the future AGV-track frequently and therefore the influence of this bottleneck is analyzed as well. Lastly, the Expedition X trucks meant for retrieving the products from Z1 are a bottleneck for the AGV functioning since they cross the AGV-track frequently.

The bottleneck analysis is primarily based upon the effects that a relocation or removal of the bottleneck might have upon the efficiency of the AGV. Within this bottleneck analysis we analyzed the following aspects:

- **Replacement Z5 Supply** – these manual truck supplies might be replaced by underground pipelines for the supply of Product X.
- **Relocation Company Y Activities** – these activities might be positioned at another location where the Company Y trucks do not hinder the AGV anymore.
- **Relocation Pallet Supplementing** – the pallet supplementing can be performed from another side to prevent the forklift trucks from crossing the AGV-track in the future.
- **Waiting System Expedition X Transports** – since the Expedition X Transports make up a part of the core business of Company X, replacement or relocation of this bottleneck is impossible. Therefore, the effect of a waiting system is tested. This waiting system ensures that the Expedition X trucks are stopped when the AGV is in the neighborhood.

Throughout the research, the impact reductions are calculated to see what influences the elimination of a certain AGV-bottleneck might have upon AGV efficiency. Besides the AGV bottleneck analysis, we look at the complications that could arise at the porter's lodge within the future situation. The activities and corresponding processing times are analyzed and consequences upon the entire logistical network are investigated. To adequately evaluate the impact upon the entire logistical network and to be able to test different scenarios, a simulation model is constructed. Via this tool, the future situation is modelled and animated to gain insights and already derive complications and be able to prevent them in the future. In total, 192 different configurations are tested in the simulation model. Where each configuration encompasses a simulation run length of 1 year to reduce variability and stochasticity. The options for the input factors that are tested are:

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The simulation is tested upon several Key Performance Indicators which give insights in the functioning of the AGV, the porter's lodge and the new warehouse. These KPIs are: (1) *Average Daily AGV Crossings,* (2) *Average Daily AGV Utilization,* (3) *Average Daily Interrupted AGV Transports*, (4) *Average Daily Congestion Rate* and (5) *Average Daily Porter's Utilization*. Based on a full factorial design, these KPIs are analyzed to check upon impacts and see what could be done to prevent that from happening in the future.

Results and Recommendations

After testing the different scenarios within the simulation model, experimental output for both the functioning of the AGV as the porter's lodge is obtained. By analyzing the data, we encounter complications for the functioning of the AGV. Vehicles frequently cross the AGV track, the AGV utilization is rather high and the number of interrupted AGV transports is high as well. These results are computed on an average daily basis where we see that there is a significant difference between the weekdays and the weekends. Furthermore, peaks of transport result in multiple bottlenecks for the AGV. Where the *Z5 Supply* and the *Company Y Activities* hinder the AGV the most. The *Z5 Supply* results in interruptions of the AGV (with a maximum of 4 on Mondays) whereas the *Company Y Activities* even result in more interruptions (with a of maximum 5 on Mondays). Impact reductions can be achieved if these bottlenecks are eliminated. Furthermore, the *Expedition X Transports* result in lots of interruptions (with a maximum of 6 on Fridays), but these can easily be regulated by means of a waiting system when the AGV is in the neighborhood. The *Pallet Supplementing* is performed internally and therefore these interruptions (with a maximum of 6 on Fridays) can be regulated. Overall, the AGV utilization is quite high with percentages ranging between the 90% and 95%, but within the model no problems arise with the functioning of the AGV.

With regards to the porter's lodge, the congestion rate caused at the waiting area is significant, with a maximum of 187 trucks waiting throughout an average Friday. Decreasing the processing time via automating porter's lodge activities results in serious impact reductions with respect to the congestion rate. The impact upon the porter's lodge utilization decreases as well, but this KPI never reaches levels higher than 78%. Based upon the simulation and the conducted investigation, solutions that are appropriate for efficient routing and planning within the complex logistical network of Company X are evaluated. The most important recommendations regarding the AGV, the porter's lodge and the new warehouse are:

- **Replacement Z5 Supply** – based on the simulation study, the extensive maneuvering of these trucks results in high chances of interruption and pipeline replacement is advisable.
- **Relocation Company Y Activities** – the simulation study showed that the Company Y trucks hinder the AGV frequently and thus transferring the pick-up location to another place is recommended.
- **Regulation Expedition X Transports & Pallet Supplementing –** make use of traffic lights and barriers for these trucks to prevent them from crossing when the AGV is in the neighborhood.
- **AGV Timeslot Strategy** – hourly timeslot strategy for the AGV functioning, bearing in mind:
    - Prevent driving in the peak hours as much as possible ≈ [04:00-08:00] & [12:00-19:00].
    - Drive frequently in off-peak hours ≈ [22:00-03:00].
    - Transport more frequently in the weekends, since the chance of interruptions is lower due to the lower presence of other vehicles.
- **AGV Priority Ruling** – to function efficiently, the AGV needs priority over the others vehicles.
- **Automating Porter's Lodge Activities –** decreasing the processing times of the porter's lodge via automation is recommended to prevent high congestion rates at the waiting area.

Further Research and Future Implementation

To eventually be able to acquire efficient routing and planning upon the Company X site, some further research is advised:

- **AGV Charging Strategy** – the charging of the AGV should be done efficiently and therefore further research into the opportunities for AGV charging moments needs to be done.
- **Number of AGVs** – in the future, Company X might consider making use of an extra AGV. Although one AGV satisfies the transports, a future increase in production could require two AGVs.
- **Simulating Inner-Logistics & Consequences Logistical Network** – besides the outer logistical network flows, simulating production processes and the AS/RS in the new warehouse could provide Company X with more improvement opportunities regarding their logistical network.

Furthermore, a roadmap is created to show the activities that could be performed in the future to ensure efficient routing and planning. We make a distinction amongst short-term (1 year), mid-term (3-years) and long-term (5-years) time horizons. Moreover, the operationality at the beginning of the year 2020 of the new warehouse is indicated within this roadmap. The colors indicate for which project the activity needs to be performed:

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Based on this research with accompanying simulation model and results, these activities are recommended to Company X. When Company X decides to do nothing in advance and just “let it happen”, the logistical network would still function. However, its efficiency regarding the routing and planning is questionable. Especially for the AGV, a lot of hindrance arises from the bottlenecks. Therefore, eliminating the bottlenecks as much as possible is desired by Company X. Regulating the Expedition X transports and pallet supplementing is a lot easier to accomplish than the replacement of the Z5 supplies. A high investment is required to replace the manual supplies with the pipelines, but this guarantees fluent AGV transport. Overall, the roadmap indicates all the activities that could be performed to ensure an efficient future logistical network for Location Y. This is primarily based on the outcomes of the simulation study performed in this research. In the future, thorough business cases with accompanying investments need to be made for each activity to help Company X in decision making whether or not to perform the activity.

Preface

This master thesis is written as part of my graduation project that I performed at Company X located in Location Y. The report is the final result of my Master Industrial Engineering and Management at the University of Twente, where I specialized in the track Production and Logistic Management. During my years at the university I enjoyed learning different theories and algorithms, but eventually encountering these aspects in practice has been even more exciting.

Doing research at Company X for half a year gave me insights into complex, interesting and most of all challenging projects within the logistical environment. I have always had a passion for logistics and this internship made me aware of the different opportunities within large companies. Furthermore, I learned to work both independently and as a team on complex logistics and engineering projects. Besides that, I am grateful for the opportunity that I got from Company X to broaden my skills and integrate them within a large company.

First of all, I would like to thank my daily supervisor at Company X who assisted me throughout the process. He had confidence in the creation of a simulation model from the beginning and made sure that people provided me with enough data and information to support my research. Moreover, he tried to help me when needed and made sure that I felt comfortable right from the beginning.

Furthermore, I would like to thank my 1st supervisor Peter Schuur and my 2nd supervisor Sipke Hoekstra on behalf of the University of Twente. They guided me through the process and provided me with guidelines to improve the quality of this thesis. We have had some useful discussions, where they questioned certain decisions and successfully triggered me into achieving the potential of this case study.

Lastly, I want to thank my family and friends for their unconditional support and help, especially during the modelling phase. Although I was motivated to complete this thesis throughout the past half year, I encountered some difficulties in the eventual construction of the model. Due to their feedback and assistance I have been able to motivate myself to be able to finish the model and thesis in time.

Enjoy reading my master thesis!

Wout Jansen
March 2019

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List of Abbreviations & Definitions

AGV – Automated Guided Vehicle
AHP – Analytical Hierarchical Process
ANPR – Automatic Number Plate Recognition
AS/RS – Automatic Storage and Retrieval System
CAD – Computer Aided Design
FTE – Full-Time-Employee
KPI – Key Performance Indicator
MU – Moving unit within the simulation model
PlantSim – Technomatix PlantSimulation Modelling Software
Porter's Lodge – Department that is responsible for the weighing and registering of in-/outgoing transports on the Company X site.

1.Introduction

This report is written for the completion of the Master Industrial Engineering & Management within the Production and Logistic Management track at the University of Twente. To do so, research is conducted for half a year at Company X located in Location Y. The research is done at the Central Engineering department of Company X. This research focuses on the complex logistical network and possibilities for efficient transportation in the future, where the impact upon that network due to the construction and integration of a new warehouse is of utmost importance. Throughout the following sections the different aspects of the investigation are discussed.

This chapter focuses primarily on the outline of the project. Section 1.1. introduces Company X as a company. Whereas Section 1.2. describes the corporation Company Z where Company X is a part of. Section 1.3. provides the motivation for doing this research and Section 1.4. states the problem description. The research questions are proposed in Section 1.5., whereas the research goals and eventual scope are described in Sections 1.6. and 1.7. respectively.

1.1. Company X

Company X can be considered as one of the major producers of Product Y throughout the world. Their goal is to produce a diverse amount of products and thereby adding value to the consumer food market. With an extensive selection of products like Product Y and Product Z, their mission is to create value from Product X. Every day Company X is trying to innovate, expand and improve their products and processes. Different product X specialties have been added to the product assortment recently. Furthermore, they are trying to expand their business to serve more customers in the international markets and thus elaborate production.

Besides that, Company X extensively produces Product Y suitable for Location Y. One of the main production lines is responsible for the production of this Product Y. The overall facility site of Company X is depicted in Figure 1-1 underneath. The production of Company X is not only performed in Location Y. Besides the production facility in Location X, Company X has more facilities in The Netherlands located in Location V, Location W, Location Y and Location Z. Furthermore, there are two facilities in Germany, one in Poland, one in Belgium and three within Scandinavia. They are all able to satisfy certain amounts of international demand.

FIGURE 1-1: VIEW OF THE COMPANY X SITE

Several processes take place at multiple production lines to produce different kinds of product X products. Generally speaking, the rough Company X production chain looks like this:

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The processing part consists of several phases, where the harvested Product X from the farmers enter the production line and eventually come out as Product Y or product X wedges for example. The process flow from product X to end product is shown underneath:

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Besides the production facilities, Company X also has a lot of cool- and F2 storage facilities. Most of them are located externally, but there are also some on-site facilities. The different processes taking place and the layout of facilities in Location X are explained further in Chapter 2.

1.2. Company Z

Company Z is a corporate governance covering multiple companies. The businesses involved within this governance are Company V,W,X,Y and Company Z. The main idea of this corporate governance is to produce food ingredients and products, with as goal to get the most out of its raw materials. Efficient use of raw materials results in potential environmental benefits and high profitability. Company Z is developing its activities to ensure that they can also incorporate sustainability in their business model. Besides the supply of food ingredients and products, they also focus on the supply of products for the animal feed sector and furthermore the residual products are used to produce biogas. Therefore, the entire supply chain of Company Z also has a reverse logistical viewpoint, where the businesses are integrated to enable the reduction in the amount of waste materials.

Company Z is established about 120 years ago. Later on, the other companies joined Company Z to make use of the strong relationships and services provided by the corporation. Today the Company Z corporation has approximately 4000 employees and has grown to become a major business. Currently, the cooperative has about 9000 shareholders.

The overall idea of Company Z is depicted in Figure 1-4. Here, three main aspects determine the processes of Company Z. The strong corporation with the farmers results in a tremendous business model for both the participating companies as well as Company Z. The sharing of know-how and strong collaboration among the companies such as Company Y and Company X results in an efficient corporation.

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1.3. Research Motivation

Company X wants to deal with the large number of transport flows on their site and furthermore they would like to store their goods more efficiently. To do so, they are building a warehouse next to the production facilities that is capable of storing finished products on the Company X location. Currently, the finished goods are transported to external locations in which they are stored for a certain amount of time and later on retrieved by customers. To prevent the transports with finished products to these locations, the future warehouse at Location X ought to diminish the invoked costs for storage transportation drastically. Furthermore, the new warehouse is built to increase capacity and thus deal with the transportation flows more efficiently. Since the logistical network changes due to the new warehouse, research needs to be done whether this has effects on different key performance indicators within Company X. Thereby, they can predict inconveniences and consequences. Eventually preventing future failures from happening.

Moreover, the processes within the new warehouse and on the factory site become semi-automatic. Automatization requires some well-thought-of strategies in order to function properly. One of the major challenges is the usage of an Automated Guided Vehicle (AGV) within the new situation. The AGV has a huge impact upon the logistical network and thus a profound analysis is required to ensure suitability and operationality of the AGV within the new situation. Furthermore, the porter's lodge at the new warehouse deals with a lot more in- and outgoing trucks. Defining whether automatization of this porter's lodge has positive or negative consequences regarding the logistics is also a critical point of interest for Company X.

1.4. Problem Description

Due to the fact that the new warehouse is being built on the site of Company X, several problems arise that need to be investigated prior to the operationality of this warehouse. In the following sections, the problems regarding the new warehouse, automated guided vehicle transport and the porter's lodge are described.

1.4.1. The New Warehouse

The building of the new warehouse has begun in July 2018 and thus multiple aspects need to be investigated before the warehouse is fully operational within a few years. This warehouse affects the logistical network of Company X drastically, since the products are stored in the future warehouse and retrieved by the customers from there. Approximately 15% of the transportation is nowadays based on customer retrieval, whereas the other 85% are used to store goods at *external* warehouses. By means of the new warehouse, the customer retrieval increases to about 85-90% at the Company X site. Therefore, different trucks and chauffeurs enter the site in comparison to the current situation. Currently, almost all the trucks and truck-drivers on-site are known by Company X and registered in their system. Within the new situation more trucks, and especially customer vehicles, drive around on the site and this needs to be coordinated as such.

Furthermore, the transportation ways to and from the new warehouse are causing significant changes to the planning, utilization and efficiency of Company X's overall performance. A detailed layout of the location of the new warehouse and the different logistical flows is shown in Appendix A1. Eventually, the new warehouse will look like the depicted image underneath.

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Company X wants to achieve the following indicators by means of the new warehouse:

- 40,700 extra pallet places
- Inbound capacity = 100 pallets/hour
- Outbound capacity = 240 pallets/hour
- Fully automated pallet handling

Doing so, results in: (1) reducing logistic costs, (2) reducing CO_2 emission, (3) reducing complexity and (4) improving service levels. In Figure 1-6. a virtual image of the new situation with accompanying driveways and parking spaces is visualized.

FIGURE 1-6: VIRTUAL IMAGE OF THE FUTURE SITUATION INCORPORATING THE NEW WAREHOUSE (BESSELS, 2018)

For the new warehouse, that ought to have space for 40,700 pallets of finished product, an automatic order-picking system is desired. An automatic storage and retrieval system (AS/RS) should store the pallets with finished products and automatically order pick them when told to do so. The trucks arrive at the docking area of the new warehouse to pick up their predestined orders. To ensure that when they arrive at the designated dock they can immediately start with the loading of their trucks, a good automatic order picking system is required. Thereby, the system needs to know in advance if the trucks are in the neighborhood to prevent long waiting times for the truck drivers and thus increase customer servitization. There are multiple strategies for the order picking process that can be thought of. The important part is that the orders are picked in an efficient and timely manner and that the loading of the trucks at the docks of the new warehouse happens as fast as possible. Doubts of Company X regarding possible future traffic congestion on its terrain need to be investigated in order to regulate and control the traffic. Since traffic congestion affects the logistical network significantly, solutions need to be found in order to monitor it beforehand and ensure that the loading/unloading processes of the different departments happen effectively. In this regard, especially the peak hours of transportation are Company X's major concern, thus a thorough analysis of the impact of the new warehouse upon the logistical network is required.

1.4.2. Automated Guided Vehicle Transport

Due to the new warehouse, the total kilometers needed for storage transportation are diminished extremely. Furthermore, the decision has been made by Company X to transport the finished goods from the production facilities to the warehouse by means of one Automated Guided Vehicle (AGV). To do so, several logistical adjustments to the current site are required. An example of this is that the functioning of the AGV should not be interrupted by other transports. The entire handling of the AGV with its own track in the transport network needs to function properly and preferably without any delays and errors. An image of the AGV that might be operational in a few years, regarding the new warehouse, is shown in Figure 1-7 respectively. The supplier of this type of AGV is Götting. The idea of the AGV and its corresponding track is shown in Appendix A2.

The AGV will be able to transport goods from the production facilities to the warehouse. The track is solely driven by the AGV, but other trucks and people might cross the track. These crossings need to be regulated in order to prevent failures within the AGV functioning when it detects a person or vehicle. Furthermore, the AGV needs to be charged every now and then to be able to keep on driving when desired. All the logistical issues regarding the AGV need to be investigated before going operational. When the warehouse is operational, the AGV needs to be able to transport full-truckloads from the production facilities towards the new warehouse without any obstruction.

FIGURE 1-7: FUTURE AGV ALTERNATIVE WITH TRUCK AND TRAILER AUTOMATED BY GÖTTING (GÖTTING, 2018)

1.4.3. Porter's Lodge

The porter's lodge that is currently in use needs to shift to another place. The porter's lodge is used for the registering and weighing of in- and outgoing vehicles. It plays an important part in the business of Company X, because it regulates all the transport on the site of Location X. Because of the fact that the porter's lodge is moved to another place, there are still some problems regarding its functionality. The main problem is the extent of automatization of the lodge. Several functionalities like the weighing and registration can be done automatically, but complications arise here as well. Automating results in lots of costs and therefore a cost-benefit analysis is required to check whether certain elements of the current porter's lodge are worth to be automated.

Furthermore, due to the increased work circumstances the arrangement of porters present at the lodge needs to be investigated. Because of the new warehouse and the expand in transportation, the work of the porters increases a lot and the availability of the current porters is not enough within the future situation. Therefore, a trade-off between automating certain functionalities and hiring more people to occupy the lodge is required. So, a grounded view and solution for the porter's lodge needs to be found.

1.5. Research Questions

To guide the research, several questions are formulated in order to acquire the desired information to be able to answer the main question:

How can the routing and planning, i.e. (1) the incoming supply of raw material, (2) the inter-warehouse transportation, (3) the AGV transportation and (4) the outbound logistics on the site of Company X be arranged in such a way that the situation incorporating the new warehouse functions efficiently?

To answer this question in the end, eight sub questions have been formulated. The reason for questioning and the desired goal of the specific questions is discussed here.

1. *What are currently all the logistical flows on and around the Company X site in Location Y?*
In order to come up with an efficient allocation of transportation flows regarding the new warehouse, a concise understanding of the current logistical flows is necessary. These insights guide the study to model the new situation accordingly.

2. *How can interruptions of the Automated Guided Vehicle (AGV) regarding the loading, its transportation route and the unloading be prevented?*
The AGV travelling from the production facilities to the new warehouse cannot be interrupted by any means. An interruption can lead to reduced capacity for the production lines, because the finished products cannot be stored on time. Therefore, preventing interruptions of the AGV is of utmost importance.

3. *What influences will the centralization of the main entrance have upon the productivity and utilization of Company X?*
Due to the new warehouse an extra complexity arises. The current entrances are combined into one main centralized entrance. Therefore, all the vehicles (both in- and outgoing) pass this entrance. This question verifies if this has any consequences for Company X.

4. *In what way can the porter's lodge function efficiently in the new situation?*
The porter's lodge is used for registering, weighing and controlling the incoming and outgoing transports. Here, congestion results in long waiting times and reduced utilization. So, in the new situation the porter's lodge should function as good as possible given the circumstances.

5. *What are the requirements of Company X to be able to integrate an AGV within their logistical network?*
In order to make use of an AGV to transport goods, the requirements of being able to do so need to be investigated. Thereby, characteristics and parameters of the AGV should be obtained. Furthermore, the activities that the AGV ought to perform need to be clear before integration within the network.

6. *What functionalities of the AGV are already developed by suppliers and possible for future use?*
To truly integrate an AGV within the logistical network, the different possibilities present on the market need to be investigated. The functionalities of the AGV play a significant role within the eventual routing possibilities in the future situation.

7. *What would be a good choice regarding the future use and implementation of the AGV on the* Company X *site?*
Based on both the market analysis and the requirements of Company X, a choice regarding the usage of the AGV needs to be provided. Thereby, well-thought of recommendations for the implementation of the AGV in the already complex logistical network are considered important. To do so, prior data gathering and data modelling needs to be done to check how the facilitating of the AGV and its process can have a positive and value-adding impact.

8. *To what extent is automating the functionalities of the porter's lodge possible?*
In addition to question 4, Company X wants to investigate whether certain parts of the functionalities of the porter's lodge can be automated in order to reduce the workload of the porters and work more efficiently. This question addresses the possibilities regarding automation.

1.6. Research Goals

By means of the proposed problem description and the established research questions, several research goals are determined. The goals of this specific research are summed underneath:

- No interruptions of the AGV transporting goods automatically from the production lines to the warehouse.
- Preventing logistical failures regarding the transportation in and around the new warehouse.
- Gaining insights in possible impacts upon the logistical network whilst integrating the new warehouse. Doing so, results in providing an overview of the logistical network forecasted in future perspective.
- Reveal possibilities for the functioning of the porter's lodge. Thereby looking at the degree of automation and checking whether the processes at and around the porter's lodge can be performed more efficiently.
- Maintain a fluent flow of products and trucks. Meaning that waiting trucks for the finished products and the delivery to the customers need to have an as low as possible waiting time with the least manual activities taking place to get the products to the designated areas.

1.7. Scope and Limitations

This research focuses primarily on logistical issues regarding the new warehouse. All the logistical transformations are thoroughly researched, analyzed and modelled. However, throughout the research there are some limitations that need to be considered:

- The location of the warehouse and the paths/ways from and to the production facilities are known and cannot be changed.
- The outdoor logistical framework, i.e. (1) the AGV and its track, (2) the transportation flows and (3) the porter's lodge is the main focus of this research. Therefore, production and storage processes are refrained here and assumed constant within this research. Efficient routing and planning on the outside of the Company X site are the core objectives and boundaries.
- The research is primarily based on past data that has been provided for the current situation (without the new warehouse).
- The construction of the warehouse is not finished by the end of this research, meaning that it is not operational yet. So adequate testing of the models and proper implementing is not possible yet.

1.8. Research Design

To obtain the required results, lots of information and data needs to be gathered. Multiple techniques are invoked throughout this research to acquire a significant amount of information to eventually come up with well-thought of and grounded recommendations for Company X. To do so, data gathering and literature review are important contributors. Data gathering is done both quantitively as qualitatively. This is achieved by means of interviews with persons responsible for certain tasks/activities and through in-depth conversations and meetings with people accountable for the new warehouse. Moreover, documents and data regarding the new warehouse are analyzed. Literature review is used to provide the groundwork for this research.

Furthermore, a simulation model is created to animate future behavior and be able to check the impact of different scenarios. Within such a simulation model, data of the logistical network is integrated to be able to forecast future behavior. For Company X, this simulation model can be used for convincing purposes since it provides them with an overview of possible complications and impacts in the upcoming years. Where they have the opportunity to eventually predict and prevent complications that might arise.

1.9. Intended Deliverables

In the end, this research delivers the following aspects:

- **Concise Master Thesis** – explaining the entire research.
- **Simulation Model** – used as underlying groundwork for the computations of the results and the eventual recommendations.
- **AGV Bottleneck Analysis** – providing a framework of possible bottlenecks for the AGV.
- **Results and Interpretations** – analysis of the computed results with accompanying interpretations to provide Company X with an overview of the outcomes of this research.
- **Recommendations** Company X – overview of recommended actions and activities to increase efficiency.
- **Further Research, Implementation Plan & Roadmap** – discussing future implementation possibilities, with accompanying time horizon and further research opportunities.

Eventually, the research focuses on the construction of the new warehouse and the accompanying logistical network. An overview of the site retrieved from a drone-camera is visualized in Figure 1-8. This view shows the construction site and within the next chapters we identify all the processes encompassing this new warehouse.

FIGURE 1-8: DRONE-VIEW OF THE NEW WAREHOUSE SITE (INTERNAL DOCUMENT, 2019)

2. Current Situation

To be able to perform a profound analysis for the transportation network regarding the new situation, first a broader indication of the current situation at Company X should be obtained. This chapter deals with the current situation. First of all, the facilities at Company X are overlooked in Section 2.1. Secondly, the transportation flows that are currently present are discussed in Section 2.2. Furthermore, the transportation planning and corresponding software called *Transporeon* is explained in Section 2.3. Lastly, the functionalities of the current porter's lodge are discussed within Section 2.4.

2.1. Facilities at Company X

The site of Company X consists mainly out of four major sectors: (1) F1, (2) the production facilities, (3) the packing and palletizing and (4) storage and retrieval. For each of these facilities an extensive analysis is performed in the following sections. Furthermore, in Appendix A3, a map of the different facilities on the Company X site is shown to clarify the transportation flows and the specific locations.

2.1.1. F1

To be able to produce 24 hours a day at Company X, lots of raw material is required. The department *F1* is responsible for the transport, receival and handling of the raw material. The Product X that arrive are being cleaned, sorted and eventually peeled. Furthermore, quality controls of the Product X take place to ensure good quality and suitability for production. Hereby, Company X ensures that the farmers deliver good Product X and are paid accordingly. F1 has a separate facility on the Location X site, but the overall planning and control is done in Dronten where they have an overseeing department for all the Company X sites.

Company X makes use of two ERP systems, namely Navision and SAP. Navision mainly deals with all the pre-production processes, whereas SAP is primarily focusing on the after-production processes like sales and turnover. Especially Navision is important for F1 since their weighing procedures and workload are incorporated within Navision. The weighting is performed by weighbridges that eventually determine the price to be paid. The amount of tons (x1000 kg) of Product X that arrive weekly on average (μ) with its standard deviation (σ) based on historic data of the past five years is calculated and shown underneath.

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The number of product X trucks arriving per day at the Company X site fluctuates a lot. However, when considering it on a weekly and monthly basis it does not fluctuate significantly. Seasonality and supply insecurity is mostly dealt with by Company X. Seasonality is avoided because the Product X are gathered and stored either in large warehouses (of more than 100,000 tons) or the farmers store the Product X themselves. In this way, F1 can plan their supplies adequately in order to ensure that the production facilities can function efficiently for 24 hours and 7 days a week. Furthermore, a bad product X season does have influences on the productivity of some Company X facilities but spreading it throughout the year diminishes this consequence since Company X can incorporate uncertainties and produce their products from smaller Product X as well. An example of the number of supply transports on a monthly basis is shown in Figure 2-1, where for this instance September 2018 is analyzed.

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Due to the peeling, a lot of waste material of the Product X arises. Furthermore, due to the cleaning of the Product X by means of water and filters, a lot of ground material and dirt water comes along. The ground material that comes off is collected by a company named *Company Z* who transport the dirt material to designated storage areas. Moreover, the dirty water is cleaned by Company X itself. The cleaning results in F3 water which can again be used for the cleaning of the Product X. In that way, Company X has almost no waste product in the preparation phase of the product X. The average amounts of waste material on a weekly basis for the peels and ground material in tons (x1000 kg) are indicated in the graph underneath:

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Company Y processes a lot of the waste material from Company X and is thus a major player within the entire supply chain. Fortunately, Company Z comprises both Company X and Company Y, influencing the relationships positively. The amount of ground material coming off the Product X is way less and *de Covik* makes sure that everything is dumped. Herewith, the processes of F1 regarding the supply and the rest materials are described. The actual transportation flow and planning of these processes is incorporated in Sections 4.1. and 4.2. respectively.

2.1.2. Production Facilities

Currently there are several production facilities on the terrain of Company X. The facilities in use are called *Z1*, *Z4* and *Z5*. Z1 focuses on the production of F3 Product Y whereas in the latter two the deep-F2 production processes take place. First of all, Z4 and Z5 are discussed, followed by the production process of Z1. Eventually, a comparison amongst the production quantities of the different facilities is performed.

F2 Production Facilities

Z4

Within this facility the deep-F2 goods are produced 24 hours per day for 7 days a week. The production of Product Y is the main responsibility of Z4. A wide selection of Product Y is produced here, from the traditional French Product Y until the "Product A". The perishable date of these products is seemingly long and thus storage in a freeze-warehouse for a longer time is a possibility. Therefore, the planning department of Company X has some buffer regarding the production of these products and the eventual turnover to customers. In total, two production lines are making the Product Y which are called *Z4.1.* and *Z4.2.* respectively. The production quantities are calculated and forecasted at Company X in tons (x1000 kg) per week. When performing an analysis upon historic data for the year 2017, the following weekly averages (μ) with their standard deviations (σ) are computed for the two production lines:

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Furthermore, the average weekly production of the year 2018 is calculated based on historic data as well:

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Z5

The main purpose of Z5 is to principally use some of the rest-material that occurred during production in Z1. The product X remains can adequately be used to produce product X and product Y for example. Therefore, the production waste is again used for other purposes. However, the remains do not cover the raw materials needed, so still some raw Product X are used at Z5 as well. Innovation is an important aspect of Z5, because lots of variations upon the current products can be found. There are also two production lines at Z5 that are responsible for the entire production of the other product X products: *Z5.1.* and *Z5.2.* The production calendars for 2017 and 2018 are computed the same way as for Z4:

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F3 Production Facility

Z1

Unlike the facilities Z4 and 5, this production line has as primary goal to produce exclusively F3 Product Y. F3 Product Y are not deep-F2 like ordinary Product Y. The eventual production of F3 Product Y at Z1 is calculated via the production calendars of 2017 and 2018 respectively.

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Overview

To give an indication of the mass production at Company X, a graph is computed in which the average periodic production for the entire year 2017 (spread into 13 periods of four weeks) is visualized:

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Cleary, it can be said that Z4 produces the largest number of tons of finished products. Since Z5 focuses on the alternative product X products, it requires more innovation and developments to ascertain the sales volumes. Whereas the F3 and F2 Product Y are a long-known product for customers and therefore the sales volumes of Z1 and 4 are significantly higher and more stable. The rest materials of Z4 are transported to Z5 as mentioned beforehand. To be able to produce the specialty products at Z5, lots of testing needs to be performed to ensure that good quality is achieved. Furthermore, the customer demands and wishes are taken into account as well here. Since it is a time consuming and challenging task to fulfill all the needs and to keep on innovating, usually the output of Z5 is lower than the other production facilities.

2.1.3. Packing and Palletizing

To be able to store and distribute the finished goods, they need to be packed. The packing in boxes happens at the end of the production lines, but lots of material is required to package the finished products. Cartons, plastics, tape, foil and stickers are the main components used for packing. The single products like Product Y and croquets need to be put together in plastics. The sealed plastics can then be merged into one carton box. The boxes on their turn are taped to make sure that nothing falls out or gets damaged. Lastly, the boxes are put on a pallet and the pallet is foiled. This packing technique is performed for all the production lines and eventually the pallets are ready for storage and distribution by trucks.

Pallet Differentiation

The pallets at Company X differ in their size which makes the processes somewhat more complicated. In total there are primarily two sorts of pallets that are frequently used for production:

- Euro pallets
- Block – IPP

The size of the pallet sorts and the accompanying pallet weights and heights are incurred in Table 2-8.

TABLE 2-8: PALLET DIFFERENTIATION WITH ACCOMPANYING MEASUREMENTS, WEIGHTS AND HEIGHTS

Pallet Type	LxWxH (mm)	Maximum Pallet Weight (kg)	Maximum Pallet Height (mm)
Euro	1200 x 800 x 144	800	2150
Block - IPP	1200 x 1000 x 161	1050	2150

For the pallets, Company X also takes two important principles into account. Namely **overhang** and **leaning**. There is some margin for these aspects, because the production and the palletizing by machines does not always turn out to function properly. Overhang and leaning are the most common errors that might occur during palletizing. Overhang indicates that the cartons are stored wrongfully on the pallet therefore “hanging over” the sides of the pallets. Whereas leaning indicates that the cartons on top are likely to fall off after or during transportation.

Company X also has a section for the rejected pallets. If the pallets do not comply with the error margins, there might be a possibility of damaging the goods due to fallen boxes during transportation for example. To prevent that from happening, adequate monitoring of the pallets is performed and sometimes these pallets are rejected. Then, they are moved to the rejection area where the pallet is restored manually or even discarded for transportation. The goods flow process incorporating the pallets and the performance of certain activities, incorporating the pallets and the palletizing, is depicted in Figure 2-4. In here, the different sorts of pallets are incorporated and also the check upon these pallets with regards to leaning and overhang is of utmost importance.

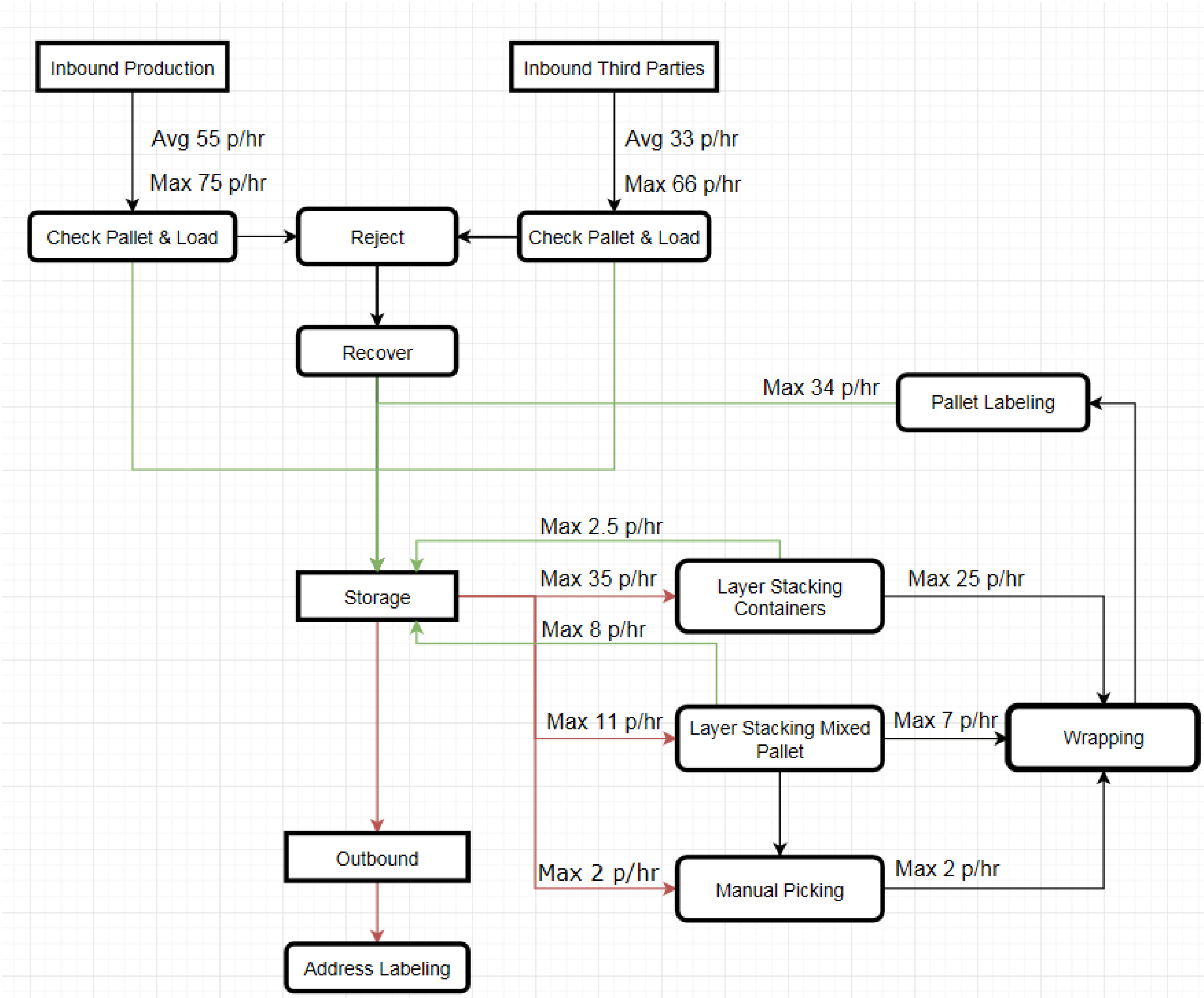

Figure 2-4: Goods Flow and Throughput Performance Measured in Pallets/Hour (p/hr) – Incoming Flows = Green and Outgoing Flows = Red

The incoming flows at the storage locations are indicated by means of green arrows. The red arrows determine the outgoing flows. The goods flow is evaluated by means of the throughput indicator pallets/hour (p/hr).

The operationality of the inbound logistics, the layer-picking and the outbound logistics are determined here. The peaks can happen at any moment, but based on historic data, Company X has a good overview of the peak moments during the week. Therefore, when necessary, they can prepare for these peaks and adapt their order picking beforehand.

Operationality:

- *Inbound from production* → 24 hours/day for 7 days/week
- *Inbound third parties* → 24 hours/day for 7 days/week
- *(Layer)-picking* → 16 hours/day for 7 days/week
- *Outbound* → 24 hours/day for 7 days/week (concentrated within 16 hours).

2.1.4. Storage & Retrieval Facilities

For the storage and expedition of the finished products, there are two internal facilities present at Company X. These are called *Expedition Y* and *Expedition X*. As described already, the rest of the products is stored at external locations. The internal storage methods are described in the following sections.

Expedition Y

The products from Z4 and Z5 are transported to the Expedition Y facility to be stored shortly. The transport from these products towards Expedition Y is done automatically. A drawing of the current transportation from the production facilities towards Expedition Y is depicted in Figure 2-5. In here, two conveyer belts transport the pallets towards Expedition Y.

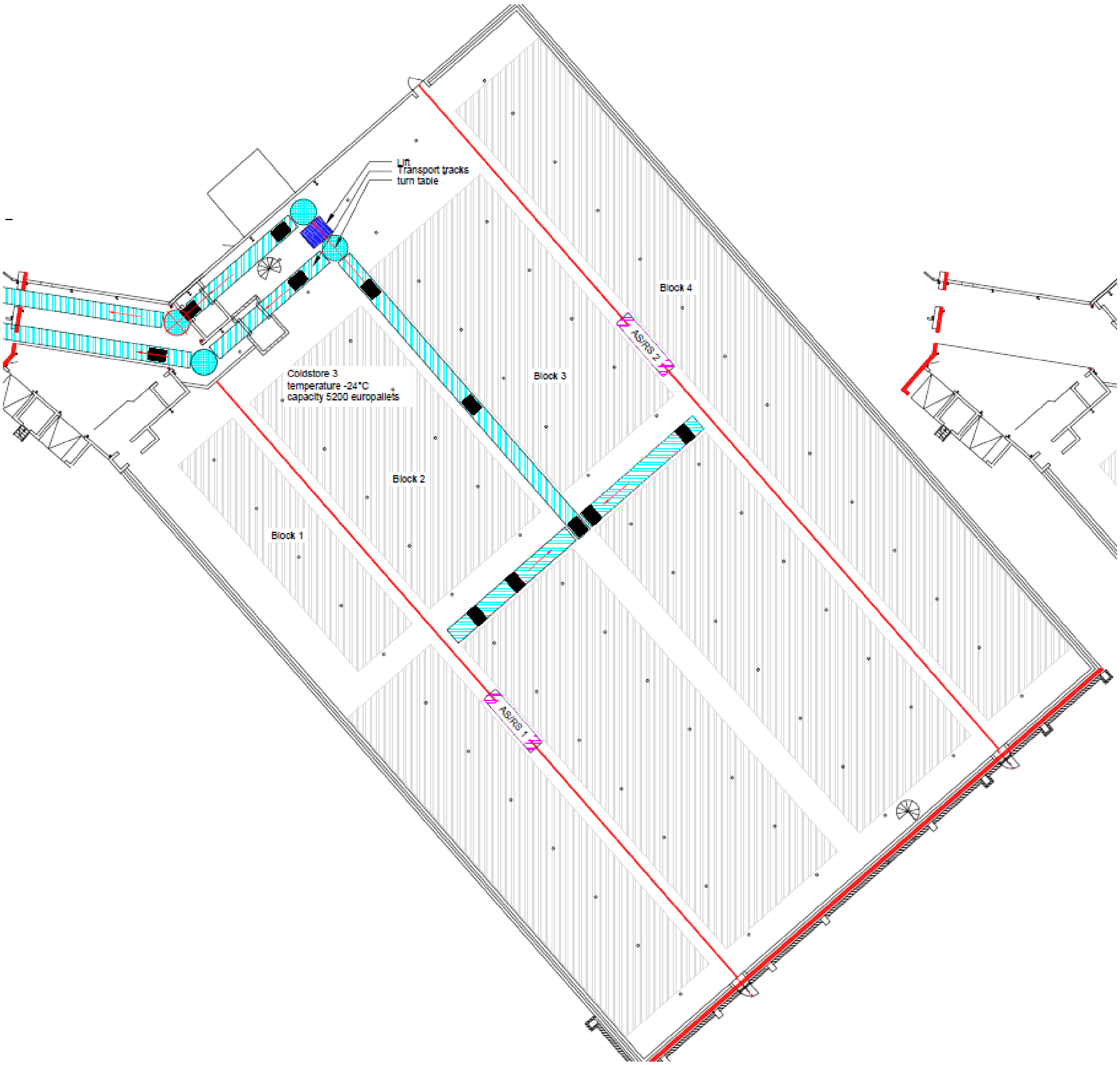

FIGURE 2-5: AS/RS WITH ACCOMPANYING CONVEYER BELTS (INDICATED IN BLUE) TOWARDS THE EXPEDITION Y AREA

SCALE 1 : 1000

Thereby, two Automated Storage and Retrieval Systems (AS/RSs) are used to pick the desired pallets from the storage location. The storage location between the production facilities and the Expedition Y functions as a buffer before pallet handling and transportation. It consists out of an upper and a lower level, where two cranes are responsible for the order picking (indicated in red in Figure 2-5) and the conveyer belts (indicated in blue in Figure 2-5) eventually move the pallets to the designated area. Some characteristics of production, the storage location and the conveyer belt transportation are:

- Approximately 40 pallets are produced per hour
- The storage location can currently store a maximum of 5000 pallets
- The length of the start of the conveyer belt until the turntable at Expedition Y is 140 meters.
- The conveyer belts have a velocity of 0.2 m/s
- Block and Euro pallets arrive randomly at Expedition Y

Based on these characteristics, it can be said that one pallet requires 700 seconds to be transported to Expedition Y. The space for 5000 pallets gives Company X the opportunity to buffer against uncertainties for a certain amount of time. Maintenance activities and production malfunctioning can for example be seen as uncertainties that they need to cope with.

Within the Expedition Y facility, manual order picking is done followed by manual truck loading which is performed by the truck driver. The temperature within the expedition zone can cool down to about -25ºC. Furthermore, a decreased oxygen level within the storage facility results in diverge working circumstances. Safety measures are therefore extremely important. Moreover, Expedition Y makes use of a transport planning software called *Transporeon*. In here, all the different timestamps for exports by customers are accurately planned. Section 2.3. gives a broad elaboration upon the transportation planning and the functionality of *Transporeon*. The lay-out of the facility is altered in the future to ensure that the AGV can easily load the pallets with finished goods and transport them to the new warehouse. The system that makes sure that the AGV is loaded automatically is depicted in Figures 2-6 and 2-7 respectively.

FIGURE 2-6: FUTURE LOADING SYSTEM TO BE USED AT EXPEDITION Y

FIGURE 2-7: FUTURE TRUCK LOADING SYSTEM AGV

The rails take care of the pallet handling, where two pallets with the standard measurements of 1200 millimeter width can be loaded simultaneously. However, since the Block and Euro pallets arrive randomly, the number of pallets that accompany a Full-Truckload (FTL) might vary. The following can happen during the loading of the AGV:

- 32 Euro Pallets = 1 FTL
- 24 Block Pallets = 1 FTL
- Mixture Block/Euro Pallets varying between 24-32 pallets = 1 FTL

Since the pallets are randomly used at the production facilities, the pallet handling is also random. Therefore, the maximum number of pallets to be loaded is 32, whereas the worst-case scenario is 24. Company X can connect the automatic loading system to the current situation to create an automatic process flow from production of Z4 and 5 to the new warehouse. To do so, several alternations to the current situation of Expedition Y are required. The overall handling of the AGV and its integration in the future is elaborated in Chapter 4, where the situation with the integration of the new warehouse is explained.

Currently, approximately 72 shipments are accomplished per day at Expedition Y. In order to efficiently transport the orders, Company X makes use of a dock planning system. In here, truck drivers are assigned to one of the four docks and the staff of Expedition Y makes sure that the order is ready to be loaded when the truck arrives and docks at the designated area. A company named *X* is primarily responsible for the transportations of Expedition Y. Since the company and its drivers are known by Company X, this process happens semi-automatic. The drivers know exactly what to do and where to be and therefore these transports happen fluently. However, staff at Expedition Y is needed to deliver the right documents for transport and payment.

Expedition X

Expedition X is actually rather the same as Expedition Y, only here the temperature is somewhat higher than at the Expedition Y facility. The products of Z1 are stored in the Expedition X facility. However, Expedition X does not yet make use of the planning software *Transporeon*. They mainly do the planning of the trucks manually. The expedition facility is renovated in the future to expand capacity, improve the storage system and refrain Company X from using its external storage locations.

Since the new warehouse is only built for the storage of deeply F2 products, the Expedition X department does not have anything to do with this research. However, the transportation flows to and from this facility interact with the entire logistical framework and therefore these transports are incorporated, because they affect the eventual logistical framework. These interruptions can cause serious impacts upon the efficiency of Company X’s network and thus the planning of the Expedition X department is something to seriously consider throughout this research.

2.2. Transportation Flows

The entire logistical framework of Company X consists primarily out of five major flows: (1) supply of Product X, carton, frying-fat, foil, stickers and other materials, (2) transportation of goods from the production facilities to the expedition facilities, (3) export to external storage locations, (4) export to customers and (5) export of rest material. These flows are discussed in the next paragraphs.

1. Supply flows

Every day, lots of raw material arrives at Company X. Besides the huge inbound of product X transports, other materials come in as well. Examples are cartons, foils and stickers which are assigned under “emballage” and are stored in large quantities to be used for production. The supply flows are lead time dependent and the planning department thus needs to take this uncertainty into account when ordering. Furthermore, *F1* is responsible for the supply of Product X and they need to work actively together with the production facilities to ensure that production can keep on going. *Supply* forms the start of the Company X process flow and can therefore be seen as an important transportation flow.

2. Internal transport

The internal transport encompasses all the flows from the production facilities to the expedition facilities. Therefore, the main flows are the pallets being moved from Z1 to Expedition X and the pallets being moved from both Z4 and 5 to Expedition Y. The finished products are palletized and transported on a moving rail to the designated expedition area. This process happens automatically thus the primary thing that needs to be done is maintaining and monitoring these internal transports.

3. External transport

The external transport flows determine currently about 85% of the total transportation of Company X. Multiple locations are used for storage. These locations can be seen as distribution centers (DC’s) for eventual transport to customers. The customers can retrieve their orders from these external locations. Therefore, order-picking at external locations is required in order to ensure that the right products per order are selected.

4. Customer transport

A limited amount of the total transport on the Company X site is dedicated to customer transport. Only important and “trustworthy” customers can currently enter the site through the porter’s lodge. At the expedition areas, multiple docks are allocated for distribution. Basically, the truck drivers know exactly where to be and what to do. The order has already been picked before the docking of the truck and the only thing that the truck driver has to do is use a forklift to place the pallets in the truck.

2.2.1. Average Transportation Trips per Week & Month

All the transportation flows that Company X currently has on the site, except the delivery to customers and external locations, are elaborated within this section. To quantify the transports, an overview of the average daily and weekly transports of all the different tasks is computed. In here, the main transport categories are (1) Product X, (2) Frying Fat, (3) PGG/PGM, (4) Chemicals/Detergents, (5) Waste Materials and (6) Other Transports. For each category, several tasks are explored with their daily and weekly trips in Table 2-9.

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As the table indicates, daily about 187 trips take place whereas weekly this amounts to 1247. Mainly, the delivery of Product X and the transportation to the sorting department of these Product X make up a significant amount of the inbound logistics. Furthermore, other materials within the PGG/PGM category essential for production like the pallets and cartons are of importance. Because there are a lot of trips happening on a daily basis, the logistical network on the current Company X site is already quite complex. Since production happens 24 hours per day for 7 days per week, the product X handling is an ongoing business for 7 days as well. However, the supply of other materials and the export of waste materials only happens during the weekdays. Because the frequency of these streams is not that high, it is possible for Company X to only process them during the weekdays. But a good planning system is required to ensure that there is always enough of those materials, for example to be able to process the production batches. Overall, the performed analysis in Table 2-9. can be used as the groundwork for the logistical network. It needs to be said though that the transportation to customers and external locations is neglected here. These transports are highly variable and dependent on the planning. Within Section 2.3. the planning regarding the outbound transportation of the production quantities is explained.

2.2.2. Current Logistical Framework

Overall, the total logistical framework with the different facilities and flows has been visualized in a flowchart. This flowchart is visible in Figure 2-8.

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The three major flows are indicated with the dotted lines. First of all, the inbound logistics encompass all the supply flows. In this case F1 and the Emballage. Furthermore, the inter-warehouse transportation contains all the flows from Z1, Z4 and Z5 to Expedition X and Expedition Y respectively. Lastly, the outbound logistics encompass the transports to customers and the external locations. In green the ingoing transports as well as the outgoing transports are denoted. Whereas in red, the main rest material streams are indicated. The rest material of Z1 regarding the Product X is transported to Z5, indicated in red. Mashed product X can be made from these rests of the Product X and with the mashed Product X the product X and product Y can then be produced in Z5.

Overall, lots of transportation activities already take place currently. Within the new situation these transports increase even more. The current transportations are known and can accurately be predicted for the coming years. This results in a reliable overview of the current logistical network, but alternations due to the new warehouse make it more complicated. The framework provides an overview of the current ongoing transports, which are quantified in the next sections.

2.3. Transportation Planning – Transporeon

To eventually be able to transport the products to the designated areas, a transportation planning is required. At Company X they make use of a planning software called *Transporeon*. In here, transports are assigned to companies. These companies accept/reject the assignment and after acceptance they assign certain trucks and drivers to perform the job. In this way, Company X keeps track of their transports and ensures that information is stored digitally. However, *Transporeon* does not have some of the fundamental parameters to make the planning of transports more efficient. For example, Company X cannot keep track of driving times and exact arrival times. Therefore, they only know if a truck arrived and at what time it arrived, but they are not able to forecast arrivals in advance in order to already prepare the orders.

Based on historic data of the transportation trips taking place per day, an analysis is performed to see what kind of influences the new warehouse might have upon transportation. As mentioned earlier, currently, 85% of the transportation is towards external storage locations of Company X and the other 15% goes directly to the customer. The expectation is that these numbers interchange in the future, meaning that 85% of the transportations go directly to the customer, whereas only 15% still go towards storage locations. To forecast the number of transportation trips, extrapolation methods have been used. Where extrapolation can be referred to as the action of estimating something by assuming that existing trends continue. Together with the Transportation Planning Department of Company X, forecasts for both the Expedition Y as the Expedition X transports have been made based on historic data. Where especially the transports for Expedition Y change tremendously due to the new warehouse. To come up with a significant overview, the decision is made to spread the transportation trips in hourly intervals on a daily basis. The overview for Expedition Y, forecasted for the year 2020 (operationality new warehouse), is shown in Figure 2-9.

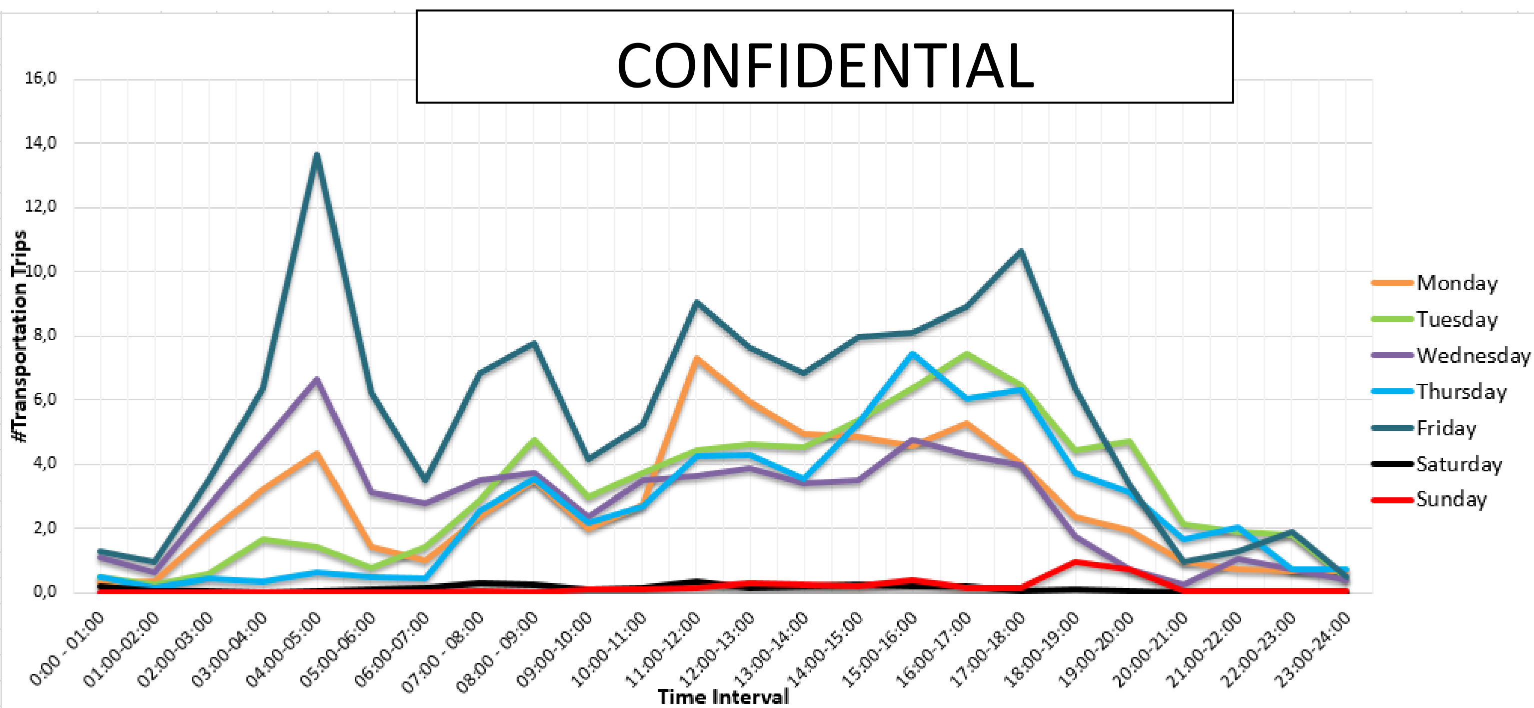

Figure 2-9: Forecasted Future Transportation Trips regarding The Expedition Y Transports for the Year 2020 (Transporeon Data Company X)

Some immediate conclusions can be withdrawn from this overview for the transportation trips of the deep-F2 products of Z4 and 5:

- Peaks in deep-F2 transportations are on average in the time intervals [03:00 – 09:00] and [12:00-19:00].
- Friday is the peak day of Expedition Y for Company X.
- The transportation trips on Saturdays and Sundays are almost negligible.
- The highest peak of transportation is approximately 14 trips within a 1-hour time interval.

Based on the analysis, future transports can be predicted and the logistical framework can be modelled with these parameters. However, fluctuations might of course occur. But by means of the enlargement of the historic data to multiple years, this variation is diminished as much as possible. The same analysis is performed for Expedition X, where their transports are analyzed based on historic transportation trips as well. The forecast for the year 2020 is visualized in Figure 2-10.

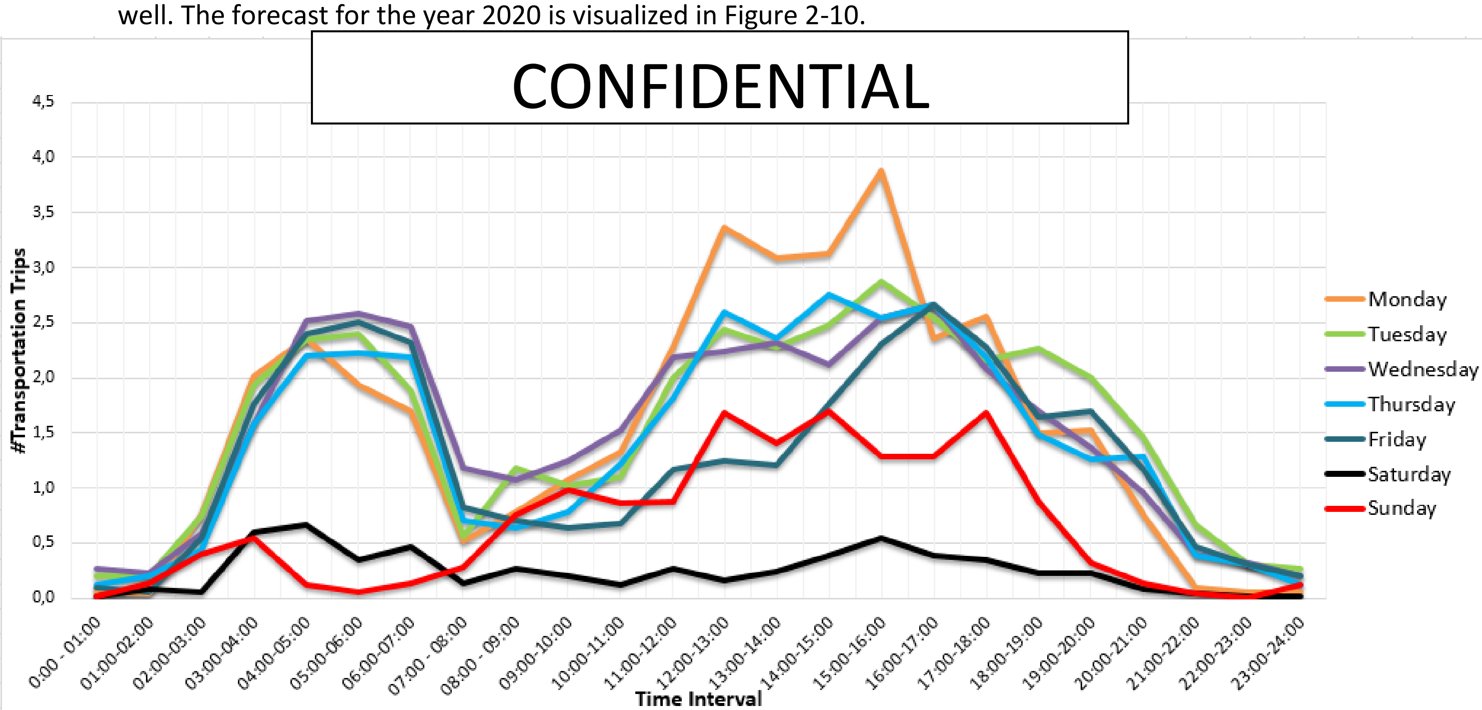

FIGURE 2-10: FORECASTED FUTURE TRANSPORTATION TRIPS REGARDING THE EXPEDITION X TRANSPORTS FOR THE YEAR 2020 (TRANSPOREON DATA COMPANY X)

When looking at the overview of the prediction for Expedition X the following stands out:

- Monday is the peak day of Expedition X for Company X.
- The transportation trips on Saturdays are almost negligible.
- Similar like the Expedition Y, the peaks are on average in the time intervals [03:00 – 09:00] and [12:00 – 19:00].
- The highest peak of transportation is approximately 4 trips within a 1-hour time interval.

Overall, based on historic transports registered via *Transporeon,* insights into peak days, peak intervals, negligible days and maximum transportation within a 1-hour interval are gained for Expedition Y and F3. Logically, the effects upon Expedition Y are higher, since their transports increase drastically due to the new warehouse.

2.4. Porter's Lodge

The porter's lodge that is currently present at Company X has several functionalities to perform. Every day porters are present to make sure that the in- and outgoing trucks handle in a correct, safe and timely manner on the Company X site. These tasks are performed by the porters and are considered very important on the site. The monitoring is done at the truck-entrance and an outside image of the current lodge is depicted in Figure 2-11.

Momentarily, trucks of multiple companies and with different loads/tasks arrive at the porter's lodge to unload their goods or load finished products to be transported to another destination. The transportation flowchart depicted in Figure 2-8 has therefore a huge impact upon the utilization and productivity of the current porter's lodge. The weighing, and especially the administration of the weighing data of both the in- and outgoing vehicles, is extremely important for the business of Company X. The porters are responsible for the registrations and monitoring of this data and therefore have a responsible task at the Company X site.

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Furthermore, safety during the execution of activities by the truck drivers, other visitors and staff members of Company X is a major concern of the porters. Overall, the different daily tasks that the porter has to perform currently are summed up in Table 2-10.

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The porter's lodge is occupied by at least one porter 24 hours per day for 7 days per week. Due to the extensive amount of work functionalities and the uncertainty of workload, the presence of at least one porter is necessary to ensure that customers and visitors are received and directed to the right persons and locations. However, currently roughly 15% of the incoming trucks are dedicated for direct customer delivery. The other 85% pass the porter's lodge on its way out to go to other external locations. Therefore, the porters know the truck drivers and since they are aware of the entering trucks they immediately know if the truck drivers know the safety rules and the behavior demands required by Company X on its site. However, in the new situation about 85% of the incoming trucks at the porter's lodge are customers. Since Company X cannot influence the classified truck drivers of their customers, they ought to give the safety instructions over and over again to the new truck drivers. Furthermore, way more trucks are passing the porter's lodge, since the customers are retrieving their orders from the new warehouse in the future.

2.4. Conclusion

Throughout this chapter, the current situation at Company X is described. First of all, the facilities present on-site are discussed. In here, the supply of Product X happens at F1 where the Product X are cleaned and sorted for production. F3 Product Y for Location Y are produced at Z1, F2 Product Y are produced at Z4 and specialties like the product X croquets are currently produced at Z5. Analysis of the throughput of the different production lines is performed based on historic data. Overall, when comparing the three production facilities it can be said that Z4 produces the highest number of tons per week, followed by Z1. Since Z5 produces specialties, their demand is somewhat lower and varies a lot, because innovation is especially important for Z5. Furthermore, the products are stored at the expedition areas. The products from Z1 are stored at Expedition X and the products from Z4 and 5 are stored at Expedition Y. The process of storing and expedition through AS/RSs is evaluated. All the characteristics of the storage location, the conveyer belts and the expedition area are discussed.

Besides the facilities on-site, the transportation flows currently present are put into a framework to give clear insights and provide the groundwork for this research. Quantifying the inputs/outputs of the facilities in combination with the number of trips taking place results in a framework of the current situation. To be able to come up with a profound analysis, the transportation planning is also incorporated. The planning, currently done via *Transporeon*, guides the current activities on the Company X site and ensures that malfunctioning is diminished. Lastly, the functioning of the current porter's lodge is evaluated. The porters are responsible that the in- and outgoing trucks handle in a correct, safe, and timely manner. The functioning of the porter's lodge is described extensively, because these functionalities alter in the future and have a meaningful impact upon the logistical framework of Company X.

3. Literature Review

Within this chapter, literature is reviewed in order to find suitable information and ground certain aspects throughout this research. Section 3.1. provides an overview of different routing models and techniques regarding: (1) an AGV, (2) dynamic routing and transport prediction, and (3) transportation network resilience. Furthermore, Section 3.2. discusses the type of simulation model that is suitable for this research. Moreover, in Section 3.3. methods for validation and verification of case studies and models are investigated. Lastly, the Analytical Hierarchical Process (AHP) is proposed for decision-making upon performance indicators, based on a model retrieved from literature.

3.1. Logistical Transportation Networks

For the logistical network, multiple routing models can be unraveled. Here, the focus lies upon the routing of the AGV, dynamic routing and transport prediction, and transportation resilience. These principles are thoroughly outlined in the following paragraphs.

3.1.1. AGV Routing

Regarding the usage of an AGV, it is extremely important that its efficiency and performance-rate are high. Interruptions during the activities of the AGV can result in serious trouble considering production and capacity. “Control of AGVs is the key to an efficient transportation system. Where control means computation of routes (routing) on the one hand and collision avoidance on the other hand.” (Möhring et al., 2005). Thus, controlling the AGV is one important measure to avoid interruptions.

Furthermore, making the designated AGV routes conflict-free could be another solution. “Collisions can already be avoided at the time of route computation, which is called conflict-free routing” (Möhring et al., 2005). To do so, two key aspects must be considered. On the one hand, the physical dimensions of the AGV and on the other hand the software approach has to be dynamic. The physical dimensions determine whether the AGV colludes when making certain moves on the track. Having a dynamic way of programming results in the fact that the AGV is reliable in its way of driving. Meaning that surrounding vehicles and other possible dangers are noticed in advance. Reliable driving in combination with a low velocity ensures that the chance of collisions diminishes drastically.

Moreover, two other safety measures called safety-tubes can be implemented. “A distance dependent safety-tube blocks an area in front of the AGV. The length depends on the speed of the AGV and is at least the distance needed to come to a complete stop (braking distance). The time dependent safety-tube on the other hand allows a little deviation from the computed time, i.e., the expected arrival time at a specific point. This is necessary because there will always be small differences between computed times in the model and the times when the AGV reaches a point in reality” (Gawrilow et al. 2007). Therefore, besides the controlling of the AGV and the conflict-free routing, distance and time dependent measures could also help in avoiding hindrance and collisions.

Lastly, the AGV should be able to integrate the logistical network of Company X within its software to keep track of all the movements and even be able to adjust its routing when necessary. The AGV routing is complex, but to ensure that the transportations from the production facilities to the new warehouse comply with the output of production and the demands at the new warehouse, the AGV efficiency needs to be high. The eventual functionality of the AGV and the competences and possibilities of the techniques are explained in Section 4.2, where information of different suppliers of AGVs is gathered.

3.1.2. Dynamic Routing and Transport Prediction

In the future situation, Company X needs to deal with a Multiple Vehicle Routing Problem with Time Windows (MRPTW). This is a hard and combinatorial optimization problem, where stochastic transportation trips are fundamental (Motemanni et al., 2005). The customers arrive within certain time windows and the orders need to be ready as soon as possible to ensure that the vehicles can maneuver efficiently on the site. Therefore, preventative transportation prediction can result in significant improvements regarding logistics.

The dynamic vehicle routing problem is strongly related to the static vehicle routing problem. The main difference is that the dynamic version alters the optimization problem, where the static problem can be formulated as: *n* customers must be served, where each customer *i* asks for a quantity *qi* of goods. Within this research, the vehicle routing problem is especially applicable and important for Company X on its site. It is of importance, because when Company X can track their incoming customers prior to the entering of the site, they will have the opportunity to prepare the orders way better and efficiently handle the trucks. Doing so, results in the logistical network not being overly crowded within peak hours for example. So, proactive dynamic routing and transport prediction are important aspects to take into account. Thereby, forecasting models are required to determine the number of transportation trips per time interval to ensure that the logistical network can deal with it. Regarding the forecasting of transports, three different elements are explained within literature (Bruhns et al., 2005):

1. **Long-term forecasts**: these forecasts represent well documented long-term trends. Although not dynamic, as they are known well in advance and are not subject to stochastic variations, these forecasts are time-dependent.
2. **Mid-term forecasts**: within the mid-term forecasting models the extent of seasonality can be addressed. Seasonality ought to be integrated to ensure that the transport prediction for certain products is good. Regression models are typically suitable for this type of forecasting.
3. **Short-term forecasts**: the short-term forecasts are usually integrated some days beforehand. The time interval is short and thus predictions can be made on a more trustworthy basis. However, companies usually refrain from this method since it is too costly and time consuming.

To be able to integrate forecasting models within a company, extensive data collection, data analysis and testing procedures are required (Potvin et al., 2004). For Company X, the integration of extensive data collection and corresponding analysis could provide significant benefits due to the efficient handling within its logistical network. Explanation of the future situation incorporating the new warehouse, regarding transportation prediction and stochastic routing within time intervals, is integrated in Section 4.4.

3.1.3. Transportation Network Resilience

To be able to predict system performance is extremely challenging, but these predictions are important to ensure that the transportation network remains functioning adequately even during emergency situations. Therefore, transportation network resilience is an important concept that deals with the levels of risks involved in the networks and tries to deal with it as good as possible. A resilient transportation system has ten properties (Godschalk, 2002):

- *Redundancy* → indicates that multiple components serve the same function.
- *Diversity* → components are functionally different.
- *Efficiency* → indicates input-output ratio optimization.
- *Autonomous components* → ability to operate independently.
- *Strength* → indicates the system's ability to withstand an event.

- *Adaptability* → implies that the system is flexible, and elements are capable of learning from past experience.
- *Collaboration* → indicates that information and resources are shared among components or stakeholders.
- *Mobility* → indicates that travelers are able to reach their chosen destinations at an acceptable level of service.
- *Safety* → suggests that the system does not harm its users or unduly expose them to hazards.
- *Ability to recover quickly* → an acceptable level of service can be restored rapidly and with minimal outside assistance after an event occurs.

The properties of a resilient transportation system ought to be taken into account when integrating an AGV within a logistical network that is already complicated. Future alternations incur higher levels of risk especially regarding crossings of driveways and traffic junctions. These fundamental issues, including the bottlenecks for Company X'sfuture situation, are explained in Section 4.2.

3.2. Simulation Study

To perform a case study, eventually a model is required to integrate the complexities and to assemble all the different pieces. Company X has the wish to obtain an animated version of reality to come up with conclusions and trade-offs prior to the operationality phase of the new warehouse. Thereby they want to make use of a simulation model as a convincing tool for the future situation. The suitability of building a simulation model for comparing it with reality needs to be investigated, since it can visualize and realize the new situation for Company X. A definition of simulation is retrieved from literature followed by the purpose of simulation with accompanying advantages and disadvantages. Moreover, the concept of Discrete-Event Simulation is explained. Lastly, the principle of simulation optimization is described.

3.2.1. Definition

Computer based dynamic simulation can be defined as: "experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and/or improving that system" (Robinson, 2014). Therefore, by means of simulation, multiple future projects can be simulated beforehand to check what the impacts are. Key Performance Indicators (KPIs) primarily determine the impact and consequences that future alternations to logistical networks might have. By means of the performance upon the established KPIs, decisions can be made beforehand via the experimentation by means of a simulation model.

3.2.2. Purpose of Simulation and (dis)advantages

Simulation modelling is a complex modelling technique. To emphasize its usefulness, this section deals with the purpose of simulation and the advantages that this technique can have on the one hand and the possible disadvantages that might occur during the process on the other hand. The need for simulation can be present within a large range of systems. Banks et al. (1996) proposed multiple systems that might have affinity towards simulation:

- Manufacturing systems
- Public systems: health care, military, natural resources
- Transportation systems
- Construction systems
- Restaurant and entertainment systems
- Business process reengineering/management
- Computer system performance

The eventual logistical purpose of simulation can be reduced to three major points:

- Analyzing supply chains
- Designing and operating transportation systems
- Designing and analyzing manufacturing systems

With regards to the impact upon the logistical network of Company X, simulation can ground the analysis of the entire network and address possible malfunctioning beforehand. Therefore, within this research the main purpose of simulation lies upon the alternation of the transportation system.

Advantages

The most important advantages of the usage of simulation techniques are explained based on literature. In total, six significant advantages in relation to other modelling approaches are provided. (Robinson, 2014).

- *Transparency* → a manager faced with a set of mathematical equations or a large spreadsheet may struggle to understand, or believe, the results from the model. Simulation is appealing because it is more intuitive, and an animated display of the system can be created, giving a non-expert greater understanding of, and confidence in, the model.
- *Creating knowledge and understanding* → the development and use of a simulation model forces people to think through issues that otherwise may not have been considered. The modeler seeks information, asks for data and questions assumptions, all of which lead to an improved knowledge and understanding of the system that is being simulated.
- *Fostering creativity* → by means of a simulation, ideas can be tried in an environment that is free of risk. This can often help to encourage creativity in tackling problem situations.
- *Modeling variability* → simulations are able to model variability and its effects. If the systems being modelled are subject to significant levels of variability, then simulation is often the only means for accurately predicting performance.
- *Consensus building* → many simulation studies are performed in the light of differing opinions as to the way forward. A simulation model can be a powerful means for sharing concerns and testing ideas with a view to obtaining an accommodation of views.
- *Visualization and communication* → visual simulations prove a powerful tool for communication. It may be that an idea has already been proven, but it is deemed necessary to build a simulation model in order to convince senior managers and colleagues of its validity.

Disadvantages

Several disadvantages are worth mentioning, since these need to be taken account when the deployment of the simulation model is performed (Robinson, 2014):

- *Time consuming* → simulation is a very time-consuming approach. Due to the extensive amount of programming, data and often a long simulation horizon, the actual simulation requires a lot of time.
- *Data hungry* → most simulation models require a significant amount of data. Often, lots of analysis is required to put it in a suitable form for simulation.
- *Requires expertise* → simulation requires skills in conceptual modelling, validation and statistics, as well as skills in working with people and project management. This expertise is not always readily available.
- *Expensive* → the simulation software is usually rather expensive and the cost of model development and use may be considerable. Especially when consultants are involved.

3.2.3. Discrete-Event Simulation (DES)

"Discrete-Event Simulation concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time" (Law, 2015). These points in time are the ones at which an event occurs, where an event is defined as an instantaneous occurrence that may change the state of the system. Therefore, discrete-event simulation focuses primarily on the change of states due to events that occur. With regards to the new warehouse of Company X, discrete-event simulation is a logical option. The state of the logistical network changes by means of different events occurring over time and interaction among agents (vehicles) is partly integrated as well.

3.2.4. Simulation Optimization

Simulation is a useful tool for evaluating the performance of systems. However, a simple evaluation of performance is often insufficient. Therefore, simulation optimization might come in handy. "Simulation optimization is the process of finding the best values of some decision variables for a system where the performance is evaluated based on the output of a simulation model of this system (Olafsson et al., 2002). Within a discrete environment optimization involves selecting the best alternative. When we have a set of alternatives, $\Theta = \{\theta_1, \theta_2, \ldots, \theta_m\}$, with *m* relatively small it may be possible to evaluate every solution and eventually compare performance. However, the simulation output is usually stochastic and comparing of alternatives becomes hard.

The two methods that can be used to statistically find (sub)-optimal solutions are (1) indifference zone ranking and selection (R&S) and (2) multiple comparisons procedures (MCP). The most common approach is to define an indifference zone δ for the performance and develop a procedure that selects a solution with performance that is within δ units of the optimal performance with a given probability, that is, if θ^* is the optimal solution and θ is the selection solution then:

$$\text{Prob}\left[\left|f(\theta) - f(\theta^*)\right| < \delta\right] \geq 1 - \alpha,$$

Where $1 - \alpha$ is the desired probability (Kelton et al., 2000).

Multiple comparisons procedures (MCPs) is another approach for selecting the best solution. MCPs calculate simultaneous confidence intervals for $f(\theta_i) - f(\theta^*)$, , i = 1, …, m, where θ^* is as before the optimal solution (Matejcik and Nelson, 1995).

When it is impossible to evaluate every solution by means of one of the two beforementioned statistical selection procedures, one might also think about a random search algorithm to iteratively find a good solution. The procedure for this random search is as follows (Olafsson et al., 2002):

0. Select and initial solution $\theta^{(0)}$ and simulate its performance $X(\theta^{(0)})$. Set k = 0.
1. Select a candidate solution θ^c from the neighborhood $N(\theta^{(k)})$ of the current solution and simulate its performance $X(\theta^c)$.
2. If the candidate θ^c satisfied the acceptance criterion based on the simulated performance, then let $\theta^{(k+1)} = \theta^{(k)}$; otherwise let $\theta^{(k+1)} = \theta^{(k)}$
3. If stopping criterion is satisfied terminate the search; otherwise let k = k + 1 and go back to Step 1.

3.3. Model Validation and Verification

After extensive data research and modelling, the eventual model needs to be checked to ensure model credibility. Model credibility is of utmost importance for this research, because the eventual outcome ought to be implemented into reality. (Sanger, 2008) describes model credibility as developing the confidence needed by (potential) users in a model and in the information derived from the model that they are willing to use. Implementation requires confidence, and confidence can be created by means of validation and verification techniques. It is often too costly and time consuming to determine that a model is absolutely valid, however tests and experiments can be performed to come close to a completely valid model. Incorporating a high level of model confidence requires broad research and thus increased costs. To ensure confidence for the decision-makers for eventual implementation, validation and verification are significant processes that should be integrated within this research. The different methods for validation and verification are discussed in the following paragraphs. Although this research cannot be implemented yet, validation and verification of the model is still important to gain confidence for future implementation.

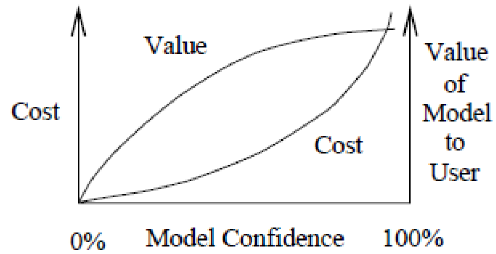

FIGURE 3-1: COSTS VS MODEL CONFIDENCE (SANGER, 2008)

3.4.1. Validation

One of the most difficult, and time-consuming elements of validation is *data validation*. Data is needed for multiple purposes: building a conceptual model, validating the model and performing experiments with the validated model. To be able to build a good model, usually enough data needs to be available to ensure appropriate and accurate performance. Data validity is defined as: “ensuring that the data necessary for model building, model evaluation and testing, and conducting the model experiments to solve the problem are adequate and correct” (Searles et al., 1988). A simplified version of this process is depicted in Figure 3-2.

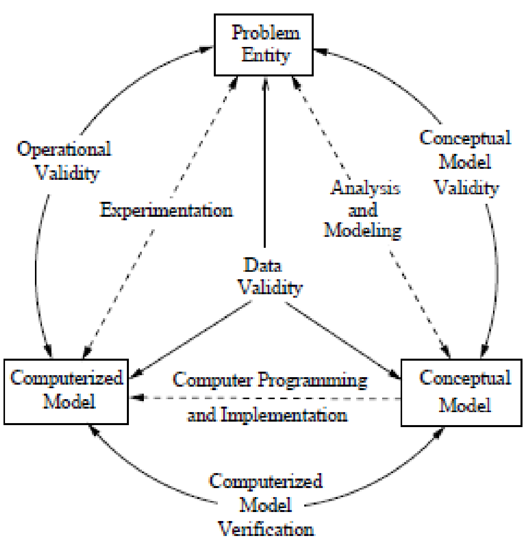

Figure 3-2: The Modelling Process (Sargent, 2008)

Multiple model validation techniques can be thought of to decide whether a model is valid or invalid. The most common and widely used approaches are:

- *Internal Validity* → several replications of a stochastic model are made to determine the amount of internal stochastic variability in the model.
- *Animation* → the model's operational behavior is displayed graphically as the model moves through time.
- *Historical Data Validation* → if historical data exists, part of the data is used to build the model and the remaining data is used to determine/test whether the model behaves as the system does.
- *Event Validity* → the "events" of occurrences of the model are compared to the real system to determine if they are similar.
- *Operational Validity* → determining that the model's output behavior has the accuracy required for the model's intended purpose over the domain of its intended applicability.

Most of the validation testing and evaluation takes place within the output sector of models. Therefore, *operational validity* is extremely important to find any deficiencies that might make the model invalid. Within the next session, three statistical approaches for *operational validity* are evaluated: (1) Hypothesis Testing, (2) Confidence Intervals and (3) Graphical Comparisons (Sanger, 2008).

1. Hypothesis Testing

Hypothesis tests can be used for comparison of statistical measures like means, variances and distributions for every set of experiments. Thereby a range of accuracy needs to be determined, and based on that, hypothesis testing can be performed. Two hypothesis states are applicable:

- **H0** → model is valid for the acceptable range of accuracy under the set of experimental conditions.
- **H1** → model is invalid for the range of accuracy under the set of experimental conditions

In testing hypotheses there are two types of errors that might occur. Type I error is rejecting the validity of a valid model and the type II error is accepting the validity of an invalid model, which is shown in Table 3-1. Here the type I error is indicated by α and the type II error by β.

TABLE 3-1: HYPOTHESIS TESTING SCENARIOS (BALCI AND SARGENT, 2002)

	when H0 is true	**when H1 is true**
Do not Reject H0	correct decision $p = 1 - \alpha$	Type II error $p = \beta$
Reject H0	Type I error $p = \alpha$	correct decision $p = 1 - \beta$

The type of errors can be categorized into the *model builder's risk* and the *model user's risk*. The model builder's risk can be referred to as the α, and the model user's risk as β. In model validation, especially the model user's risk is extremely important and must be kept small (Balci and Sargent, 2002).

2. Confidence Intervals

The confidence intervals can be used for the output variables of the configured model and accompanying system based on the experimental conditions. The mean and variance of a set of data determine its corresponding confidence interval. Furthermore, analysis based on experiments can be performed to check which experiment performs better and also to perform hypothesis tests to verify validity based on the confidence intervals. Confidence intervals can be made smaller by increasing the sample size. However, a tradeoff needs to be made among the sample sizes, confidence levels and the level of accuracy.

A box plot, depicted in Figure 3-3, is one of the methods in which confidence intervals can be used to determine the accuracy of model validation. In here, the means and accompanying variances of the model and system can be plotted to check the elasticity and the similarity among the two.

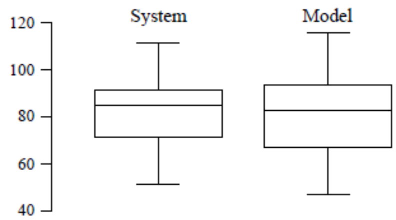

FIGURE 3-3: EXAMPLE BOX PLOT OF SYSTEM VS. MODEL (BALCI AND SARGENT, 2002)

To come up with the confidence intervals, a confidence level needs to be determined. This confidence level is determined by means of (1 – α), where α indicates the error-margin.

3. Graphical Comparisons

Comparing behavior for a various set of experiments of a specific model can easily be graphed to check performances. Common and well-known types of graphs are: histograms, box plots and behavior graphs. As said, the box plot makes use of the mean and the variance, indicating the range of output. Within a histogram the frequencies of occurrence among the mean are determined. The behavior graph validates how the model reacts when certain indicators are altered, therefore leaving space for preferred adjustments regarding key performance indicators. The graphs can be used to make a subjective judgement whether a model suffices the intended purpose. Furthermore, it provides a visual representation which significantly improves the way of thinking of decision-makers.

3.4.2. Verification

Besides the different validation techniques, verification is an important aspect with regards to the structure and contents of the model. *Verification* occurs when the model developer exercises an apparently correct model for the specific purpose of finding and fixing modeling errors. It refers to the processes and techniques that the model developer uses to assure that his or her model is correct and matches any agreed-upon specifications and assumptions (Carson, 2002). The modeling errors that occur frequently can be grouped into the following categories:

- **Data and Data Model Errors** → data errors in the input data, as well as data modeling errors, occur frequently. The data modeling errors refer to how the data is used in the model, where a typical error is to assume an inappropriate statistical distribution for random data.
- **Logic Model Errors** → these errors refer to the model's specification or implementation due to errors in its language. Thereby, "faulty indexing is the number one source of computation errors in modelling" (Schriber et al, 2001). In larger, and more complex models, this type of error is more likely to occur. Therefore, thorough analysis upon the logic of the computed model is necessary.
- **Experimentation Errors** → there are several common errors that can occur during experimentation and the misinterpreting of confidence intervals. Mostly these errors are not included in verification and validation discussions, but they may lead to models not being useful.

Throughout the modelling, matters of verification need to be taken into account to ensure that the model is built, programmed and analyzed in a reliable way. The above-mentioned errors are very common, and it is best to already keep them in mind and consider them during the modeling process.

3.5. Analytical Hierarchical Process (AHP)

To be able to perform a criteria analysis throughout this research, the impact per variable is investigated by means of the Analytical Hierarchical Process (AHP). "AHP is a model that can be used to make decisions in situations involving more than one criterion, and when multiple objectives are important to a decision maker, it may be difficult to choose between these alternatives" (Winston, 2004). If there are *n* possible criteria, then an *n x n matrix* can be used as a pairwise comparison matrix. An example of such a matrix is depicted in Figure 3-4:

$$A = \begin{bmatrix} \frac{w_1}{w_1} & \cdots & \frac{w_1}{w_n} \\ \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \cdots & \frac{w_n}{w_n} \end{bmatrix}$$

FIGURE 3-4: EXAMPLE PAIRWISE COMPARISON MATRIX (WINSTON, 2004)

In here, the entry in row *i* and column *j* of A (a_{ij}) indicates in this case how much more important criteria *i* is than criterium *j,* whereas w_i indicates the weight of criterium *i*. The value of a_{ij} can take on different values, ranging from 1 to 9 in this case:

TABLE 3-2: VALUE INTERPRETATION MATRIX FOR AHP (WINSTON, 2004)

a_{ij}	Value Interpretation
1	Objective *i* and *j* are of equal importance
3	Objective *i* is weakly more important than objective *j*.
5	Objective *i* is strongly more important than objective *j*.
7	Objective *i* is demonstrably more important than objective *j*.
9	Objective *i* is absolutely more important than objective *j*.
2,4,6,8	Intermediate values

Within the pairwise comparison, the vectors **w** = $[w1, w2, w3 \ldots wn]$ need to be determined, where the weights of each of the possible criteria are analyzed by means of this vector. To be able to do so, we need to consider the following formula based upon *n* equations:

$$Aw^T = \Delta w^T$$

In this case Δ is an unknown number and w^T is an unknown column vector. In that case if A is the pairwise comparision matrix of a consistent decision makers, and it is not allowed for Δ to be 0, then the only nontrivial solution to the system is Δ = *n* and w = $[w1, w2, w3 \ldots wn]$ (Winston, 2004). But if the decision maker is not perfectly consistent, then an approximation procedure is put in place. In this case, we need Δmax to be the largest number for which the system has a non-trivial solution $Wmax$. If the comparisons among the criteria do not deviate that much from the consistent ones, then it is expected that Δmax can get close to *n* and $Wmax$ is close to w. To check consistency for the decision maker, one could look at the closeness between Δmax and *n* to get justifiable insights. Approximating $Wmax$ can be done according to literature via a two-step approximation procedure:

1. Divide each entry in column *i* by the sum of the entries in column *i* for each of the columns in the pairwise comparison matrix of Figure 3-4. Thereby, a new matrix $Anorm$ is created where the sum of each column should be exactly 1.

2. Find an approximation for $Wmax$. To do so, an estimation of wi can be found by calculating the average of the entries in the rows of $Anorm$.

Afterwards, the decisions must be checked upon consistency to see whether they are justifiable. To do so, a procedure is put into place (Winston, 2009):

1. Compute Aw^T, which can be done by a multiplication of the matrix A and the vector w. Doing so, results in a new column matrix.

2. The Consistency Index (CI) needs to be computed. For that, one specific formula can be used:

$$CI = \frac{\left(\frac{1}{n}\sum_{i=1}^{i=n}\frac{i\text{th entry in Aw}^T}{i\text{th entry in w}^T}\right) - n}{n-1}$$

3. Comparison between the Consistency Index (CI) and the Random Index (RI) is required to check if CI is sufficiently small. If they are small enough than the decisions made by the decision-maker are consistent enough to give useful prediction of the weights and the ranking among the criteria. The RI is dependent upon the number of criteria, in this case depicted by *n*. The values corresponding to the RI are retrieved from literature and implied in Table 3-3. The consistency is acquired when $\frac{CI}{RI} < 0.1$. If it is higher than 0.1, inconsistencies within the decisions arise. Therefore, this check upon consistency is incurred in the comparison among performance measures throughout the research.

Table 3-3: RI Values (Winston, 2009)

n	*RI*
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

Eventually, at the end of this research, this AHP method is used to compare the criteria with each other and derive a hierarchy of importance based on assigned weights.

3.6. Conclusion & Integration of Literature

Within this chapter, a literature study is performed to be able to gather information. In here, the AGV and its conflict-free routing are investigated. Furthermore, dynamic routing and transportation forecasting are discussed. Moreover, the concept of transportation network resilience is addressed to gather the fundamentals for a transparent and functional logistical network. Besides that, discrete-event simulation is explained to check its suitability for this research. Simulation has multiple advantages and some disadvantages that are all addressed as well. Furthermore, validation and verification techniques are discussed to ensure that a model is trustworthy and applicable in reality. Especially, operational validity and data verification are of utmost importance throughout the modeling process. Statistical approaches for operational validity are: (1) hypothesis testing, (2) confidence intervals and (3) graphical comparisons. Within the verification phase, the common modeling errors are discussed. Lastly, a method for comparison among criteria is proposed. In this case, AHP is investigated to derive suitability for this research and eventually use it to come up with significant results and grounded recommendations.

Conclusively, the literature framework grounds this research and is incorporated in the decisions made and analyses performed. The determined research questions and goals are investigated within the following chapters, where the literature is the underlying line of thought. Usage of this literature is integrated in the following chapters to perform a grounded research. We will make use of the forecasting methods to predict future behavior on the Company X site. Furthermore, the discrete-event simulation model is created to animate the logistical network and check upon Key Performance Indicators (KPIs). Moreover, the validation and verification techniques are addressed in the end to ensure that a reliable model is created. Lastly, the AHP method is used to come up with significant results incorporating input from Company X.

4. Case: Integration of The New Warehouse

Within this chapter, multiple aspects regarding the integration of the new warehouse and the accompanying changes in logistics are discussed. First of all, the inbound logistics of the new warehouse is analyzed in Section 4.1. Secondly, the AGV and the alternations that Company X should perform to let the vehicle drive efficiently and fluently are grounded in Section 4.2. In here, the bottlenecks and characteristics of the AGV and its routing are evaluated. The order picking within the new warehouse is discussed shortly in Section 4.3., which is followed by the outbound logistics resulting from this process in Section 4.4. The functioning of the new porter's lodge covering both the in- and outgoing flows is explained in Section 4.5., where its degree of automation is verified by means of a market analysis. Lastly, the internal workforce and increased burden upon logistical activities accompanying the operationality of the warehouse is determined in Section 4.6. The overall structure of this chapter is outlined in Figure 4-1.

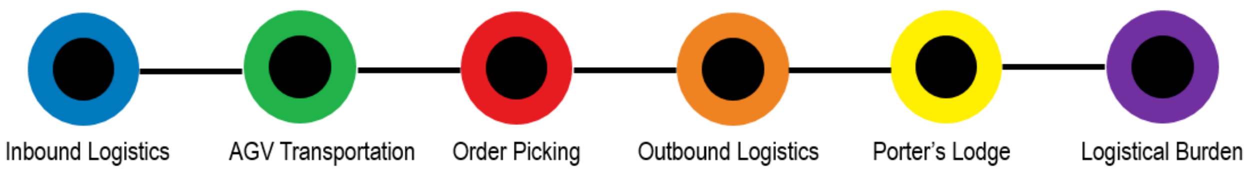

FIGURE 4-1: STRUCTURE OF THE CASE STUDY INTEGRATING THE NEW WAREHOUSE

The focus of this chapter lies upon the future plans of Company X regarding its new warehouse and the AGV track depicted in red in Figure 4-2. All the alternations and impacts upon logistics due to the integration of this warehouse are explained throughout the next couple of sections. Lastly, key performance indicators are described per section, which are further analyzed in Chapters 5 and 6.

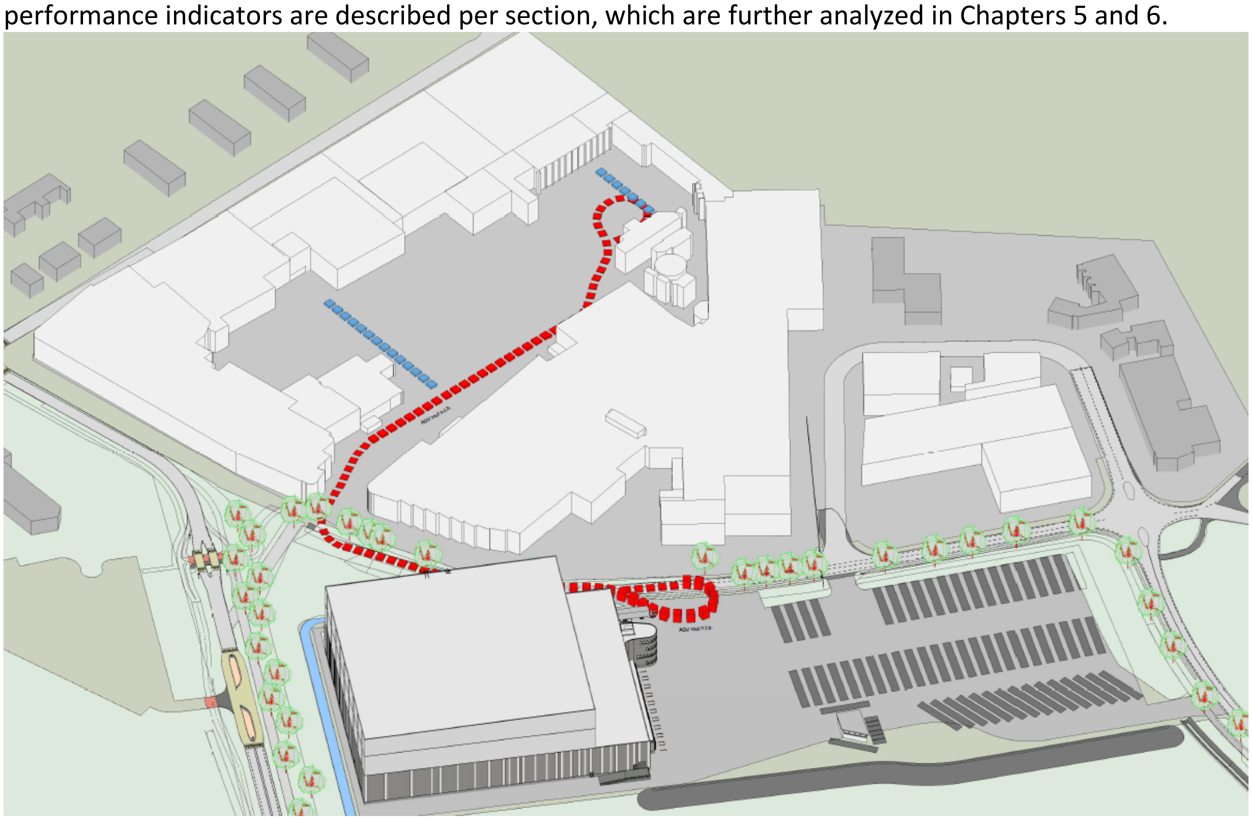

FIGURE 4-2: MASTER PLAN COMPANY X INCORPORATING THE NEW WAREHOUSE AND AGV TRACK (COMPANY X INTERNAL DOCUMENT, 2019)

4.1. Inbound Logistics

The inbound logistics of Company X is not changing drastically, due to the fact that the incoming supply of raw materials (i.e. Product X) and emballage remains constant over time. Therefore during modeling, the inbound logistics can accurately be modelled due to the fact that based on historic data a statistical analysis with corresponding distribution can be fitted through the data to see resemblances and trends. Based on that, future predictions can be put into play in a simulation model. The key performance indicators that have a significant impact upon the inbound logistics are: (1) Average Daily F1 Transports, (2) Average Daily Z5 Transports and (3) Average Daily Pallet Transports. These indicators are elaborated in Section 5.3.

4.2. The AGV

To be able to integrate the AGV into the new situation, a market analysis upon the possibilities and opportunities of its functionality is required. Thereby, we look at the AGV track and its routing, the bottlenecks upon the Company X site and the different parameters and characteristics that are available on the market. One of the potential suppliers of the AGV is Götting, a German company that is specialized in the production of automated guided vehicles and the guidance systems and components that ensure driverless transportation systems. An interpretation of one of their driverless transportation systems for outdoor usage is shown in the following video: https://www.youtube.com/watch?v=3tE3HMnPTEk. Integration of such a system requires adjustments to the current situation, and therefore an outline of the AGV and its guidance track ought to be obtained. Furthermore, the bottlenecks within the current logistical network that could cause interruptions are analyzed. Lastly, calculations regarding the cycle time of the AGV are performed.

4.2.1. AGV-Track and Routing - Götting

A guidance track for the AGV is applicable for the Company X site, since they instantaneously want to make use of only 1 AGV. Therefore, the AGV track covering the distance from the current Expedition Y area towards the new warehouse (depicted in Figure 4-2) can be a two-way track driven by one AGV. This track could be guided by means of transponders along the track. The transponders that are used are RFID transponders that are placed within the road. These transponders are depicted in Figure 4-3, whereas the vehicle setup that would be used to drive upon a guidance track with possible guidance systems is depicted in Figure 4-4. Major advantages of these sensors are that they are highly reliable since they do not fatigue and ensure a high precision level, because the sensors align the AGV upon the track. Furthermore, within this case there is continuous transportation since the AGV can be seen as a commuting service between the production area and the new warehouse. The suppliers ensure that the transponders work even better when there are not many deviations within the routing and thus continuous transportation along one track is applicable.

FIGURE 4-3: EXAMPLE OF A TRANSPONDER (GÖTTING, 2018)

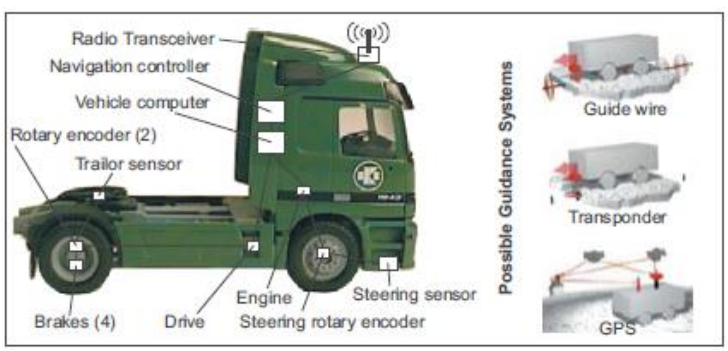

FIGURE 4-4: AGV SETUP FOR ROUTING (GÖTTING, 2018)

An example of a truck that is in use at multiple companies already, and deployed by Götting, is shown in Figure 4-5. This vehicle is able to transport up till 32 pallets, where automatic racks are used to be able to do the loading and unloading automatically as well. Furthermore, safety bumpers are attached to the sides and front. These bumpers are purely used as safety measure in case of possible collisions with other vehicles or pedestrians. However, these collisions ought to be prevented. To do so, software is used based on detection sensors attached to the truck that check whether other vehicles are in the neighborhood.

FIGURE 4-5: EXAMPLE GÖTTING AGV TRUCK AND ACCOMPANYING TRAILER (GÖTTING, 2019)

Moreover, the truck can be either a diesel or an electrical one. The diesel and electrical trucks have both their advantages and disadvantages. These are shortly explained, grounded by meetings with Götting:

Diesel Truck

Advantages

- Reliable technique, since it is already used quite frequently.
- Refueling is not required that often, due to the small distances that the AGV has to cover on the site of Company X.

Disadvantages

- Lots of noise which might result in noise complaints from neighbors if the AGV operates at night.
- The diesel truck stinks when comparing it to an electrical truck.

Electrical Truck

Advantages

- Sustainable transportation mode, which might give Company X an improved charisma to the outside.
- Almost no noise during transportation.

Disadvantages

- Life time of the electrical battery is uncertain, with possibilities of default.
- Multiple recharging moments are required, more than comparing it to the Diesel truck.

Overall, a decision upon the type of truck with accompanying trailer needs to be made. Götting is one of the major suppliers of the automatic vehicle techniques and therefore they are addressed here. A simulation model is used to verify the process integrating a similar AGV as depicted in Figure 4-5 with its track and transponders as described. Herewith, multiple key performance indicators of the AGV can be tested to see which influences this has on both the logistical network as on the other business processes like production output and storage. Important indicators for the AGV are: (1) Average Daily AGV Transports, (2) Average Daily Interrupted AGV Transports and (3) Average Daily AGV Utilization. These indicators are addressed further in Section 5.3., where they are tested based on a simulation model and their performance is analyzed.

4.2.2. Bottlenecks

The routing of the AGV and its described guidance track on the Location X site come along some serious bottlenecks regarding efficient and automatic transportation. The following bottlenecks can occur frequently and therefore have impact upon the AGV and its functionality:

1. Transports Expedition X
2. Company Y
3. Manual Supply Z5
4. Pallet Supplementing
5. Pedestrians
6. External Transport Streams

So, the "influencer framework" of the AGV depicted in Figure 4-6, needs to be resolved as much as possible to prevent future interruptions and initiate efficient and fluent transport.

FIGURE 4-6: THE FUTURE AGV & ITS HAZARDS AND OPPORTUNITIES

To clarify the network, the reasons that pictures 1 until 6 are possible bottlenecks for the AGV are explained. These are described in the following paragraphs, where possibilities for prevention or impact reduction upon the AGV logistics are indicated. Moreover, pictures 7 and 8 are the desired goals for the AGV track and AGV to function properly on the Company X site. Within Chapter 5, a simulation model is created to check the impact of the different bottlenecks and see if preventative actions can be performed. Herewith, the framework is investigated to incur efficient transportation of the AGV.

1. Transports Expedition X

The Expedition X department is not affected by the changes due to the new warehouse, thus their transportation trips remain almost the same as described in Chapter 2. As pointed out already, the trips towards and from Expedition X cross the AGV-track. A truck crosses the track at least twice, resulting in possible interruptive moments for the AGV when one of these trucks is detected. Since Z1 and Expedition X contribute to the core business of Company X, there is not much that can be done about this bottleneck. However, safety instructions for the drivers could help in order to avoid collisions or interruptions of the AGV. Furthermore, traffic lights and barriers can prevent the foreign drivers to enter the site and cross the AGV track without acknowledging the consequences when they interrupt this AGV.

2. Company Y

The rest material streams of Company Y contribute to the logistical network as well. Especially the collection of the product X happens frequently. Company Y gets signals when certain rest material streams are almost ready to be taken away from the Company X site and then they perform the transports on their own. Since Company Y and Company X work closely together, the truck drivers know exactly where to be and what to do. However, they will be the ones together with the transports of Expedition X who cross, interrupt and interact with the AGV and its track the most. Therefore, in the case of Company Y, Company X might need to reconsider the pick-up places for the rest material. When these are located further away from the track, then the Company Y trucks are not standing still on or besides the track causing major complications. The simulation study presented in Chapter 5 needs to check the impact of this bottleneck to verify if alternations for Company Y are required.

3. Manual Supply Z5

There are two manual supply streams of Product X for Z5, where parts of the specialty products are made from. These locations are rather narrow, as depicted in picture 3 of the framework, and therefore the truck drivers need to maneuver quite often to be able to dock their trailers with Product X. During maneuvering, the trucks cross the AGV track multiple times and therefore this is a bottleneck to consider as well. One of the possibilities to refrain this from happening is to make use of pipelines for these specific product X supplies as well. The pipelines currently in use are mostly for the delivery of Product X to both Z1 and 4, but investing in pipelines for the extra supply of Z5 is a good opportunity to diminish transportation activities on and among the AGV and its guidance track. Thus, the model of this research focuses on the supply of Z5 as well to check whether this bottleneck has influences on the functioning of the AGV and see if the usage of pipelines has positive effects in the future.

4. Pallet Supplementing

The pallets that are used in the different production facilities need to be supplemented every now and then. These pallets are stored alongside the future AGV-track, where they are retrieved for production by fork-lift trucks when necessary. The replenishment of the pallets requires transportation trips and the transport to the production facilities requires this as well. These transports happen daily, and since they are seemingly close to the AGV track, the drivers need to seriously take these activities into account.

5. Pedestrians

Several employees, visitors and other people cross the roads on the Company X site and thus they will be crossing the AGV track. Of course, it is impossible to remove pedestrian crossings, because people need to be in certain facilities at different moments. However, the crossings can be regulated via traffic lights or barriers for example to stop people from crossing the road when the AGV is nearby. Furthermore, reducing the number of crossings would be a good measure to make the activities upon the terrain more safe and prevent collisions between the AGV and crossing pedestrians.

6. External Transport Streams

Besides all the other more internal bottlenecks, there are also several external transport streams that can cause interruptions of the AGV. For example, multiple parcel vans drive around on the site to deliver packages. Since this is a highly variable and stochastic process, it is unlikely that it is possible to incorporate the external transport streams like the parcels and other small deliveries into the planning and strategy of the AGV. However, again safety regulations can be put in place here. Company X could for example decide to handle the external transport streams exactly the same as the Expedition X transports.

4.2.3. AGV Parameters and Characteristics

Now that we have explored the AGV, its track and accompanying bottlenecks, let us focus on the different parameters and characteristics of such an AGV. After performing a market analysis regarding the AGV, several possibilities, parameters and characteristics stand out that might be suitable for Company X regarding its requirements:

- The velocity of the AGV is approximately 6 km/h, but variations upon its speed are possible.
- Track guidance is necessary based on approximately 200 RFID transponders along the track.
- Transmission of camera image to traffic control.
- Safety equipment like bumpers.
- The trailer is attached to the AGV and no (de)-coupling of trailer and truck is necessary.
- The (un)-loading of cargo on both sides can be done automatically (as indicated in Figures 2-6 and 2-7 respectively).
- Manual takeover is possible.
- Both diesel and electrically driven AGVs are present on the market.

The described bottlenecks need to be diminished and the characteristics of the AGV can help in doing so. Variations upon the speed result in a possible increase in AGV transports when necessary, where fluctuations within its planning are also a possibility. For example, the AGV might transport more in the off-peak hours to reduce the number of transports on the site and thus reduce the chance of interruptions. Furthermore, camera and detection software results in safe and fluent transportation of the AGV. Lastly, the guidance track provides certainty that the AGV maneuvers exactly as prescribed and does not alter its route at all. Therefore, via the suppliers of the AGV and its technology, the impact of the previously mentioned bottlenecks can be reduced. However, some of them require adjustments to the current site to ensure that fluent transportation is possible. By means of modelling the future situation, these possibilities are revealed, where the above-mentioned characteristics and logic of the AGV is integrated as well.

4.2.4. AGV Transports and Cycle Time

To obtain an indication of the future situation, the AGV transports and corresponding cycle time of a single transport are analyzed. For an overview of the cycle time of one round trip of the AGV, we make a distinction in location A and location B. Location A is the start position which is at *Expedition Y*, whereas location B is the final destination of the AGV which is the *New Warehouse*. To check how many times the AGV is able to perform a transportation, we first need to compute the cycle time of one round trip.

The calculation for the cycle time, in coordination with Götting, is performed here:

Distance

- One-way distance A (Expedition Y) to B (New Warehouse) = 390 meters
- Maneuvering backwards at B = 7 meters
- One-way distance B (New Warehouse) to B (Expedition Y) = 440 meters
- Maneuvering backwards at A = 25 meters

Total Distance Round Trip = **862 meters**

Driving Time

- Average speed driving forwards = 6 km/h = 1.67 m/s
- Round trip A ↔ B = $\frac{390+440}{1.67}$ **=** 498 seconds
- Average speed driving backwards = 0.3 m/s
- Maneuvering at backwards ramps = $\frac{25+7}{0.3}$ = 107 seconds

Total Driving Time = **605 seconds**

Time Load Transfer

- Switching time before changing driving direction 5 seconds
- Open container roll-p door and sectional door 10 seconds
- Idle time 5 seconds
- Automated loading or unloading of the container 195 seconds
- Idle time 5 seconds
- Close container roll-up door and sectional door 10 seconds
- Switching time before changing driving direction 5 seconds

Total time load transfer ***=*** **235 seconds**

Cycle Time

- Round trip A ↔ B = 605 + 2*235 = **1075 seconds**
- Number of cycles = $\frac{3600}{1075}$ = **3.35 cycles/h**

Based on the calculation above we can say that in the ideal situation, the AGV is able to perform 3.35 transports per hour at the most. This situation indicates that the AGV is not interrupted and performs its activities efficiently. Meaning that it is possible to perform 3 transports in total from Expedition Y towards the New Warehouse. This cycle time is integrated into the simulation model, where we check upon the interruptions of the AGV to derive if future complications might happen if the AGV is not able to perform the necessary transports.

4.3. Order Picking

The order picking within the new warehouse happens completely automatic. Thereby, automatic storage and retrieval systems (AS/RSs) are used to store the products entering the warehouse by means of the AGV and to prepare the orders for customer retrieval. Within this research, this process is not addressed any further. But since the order picking process is important for the entire logistic network it is shortly visualized. The inner layout of the new warehouse is depicted in Figure 4-7. During modeling, the order picking process is not neglected, because both inbound and outbound logistical transports are dependent upon this process. However, no performance measures are attached to this logistical process. And since the order picking process is beyond the scope of this research, storage and retrieval are assumed constant. By constant we mean the following:

- The AGV drops its entire load at the warehouse and it is stored randomly.
- Order picking and loading of trucks happens automatically and at a fixed time.

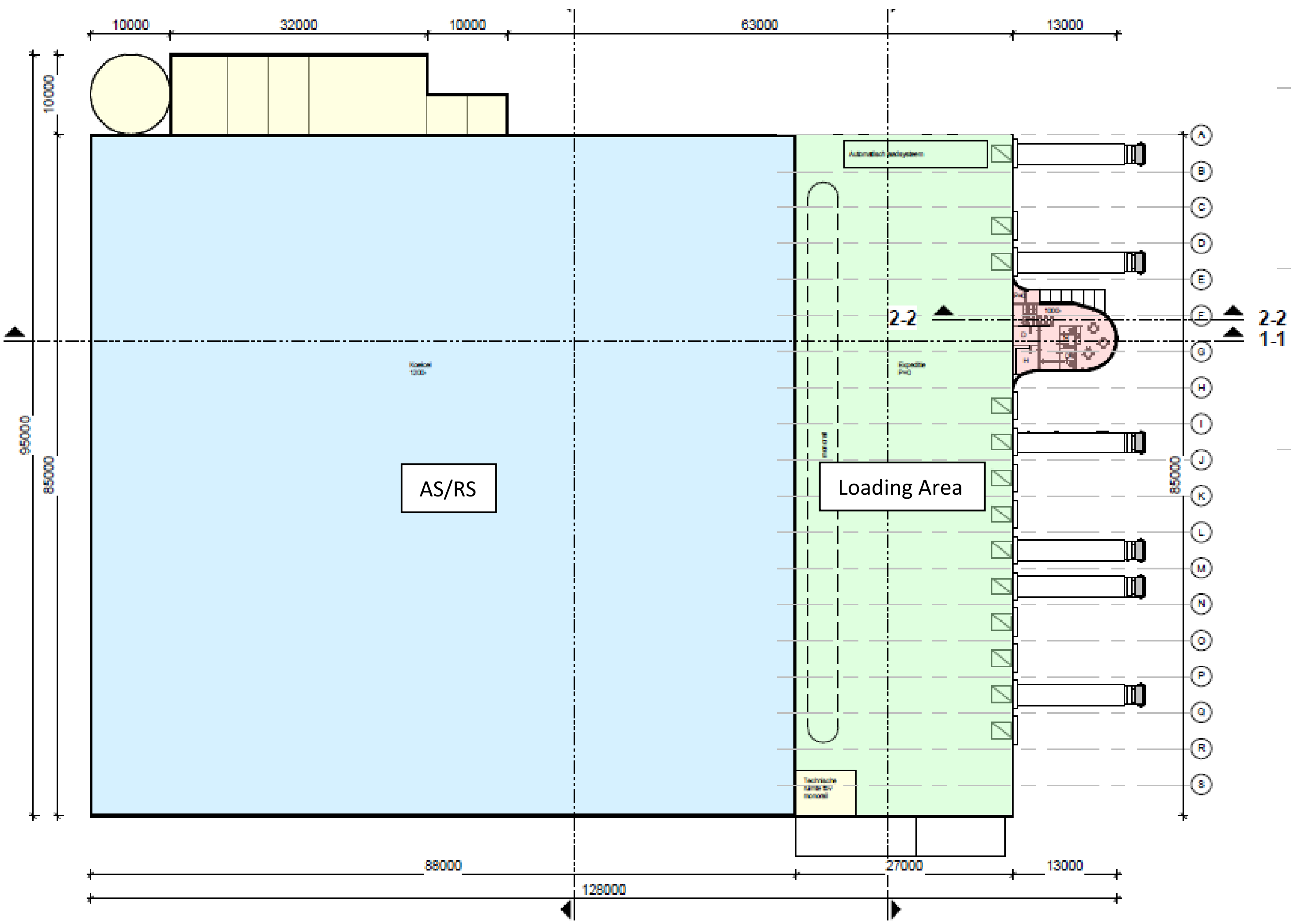

FIGURE 4-7: INNER LAYOUT OF THE NEW WAREHOUSE (COMPANY X INTERNAL DOCUMENT, 2019)

4.4. Outbound Logistics

The outbound logistics contribute to a large amount of the logistical network and thereby especially the changes that are required to ensure fluent transportation. The main focus is based upon forecasting models, in which the incoming customer and external transports are forecasted by means of a statistical distribution based on historic data. In here, we try to fit a distribution through the datasets to forecast future behaviors. Furthermore, a goodness-of-fit test is performed via a *Chi-Square* analysis. The *Chi-Square* test can be performed like this:

$$\chi^2 = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{(Oij - Eij)^2}{Eij}$$

- Oij = a contingency table with **observed frequencies** within the forecast.
- Eij = a contingency table with **expected frequencies** that should have been found if the variables are really independent of each other based on the statistical distribution.

By means of the Chi-Square we can determine the reliability of the dataset when a statistical distribution is assumed and fitted. Due to the statistical distribution with corresponding average (μ) and standard deviation (σ), the level of confidence ought to be high to ensure a good and reliable simulation model. The Chi-Square outcome χ^2 can then be tested based on the degree of freedoms within the dataset. The degrees of freedom can be determined by the number of variables (i) and the sample size (j):

$$df = (i-1) \cdot (j-1)$$

Besides the outbound flows regarding the finished products towards customers and external locations, recall that Company Y also contributes a lot to the outgoing transportation. Therefore, the rest material streams of Company Y are investigated and modelled as well. They do not have an immediate effect upon the new warehouse, but might cross and interrupt the AGV. To get a clear insight upon the influences of this bottleneck, forecasts of the transportation flows for Company Y are also done to integrate its data within this research. An example of the outbound logistics procedure at the new warehouse is shown in Figure 4-8, where the preparation phase of the loading at the docks is indicated.

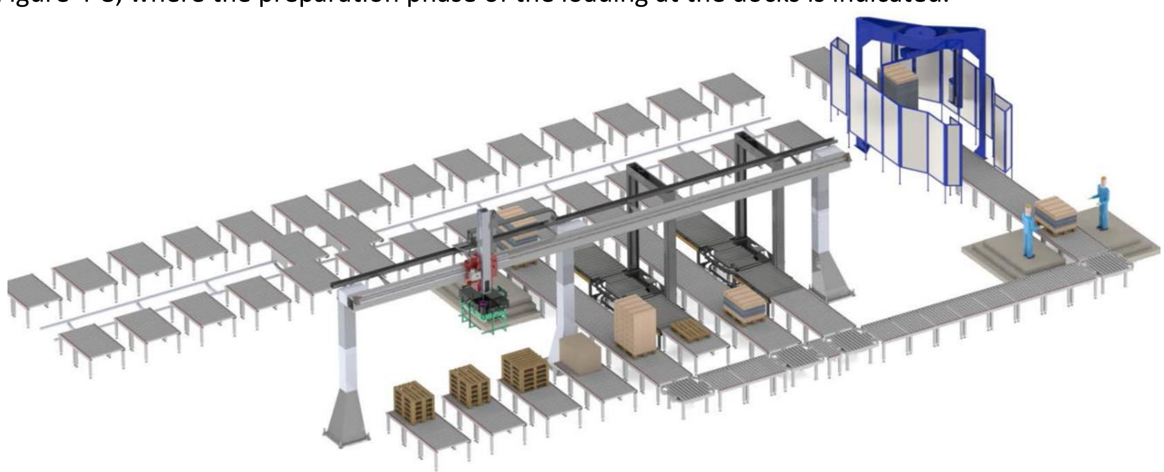

FIGURE 4-8: OUTBOUND LOGISTICS HAPPENING AT THE NEW WAREHOUSE (COMPANY X INTERNAL DOCUMENT, 2019)

Regarding the outbound logistics, the measures for performance that are investigated in the next chapters are: (1) Average Daily F2 Transports, (2) Average Daily F3 Transports, (3) Average Daily Company Y Transports and (4) Average Daily AGV-track Crossings.

4.5. The Porter's Lodge

Regarding the porter's lodge and its degree of automation, several suppliers of related technologies have been approached to investigate the developments upon the market and identify functionalities that can be done more efficiently. Furthermore, the degree of performance measurement is described within this section. An overview of the future porter's lodge is depicted in Figures 4-9 and 4-10.

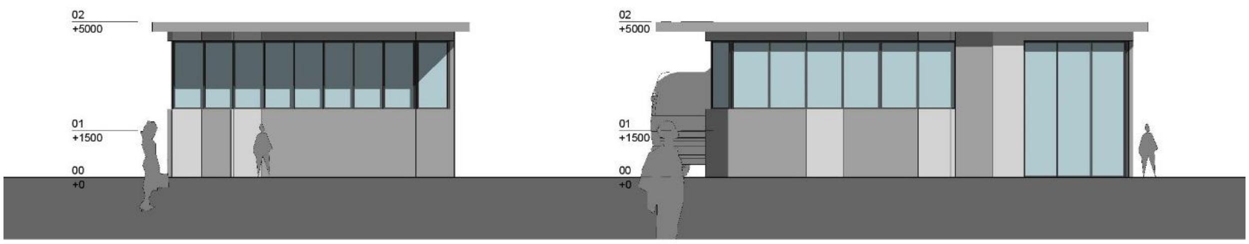

FIGURE 4-9: OUTSIDE VIEW OF THE FUTURE PORTER'S LODGE (COMPANY X INTERNAL DOCUMENT, 2019)

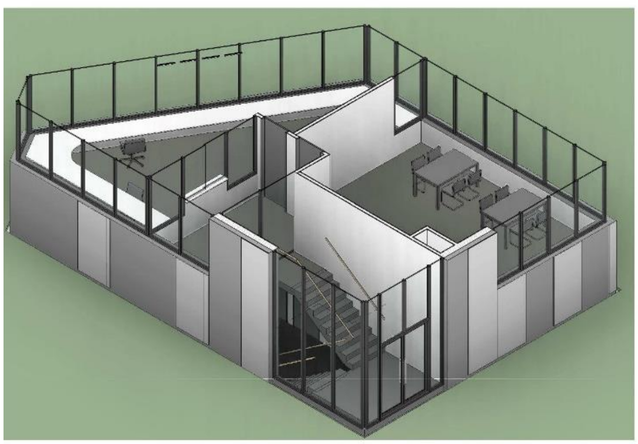

FIGURE 4-10: INSIDE VIEW OF THE FUTURE PORTER'S LODGE (COMPANY X INTERNAL DOCUMENT, 2019)

4.5.1. Market Analysis – Potential Suppliers

PreciaMolen and Mettler Toledo are potential suppliers of the weighbridges and accompanying software at the porter's lodge. Moreover, they have a wide selection of accessories that can improve transportation around the porter's lodge and the process at the weighing bridges. During the discussions with both, potential options and functionalities were opted by the suppliers. Thereby, the degree of automation upon the wishes and requirements of Company X is outlined. As described earlier, the major problem with the processes at the porter's lodge is that in the future a lot of unknown drivers arrive at the site. They need safety instructions and thus distinctions among the drivers need to be made. Furthermore, the customers coming for the finished products at the new warehouse are bound to a dock planning. Therefore, when the truck drivers arrive too early, they need to wait at the designated parking places until the operators at the warehouse give a sign that the customer is allowed to enter the site. For this process to happen fluently, decisions upon functionalities and processes ought to be made. All the automatic alternatives that are present on the market and discussed with potential suppliers are shortly described in the following paragraphs. The reason for doing this is to be able to evaluate all the possibilities and ensure good transportation flows around the porter's lodge.

Automatic Number Plate Recognition (ANPR) – with the currently available and advanced technology, automatic number plate recognition is a suitable option for increasing efficiency. To do so, a distinction between trucks and trailers needs to be made. This needs to be done because F1 truck drivers for example store their trailer with Product X on the shunting area, where they might take another trailer on their way out. Number plate recognition results in automatic processing of the weightings and thus efficient transportation handling and reduced workforce for the porters. However, ANPR is rather unreliable since multiple aspects might influence its accuracy. Due to freezing, dirt and other circumstances, the number plates might become unreadable for the system. In that way, inadequate recognition can affect the weightings and therefore the business model of Company X.

Self-Service Terminal – to automate the weighing process, a self-service terminal can come in handy. The following functionalities might be integrated in such a self-service post, which is depicted in Figure 4-11.

- *Intercom* – an intercom provides the possibility of having contact with the porter. In case of problems during weighing or something else, the truck driver can always ask the porter what to do via the intercom.
- *Multi-lingual informational touchscreen* – due to the fact that the drivers are mostly unknown at Company X and a wide variety of nationalities will arrive on the site, the information provided at the self-service terminal should be in multiple languages to ensure that safety regulations are met and understood. Furthermore, it is also essential for the drivers to know exactly where to be.
- *Barcode/Permit* – some of the truck drivers are already known at the Company X site and can get a sort of privilege treatment. Since they are known, they do not need to have extra information and can actually perform the weighing within seconds and drive to their designated destination afterwards. Truck drivers of Company Y can for example perform their activities independently. Therefore, they could get a barcode or a permit to enter the site frequently, without the porters needing to intercept them or instruct them what to do.

FIGURE 4-11: SELF-SERVICE TERMINAL FOR THE TRUCK DRIVERS (PRECIAMOLEN, 2018)

Interactive Waiting Time Communication

Since the trucks usually need to wait in order to be processed at the porter's lodge, some form of communication with them is acquired. First of all, the possibility of having interactive waiting time communication might be a solution. In here, the drivers get to know that it is their turn to go to the weighbridge and enter the site. This can be achieved based on showing their number plate on a large electronic screen at the waiting area for the porter's lodge for example.

Logistic Summon System
When the truck drivers are allowed to enter the site, they need to receive a signal. One of these semi-automatic signaling methods is a logistic summon system. These systems make use of transmitters that summon the truck drivers to drive towards the weighbridges. An image of possible summon systems is indicated in Figure 4-12.

FIGURE 4-12: SUMMON SYSTEMS FOR THE WAITING TRUCKS (VEDOSIGN, 2018)

Traffic Lights & Barriers – to ensure that the weightings are performed both automatic and correctly, traffic lights and multiple barriers are required for the ingoing weighting as well as the outgoing weighting. Furthermore, truck drivers are not allowed to enter the weighbridges without permission.

Integration Software with ERP systems – lastly, integration of the weighting software with Company X's ERP systems SAP and Navision is preferred to be able to communicate among the software. By means of the integration, analysis based on planning and prediction can for example be done. Due to the weighting process and extensive data storage, daily patterns might be detected after a while which can help Company X to do adequate (seasonal) forecasting.

Within Chapter 6, the eventual decision-making process is integrated in which the possibilities are compared to make consistent and well-thought of decisions of the structuring of the porter's lodge, its functionalities and the weighing process.

4.5.2. Measuring Performance
Due to the automation of certain functionalities of the porters, possibilities for decreased utilization and increased efficiency exist. To be able to test whether this has influences in the future, varying among the processing times within the simulation model indicates if traffic congestion arises when the porter's utilization is too high for example. A high utilization results in long waiting times for the truck drivers which is of course not preferable. The most important performance indicators regarding the porter's lodge to be tested within this research are: (1) Average Daily Porter's Lodge Utilization, (2) Average Daily Congestion Rate and (3) Average Daily Transports at the Porter's Lodge. These are explained, elaborated and tested in the upcoming chapters. Thereby, the innovative possibilities upon the market are considered to see whether implementing certain automation techniques has impact upon utilization and congestion on a daily basis.

4.6. Workforce and Logistical Burden

Based on the case description of the previous paragraphs, matters of workforce and logistical burden are affected due to the integration of the new warehouse. In this section, three major influences are described. First of all, the workforce at the new porter's lodge is analyzed where possibilities of transferring tasks towards the porters are investigated. Secondly, the transition from the Expedition Y department towards the new warehouse is briefly addressed. Lastly, the opportunity of increasing production throughput due to the extra storage space is explained. Further investigation of the logistical burden is done by means of the simulation model and computation of experiments with the key performance indicators.

4.6.1. Workforce Porter's Lodge

The workforce at the porter's lodge is about to increase due to the extensive amount of transportation and the large number of unknown drivers entering the Company X site. Therefore, an analysis of the time required per activity per day is computed. Where the activities of the porters depicted in Figure 2-1 are the same in the new situation. These activities have been quantified in Appendix A5. Based on that, approximately 2.53 Full Time Employees (FTEs) are required to fulfill the current tasks. However, due to the new situation, several tasks of other departments might be transferred to the porters lodge as well. The transferring of work is pointed out by the different departments and their estimation is that approximately 2.4 FTE could be assigned to the porters, making it a 5 FTE working job. The assigning of different tasks of the other departments is also indicated in Appendix A5, where the calculations for the FTEs are stated. Automating certain activities at the porter's lodge, as described in the previous section, might result in a reduced FTE amount required. However, a cost-benefit analysis is acquired to see whether this is a possibility. The functioning of the porter's lodge and accompanying decision-making whether to automate certain activities or not is incremented in Chapter 6 where the AHP analysis is performed with the performance measures for the porter's lodge. Thereby, the workforce as described here is considered as underlying reason for possible alternation of the KPIs.

4.6.2. Transition Expedition Y → New Warehouse

The control and monitoring of the expedition area is transmitted from the Expedition Y area towards the new warehouse. Therefore, the operators need to monitor both the storage by the AGV, the order picking by AS/RS and the retrieval by customers. They are controlling their operations from the new office depicted in Figure 4-13.

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Due to the increased work circumstances because of the new warehouse that is way bigger, multiple new employees need to be hired to fulfill the tasks. Furthermore, a piece of transition management is required to make sure that the current employees fit to the new working environment.

4.6.3. Production Increase – Number of AGVs

Due to the extra storage space and the efficient transportation resulting from the new warehouse, in the long-term Company X might want to think about increasing production throughput. One of the major drawbacks of increasing production is that the AGV should drive even more to make sure that the production output is stored in a timely manner. Therefore, for the long-term strategy it might be an option to integrate an extra AGV in the network. Of course, complications regarding routing and planning arise here but by implementing two AGVs, the transports can happen more frequently and efficiently. And thus the option of integrating an extra AGV in the future might be investigated as well.

4.7. Conclusion

Within this chapter, an elaboration upon the future case for Company X is presented. In here, the entire transportation network encompassing the new warehouse is analyzed. To be able to compute performance scores in the following chapters, multiple KPIs are defined. The inbound logistics are not altered that much, since the deliveries of Product X and emballage remain constant. The AGV and its guidance track make up the most drastic change to the logistical network. Its parameters and characteristics, after comparison among suppliers, are defined for simulation. Important indicators for the AGV are the number of transports and interruptions per day. The interruption rate and the number of transports give a critical insight in the effectiveness of the AGV. The decision has been made to look at the key performance indicators on an average daily basis. Based on that, distinctions among the different days can be made and clear insights of the functioning of the future AGV can be provided to Company X.

Furthermore, the outbound logistics play a critical part within this research. The network is rather complex due to the immense amount of trucks arriving at the site to retrieve their orders. Especially the arrival of a lot of unknown drivers results in complications in the beginning at both the porter's lodge and the warehouse. They need to be processed by the porters based on safety regulations and driving rules. Moreover, they cannot be processed simultaneously and therefore waiting times are incurred. These waiting times need to be as short as possible. Besides that, Company X wants to minimize traffic congestion at both the porter's lodge and on the site. Thus, multiple performance indicators are measured based on a simulation model to get adequate insights in possible future impacts upon the logistical network.

A market analysis, with related suppliers, is performed for the porter's lodge and the weighting process. Several automatic functionalities that are present upon the market are outlined. Eventually, decision-making needs to be done by Company X to determine their level of automation regarding this facet. However, based upon the performance measures like average daily utilization and average daily congestion rate, insights can be gained to check which influences certain activities have when they are controlled manually or automatically. Lastly, the workforce regarding both the porter's lodge and the transition from the Expedition Y area towards the new warehouse is analyzed.

5. Modelling the Logistical Network

To adequately evaluate the impact upon the logistical network, a simulation model is constructed to analyze the future situation. As concluded in Chapter 3, simulation has multiple advantages to incur transparency and provide an animated version of reality to come to consensus regarding the impact upon the logistical network in the future. Within this chapter, first of all in Section 5.1. the simulation model that is created, designed and modelled is explained and described. Secondly, in Section 5.2. the key performance indicators (KPIs) of Company X determine the basis of the analysis and derive the important contributors for this research. Furthermore, the input data gathered from the different departments of Company X is analyzed and most importantly made applicable for simulation purposes in Section 5.3. Moreover, the method of experimentation is described in Section 5.4. where the setup for the different experiments is determined. The results of these experiments are then discussed in Chapter 6. The simulation model is primarily based upon the outlined drawing of the new warehouse with its accompanying logistical processes, as depicted in Figure 5-1 underneath.

FIGURE 5-1: 3D UPPER VIEW OF THE NEW WAREHOUSE AND PORTER'S LODGE (BESSELS, 2018)

5.1. Simulation Model – Technomatix PlantSimulation

To simulate the future situation incorporating the new warehouse and to be able to acquire a near-realistic approach, the software *Technomatix PlantSimulation* supported by Siemens is used. In here, multiple simulation tools within 2D are applicable. This simulation software is able to simulate discrete events based on the user's input and logic. To do so for Company X, a *ControlPanel* is constructed where the eventual simulation is controlled and monitored. In here, the algorithms used for modelling purposes are integrated. An overview of this *ControlPanel* is depicted in Figure 5-2. The experiments can also be performed from here, but the actual simulation happens in a separate frame called Company X. Since this frame is rather large and complex, multiple pictures are depicted in Appendix A6. It provides all the essential information to derive the bottlenecks, impacts and consequences within the future due to the alternations. The structure, decision-making and characteristics of the model are outlined in the following sections. First of all, a list of model assumptions is provided. Besides that, the data is stored into tables for analysis and variables are monitored during the simulation to be able to compare simulation with reality. Thereby, movable units are used for animation purposes. Lastly, the logic that is integrated into the so-called *Methods* is explained. These methods are divided into multiple categories. The most important ones for the programming of the logistical network and the eventual simulation of the case study are explained and highlighted.

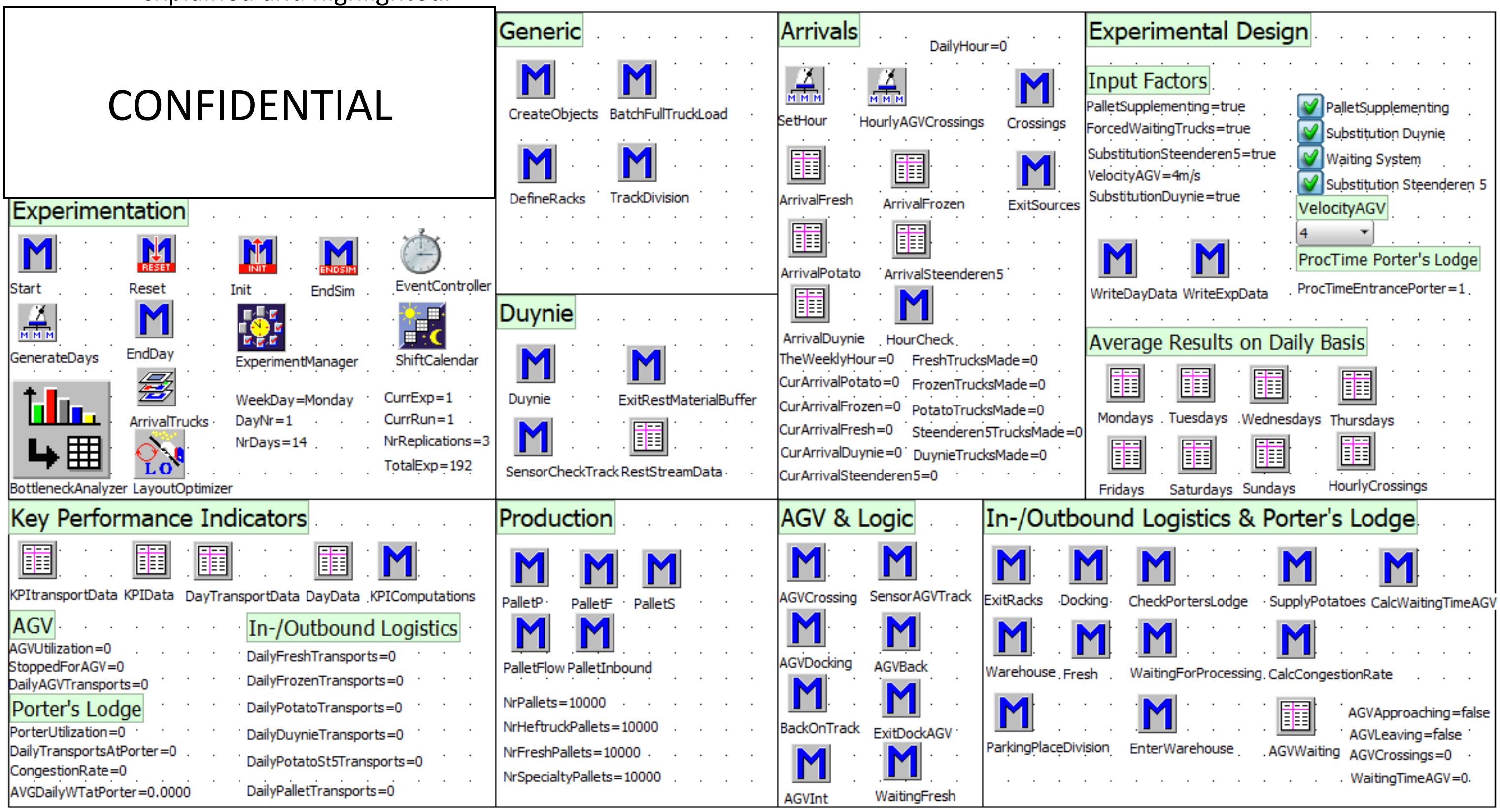

FIGURE 5-2: CREATED CONTROLPANEL FOR GUIDANCE OF THE SIMULATION MODEL

5.1.1. List of Model Assumptions

Some assumptions are made to be able to simulate future behavior. Since not all the information is available already, and several processes are highly variable, these assumptions guide the model and user to obtain results. In coordination with Company X, the following assumptions are presumed throughout the rest of this research:

- **Velocity on-site**. Trucks drive at a constant speed of 10 km/h on-site.
- **Velocity off-site**. Trucks drive at a constant speed of 60 km/h on the public road.
- **Rules & Regulations.** People and drivers on-site know about the AGV, the safety regulations and priority ruling.
- **Priority Ruling.** The AGV has priority over the other vehicles, meaning that it will always have traffic priority and the normal traffic rules do **not** apply for this vehicle
- **Interruption of the AGV.** The AGV-movement is only interrupted when a vehicle or person is detected at a radius of 5 meters.
- **Load of the AGV.** A Full-Truck-Load of the AGV varies between 26-32 pallets, dependent upon the pallet sort.
- **Recharging/refueling of the AGV.** Charging of the AGV is done when it is standing still waiting for a batch to be transported to the warehouse and assumed to be constant in the model.

- **No distinction among products.** Pallets with accompanying weights in tons (x1000 kg) are transported regardless of the diversity of products. Therefore, it is assumed that one pallet can contain different products, but the diversity of the specialty-products at Z5 is for example ignored.
- **Full-Truck-Loads.** Trucks for outbound logistics are always transporting Full-Truck-Loads.
- **Constant Order Picking**. Order picking is assumed to be a constant and automatic process.
- **No Maintenance.** Maintenance and lockdowns are neglected, since they do not have a significant impact on the outside efficiency.
- **Data Applicability.** Input data is made applicable for simulation based on historic data and statistical distribution fitting as a forecast method for future behavior.
- **The Porter's Lodge.** Utilization of the porter's lodge is based upon the shifts of the porters provided by Company X. Furthermore, the degree of automation is incurred within the processing times.
- **Starting Time.** Simulation starts at midnight on Monday (00:00) for every run.

5.1.2. Table Files, Variables & Moving Units

Besides the general structure of the simulation model, there are multiple *Table Files*, *Variables* and *Moving Units* (MUs) that contribute to the data analysis and animation of the model. The table files and variables are depicted in the *ControlPanel* of Figure 5-2, whereas the MUs are solely used for animation purposes. These three elements are briefly described to explain their usefulness and work procedure.

Table Files

Within *PlantSimulation* the table files are the eventual tools for analysis. In here, all the experimentation and variability can be stored, checked and calculated. Throughout this research, extensive usage of these files is done to store every instant of the discrete-event simulation for further analysis.

Variables

The variables can be tracked both locally and globally. Based on these, the key performance indicators can eventually be computed. Tracking information of all the systems and processing stations is required to gather data of the entire model.

MUs

To model all the different transportation modes, a distinction among the MUs within 2D-perspective needs to be made. By incorporating different colors for the specific trucks, these distinctions are realized. In Figure 5-3 the different incoming and outgoing trucks are depicted. These movable units represent the basis for animation purposes and are arranged throughout the network based upon the *CheckPortersLodge* logic.

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The other vehicle present within the system is of course the AGV. This MU is driving around on the designated track indicated and animated as in Figure 5-4.

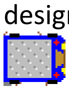

FIGURE 5-4: 2D-ANIMATED AGV WITHIN THE SIMULATION MODEL

Furthermore, pallets with finished products and accompanying weights are moving through the system. These are eventually picked up by the *F3* and *F2* trucks, whereas the rest material streams are MUs that are taken on by the *Company Y* trucks. All these MUs make sure that the end-user eventually gets a realistic, representable and animated thought of the future processes.

5.1.2. Logic – Methods

The most important part of the simulation is the guiding logic by means of *Methods* (indicated with the M-icons in Figure 5-2), where coding and algorithms for several decisions and considerations are performed. The five most important pieces are indicated here, where the coded algorithms and accompanying rules are explained briefly.

CheckPortersLodge

At the porter's lodge two checks are performed. One of them is the identification of the type of truck that arrives. Due to this identification the porters know where the driver has to be and the truck can drive to the designated area. On the way out, a check is performed to ensure that everything is in order and the right documents are handed over the truck drivers. Logically, the processing times of the porter's lodge at both the ingoing as outgoing weighbridge are integrated, where truck drivers are forced to wait until told to drive towards the ingoing weighbridge. Such a situation is depicted in Figure 5-5 on the right. In here, multiple trucks are waiting for their turn.

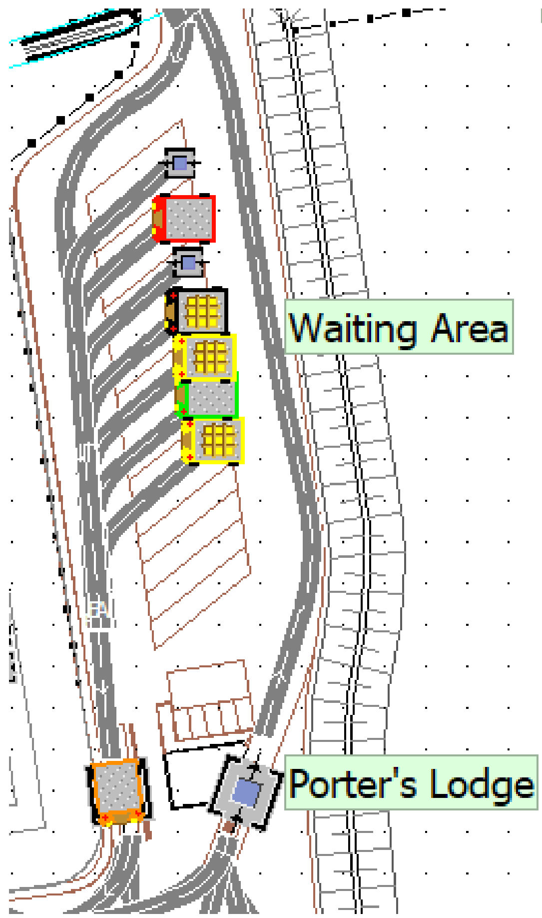

Figure 5-5: Simulated Situation at The Porter's Lodge With Waiting Trucks

ExitSources

The arrival frequencies of the MUs depicted in Figure 5-3 need to be modelled as such that it represents reality. This is done in the *ExitSources* method, where in synchronization with the planning department of Company X and the forecasting computations the input is acquired. Based upon this method, the hourly arrivals are modelled. Meaning that for every day of the week and every hour of the day an arrival frequency for the different trucks is generated. Because of the stochastic behavior, the decision is made to model it with accompanying variance per hour interval as well. This method ensures that from both directions on the public road several trucks with different kinds of destinations upon the Company X site are created.

Bottleneck Analyzer

The entire system should be checked upon bottlenecks. The bottleneck analyzer makes sure that complications at each station and event within the network are pointed out. Based on this output, experimentation can gain insights into the impact of the bottlenecks and the consequences that it can have on the entire business model of Company X. This bottleneck analyzer can be configured up to the desires of the user. The three main aspects that can be evaluated are production, transport and storage. Since we assumed constant production and storage, the main analysis upon the bottlenecks is performed for the transportation modes. Especially the AGV transportations are a concern here, because they can get interrupted by other vehicles. Thus the bottlenecks upon and surrounding the AGV and its track can be evaluated with this *Bottleneck Analyzer*.

AGVLogic & AGVCrossing

The maneuvering of the AGV is primarily modelled based on the production output. If there are enough pallets ready to make up a Full-Truck-Load of the AGV, the AGV is triggered to perform the transport. After unloading at the warehouse, it immediately drives back to its original starting position. Furthermore, the number of times that the track of the AGV is crossed by other vehicles is counted. These counts are performed based upon sensors. The sensors are placed onto every crossing and circled in red in Figure 5-6. Here, the major crossings are visualized. These crossings are caused by: (1) Expedition X, (2) Z5 Supplies, (3) Company Y Activities and (4) Pallet Supplementing. Recall that these aspects make up a part of the bottleneck framework presented earlier.

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ExitLogisticalNetwork

When trucks leave the network, the generation of results takes place. The waiting times at each station are tracked and the transportation routes and times are traced. If the truck leaves the simulation at one of the two end-points, this information is stored for further analysis.

5.2. Key Performance Indicators (KPIs)

To measure performance and see whether efficient transportation can be achieved by altering parameters, the usage of key performance indicators (KPIs) is introduced. Lots of KPIs are applicable throughout this research, since the logistical network is rather complex, crowded, and stochastic. An overview of the KPIs that are tested is shown in Table 5-1. In total, 13 KPIs have been computed throughout this research. However, the importance for Company X and the reliability of the performance upon these KPIs needs to be compared to each other. To do so, recall that in Section 3.5. we outlined the Analytical Hierarchical Process (AHP). Eventually this AHP is computed within Section 6.1. Doing so gives an indication of the ranking of the KPIs and the need for significant results upon these indicators for future purposes. Therefore, the weighting is done based on literature on the one hand and expertise from Company X on the other hand. Eventual decision-making regarding the efficient routing is done by the decision-makers of Company X and therefore their input is used in computing the AHP. But before doing so, the KPIs are shortly elaborated and some of them are illustrated in the following paragraphs.

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Before explaining the KPIs, it should be mentioned that for Company X the different days during a week are considered important and many fluctuations amongst these days are present. Company X makes use of a 24/7 production process, but regarding the transportations and logistics surrounding the business model of Company X there is a lot of deviation present. Therefore, the decision is made to work with "Average Daily … "KPIs in which the performance per Monday, Tuesday …. Sunday is measured. In that way, peaks and off-peaks among the days can be reflected and used to gain insights in the future logistical network and check whether planning and routing can be adjusted to the outcomes. The eventual results of the KPIs are described in Chapter 6. First an explanation of each KPI and its computation method is provided. All the KPIs are measured by means of the simulation model, so the methods for accomplishing that are described in the following sections.

To clarify this section again, we refer to the layout structure of Chapter 4. However, since the order picking is assumed constant, we make use of the following processes with regards to performance measurement:

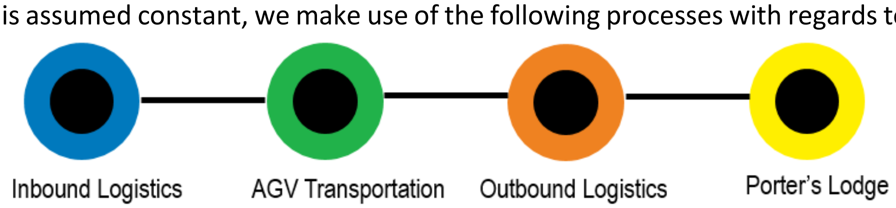

Figure 5-7: Structure Logistical Processes - Performance Measurements

5.2.1. Inbound Logistics – KPIs

Recall that the inbound logistics are not altered that much by the introduction of the new warehouse. Still performance measures are incurred to check the inbound logistics and see patterns throughout the simulation runs. To do so, three KPIs are tracked as output of the simulation regarding this logistical process.

Average Daily F1 Transports – the major influencer with regards to the inbound streams are the product X transports. The logic behind these product X transports is that there is a shunting yard and a processing facility of *F1* available on the site. The trailers filled with Product X are placed on the shunting yard awaiting approval for processing. An example of such a situation is depicted in Figure 5-8, where currently one trailer of Product X is being processed at the *F1* facility and three trailers are waiting at the shunting yard. All the product X transports are tracked throughout the simulation to also ensure that the simulation gives a realistic representation of reality here

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Average Daily Z5 Supplies – as we saw earlier, production area Z5 is manually supplied with Product X. Here, 2 docks are present for the supply by means of the product X trailers. Recall that we noticed that a lot of maneuvering is used to be able to park the trucks correctly at their dock. These Z5 supplies are counted within the model to ensure that it represents reality in a good way and possible adjustments of this previously mentioned AGV bottleneck can be found.

Average Daily Pallet Transports – besides both the product X transports, pallets are required in huge amounts at the production facilities to be able to transport the finished goods to customers eventually. These pallet transports contribute significantly to the logistical network and this indicator keeps track of the number of transports on a daily basis. In this way, impacts upon the AGV functioning can be derived for this transportation method as well. Since the pallet fork lift trucks are crossing the AGV track frequently, they need to be modelled in a correct and realistic way. By means of this indicator, the pallet transports are tracked to eventually make sure that the model is constructed in a reliable manner regarding the pallet transports. Since we saw that pallet transports also can be seen as a bottleneck for the AGV and its routing, adequate modelling of the transports is required.

5.2.2. AGV – KPIs

Let us now look at the performance indicators with respect to the AGV. Regarding the AGV and its track, multiple KPIs are measured and tracked along the way. These KPIs mainly influence the efficiency of the AGV. They are explained with several examples to clarify what consequences the performance upon these indicators can have.

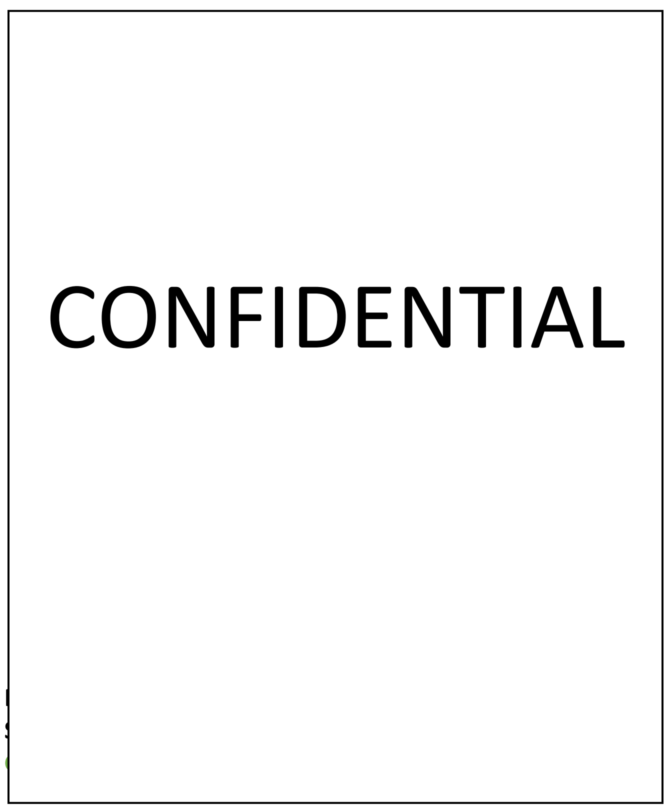
Average Daily AGV Transports – the AGV transports are counted to check if any deviations are present among the weekdays. The initial idea of Company X is to have the AGV transport about 2-3 times per hour to ensure that all the production output is handled. However, due to unexpected behavior or the charging of the AGV for example,0 this might fluctuate among the weekdays. Logically, weekdays with higher frequencies of other transports affect the maneuvering of the AGV more. So, by counting the daily transports of the AGV, an overview of the impact can be provided for the seven weekdays. In that case, Company X could adjust the strategy of the AGV to for example transport more in the off-peak hours.

Average Daily AGV Utilization – at every instant of the simulation, the utilization of the AGV should be traceable. The utilization of the AGV is tracked by means of the following:

$$\% = \frac{Driving\ Hours + Loading\ Hours + Unloading\ Hours}{Simulation\ Hours}$$

This percentage is measured at every instant of the simulation and a graphical representation of the utilization can be made to get insights whether or not the AGV is overloaded with activities.

Average Daily Interrupted AGV Transports – when the AGV detects a vehicle in a radius of 5 meters within the simulation it comes to a stop. In here, we make a distinction amongst a **resolute** stop and a **normal** stop. A resolute stop is caused due to sudden unexpected crossings of other vehicles which cause the AGV to stop immediately to avoid dangerous situations. Such a stop requires approximately 5 to 10 minutes to restart and needs to be done manually. When it concerns a normal stop where the AGV already detects the other vehicle from a long range, it is able to automatically restart driving which requires 3 to 5 minutes. Logically, the time it takes to continue driving is dependent on the truck that causes the interruption and the time it needs to get out of the AGV's way. An example of an interruption (normal stop) is depicted in Figure 5-9. In here, a truck of Expedition X (depicted in green) has picked up its load and is on its way out. However, the crossing with the AGV (depicted in blue) is not regulated and a situation like Figure 5-9 occurs. The AGV detects the truck on its guideway and stops in advance in order to avoid collisions. Every time this happens, we count that as an "interrupted AGV transport". Eventually, the average number of interruptions is computed on a daily basis.



5.2.3. Outbound Logistics – KPIs

For the outbound logistics, in total four KPIs are determined that keep track of the transports and the influence upon the network. These are outlined in the next paragraphs.

Average Daily F2 Transports – the incoming F2 transports need to be checked to ensure that the distribution method used for the forecasting represents significant and logical behavior. Therefore, all the steps, decisions and behavior that a truck designated for the new cold store is making are tracked. Every move is known and whenever a truck "leaves" the simulation at one of the two exits, this information is stored for further analysis. These exits are depicted in Figures 5-10 and 5-11 and modelled according to the actual coordinates for (1) the direction Zutphen/Deventer and (2) the direction Arnhem/Doetinchem:

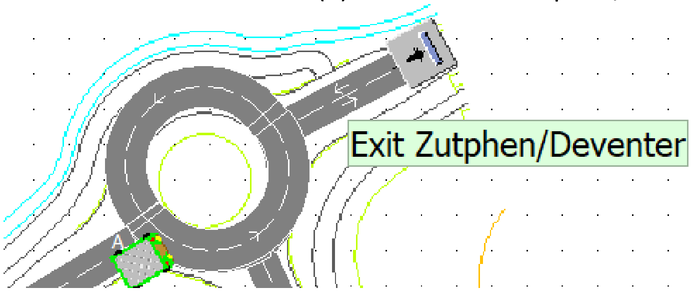


FIGURE 5-10: EXIT 1 IN THE SIMULATION MODEL

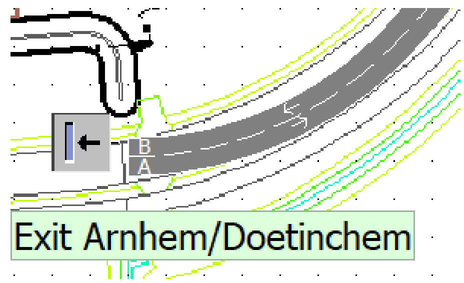


FIGURE 5-11: EXIT 2 IN THE SIMULATION MODEL

Average Daily F3 Transports **–** regarding these transports, the performance is measured similarly as the F2 transports. Meaning that information is stored whenever they leave the simulation. However, the F3 transports require extra movements and waiting times due to the AGV and their travel distance. But since they are known, computations can be performed based on historic data.

Average Daily Company Y Transports **–** Company Y can be regarded as a totally different form of transportation, since they know exactly where to be and what to do. Recall that the opportunity of having them be processed faster at the porter's lodge is investigated. This will logically have influences on their transportation/waiting times. By tracking them accurately, the differences among the trucks can be analyzed.

Average Daily AGV Crossings **–** in the logic we looked at the sensors present in the model that count the AGV crossings, as depicted in Figure 5-6. The idea is that this KPI provides an overview for every day of the week based on the simulation run length, to see how many AGV-track crossings there are on a daily average basis.

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5.2.4. Porter’s Lodge – KPIs

As we have seen, the porter’s lodge plays a significant role in this case study. To be able to measure its performance by means of the model, we came up with three KPIs:

Average Daily Porter Utilization – to calculate the utilization of the porter’s lodge, a *ShiftCalendar* is integrated into the model. The shifts of the porters are decided at Company X and by means of the amount of available working time the percental utilization can be calculated:

$$\% = \frac{Employees\ Working\ Hours}{Employees\ Clocking\ Hours}$$

In the model, the ingoing and outgoing transports are modelled based upon two *Processing Stations*. These stations represent the activities of the porters for both directions as depicted in Figure 5-13.

FIGURE 5-11: ENTRANCE OF THE PORTER’S LODGE (LEFT STATION) AND EXIT OF THE PORTER’S LODGE (RIGHT STATION)

For each of these processing stations the related statistics are modelled and retrieved. Thereby, the working time and relative occupation make up the utilization of the porter’s lodge. Recall that only one truck can be processed at a time. An example of an instance of the simulation regarding the utilization of the porter’s lodge is given underneath in Figure 5-14.

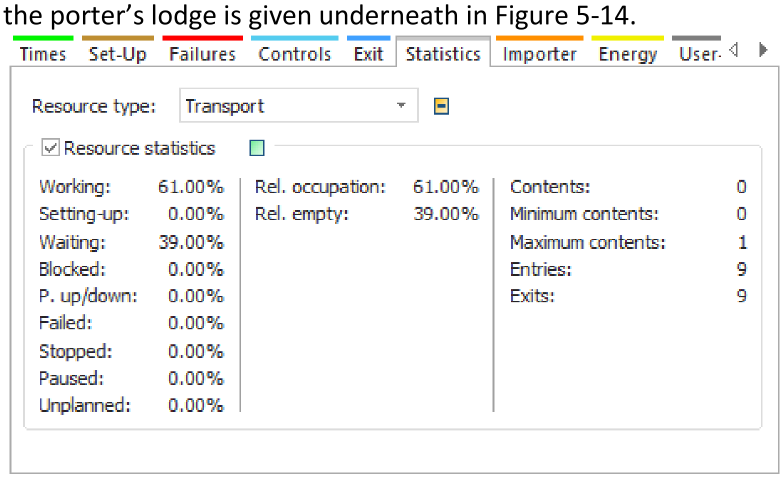

FIGURE 5-12: TRANSPORT STATISTICS AVAILABLE FOR THE PORTER'S LODGE

Average Daily Transports at Porter – the transports arriving at the porter’s lodge are tracked throughout the entire simulation to be able to calculate the average daily incoming transports. Based on that, Company X can gain insights into peak and off-peak periods for both the porter’s lodge as well as the other sectors of its internal logistical network.

Average Daily Congestion Rate – the congestion rate is caused due to the extensive amount of trucks arriving on a day and especially the safety rules and regulations that apply on the Company X site. In the beginning, the processing times of the porter’s lodge are somewhat longer since all the new truck drivers need instruction. Automating pieces of the activities at the porter’s lodge ought to make the throughput faster at the porter’s lodge. By means of this KPI, the number of trucks waiting are counted. Thus, whenever a truck is parked waiting to be processed at the porter’s lodge, this is counted as congestion of +1.

5.3. Applicability Input Data

To be able to create a suitable, reliable and applicable simulation model the data needs to be prepared and tuned for modelling purposes. To do so, several aspects are analyzed before integrating it in the model: (1) CAD Models with corresponding coordinate scaling, (2) data preparation of the transport frequencies, (3) vehicle dimensions and characteristics and (4) production output and facility layout. The input preparation of these elements is described here.

5.3.1. Integration CAD Models – Coordinate Scaling

To be able to integrate the entire site with the future warehouse building within a simulation model, Computer Aided Design (CAD) Models are used to ensure good dimensioning. Due to these CAD models we are able to perform coordinate scaling. Coordinate scaling makes use of the actual coordinates of the Location X site. Since the coordinates are aligned in the model, every adjustment by means of a track, vehicle, production line or loading/unloading dock is scaled. Therefore, the outline of the model is a realistic representation of the future case. These CAD models are the starting phase of model computation for Company X. A representation of the starting phase of the modelling is depicted in Appendix A3.

5.3.2. Transport Frequencies – Data Preparation & Input

A major contributor for the input data of the model are the transport frequencies. Recall that Company X has a 24/7 working environment, meaning that for each hourly timeslot of the week an analysis is performed. First of all, the number of transports is computed on an average basis. One of the so-called "peak-days" of Company X, being the Friday, is analyzed further here.

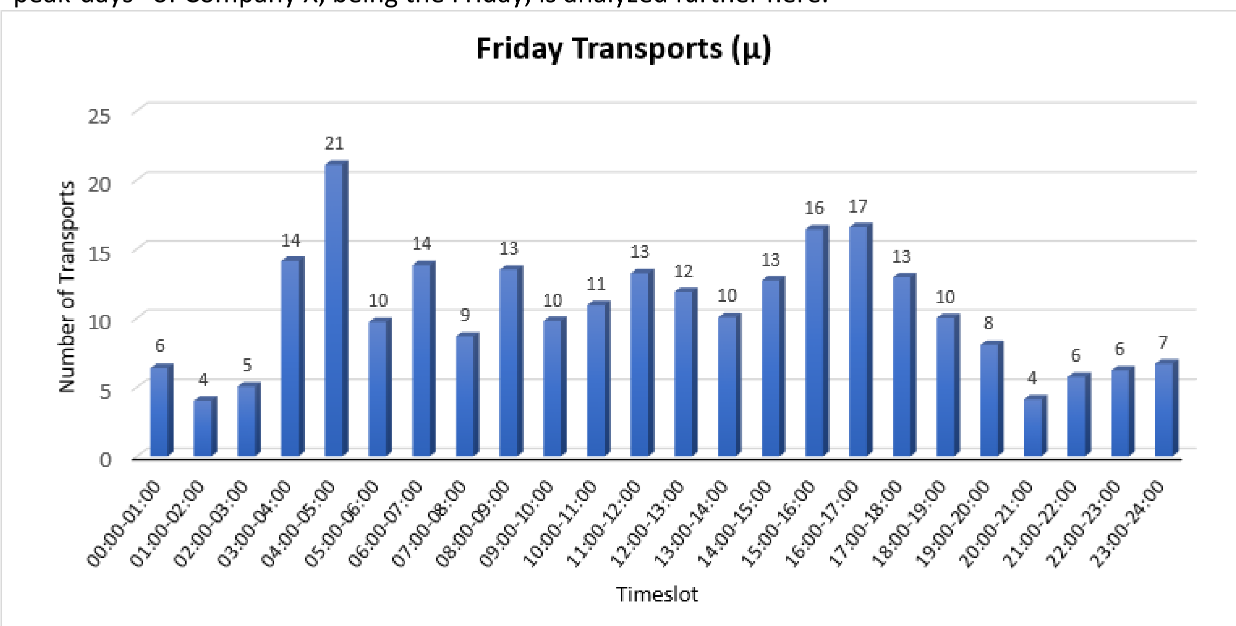

FIGURE 5-13: AVERAGE TRANSPORTS OCCURRING ON FRIDAYS PER HOURLY TIMESLOT

These transports are integrated in the simulation model via an empirical discrete distribution technique. Where the timeslots are initiated as discrete events and fluctuations amongst the numbers is integrated based on standard deviation. However, this overview provides an indication of an ordinary Friday where the different transports are summed. To distinguish the transport modes from each other and be able to integrate different arrival strategies and frequencies for these modes we need to model them separately. An overview of the transport frequencies on Friday for different transportation modes is depicted in Figure 5-16.

In here, five categories are identified for further analysis and eventual model integration:

- **F1 Transports** – incoming product X transports for processing at F1.
- **Product X Z5 Supply Transports** – transports meant for manual supply at Z5.
- **F3 Transports** – incoming transports for product retrieval at Expedition X.
- **F2 Transports** – incoming transports for product retrieval at the new warehouse.
- **Company Y Transports** – incoming transports performing all the Company Y activities on-site.

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An example of the computation of these frequencies within the model will now be explained. Let us take the number of trips for the peak of the F2 transports at timeslot 04:00-05:00. The actual value of this peak is 13,6777 trips. But since we only model integers within the discrete simulation, in that case the average within that timeslot is set at 14. However, with certain possibilities this value is 13 or 15 on some Friday mornings throughout the year. Therefore the chance (in %) that a value occurs during a year is modelled as well, to ensure that fluctuations for every timeslot and every transport mode are integrated. The described example focuses on the Fridays, but all the other days are also analyzed to make the transport frequencies applicable within the simulation model. The corresponding graphs are visualized in Appendix B1.

5.3.3. Vehicle Dimensions & Characteristics

Recall that the characteristics of the AGV and its track are indicated in Chapter 4. For all the vehicles driving around within the network, the physical characteristics and parameters are taken into account. For example, the velocities of the vehicles with corresponding acceleration and decelerations. Furthermore, backwards docking is incurred for both the trucks and AGV respectively to make the simulation even more realistic.

5.4. Experimental Design

To be able to come up with answers regarding the impact upon the logistical network, both the *ExperimentManager* and the *EventController* are used within the simulation software. To do so, decisions upon the run length of the simulation (**1**) and the warm-up period are required. Furthermore, the experimental setup encompassing the experimental input factors (**2**) and KPIs (**3**) are described. Lastly, the number of replications per experiment (**4**) are explained, which determine the running time for concise analysis and deal with the extent of variability.

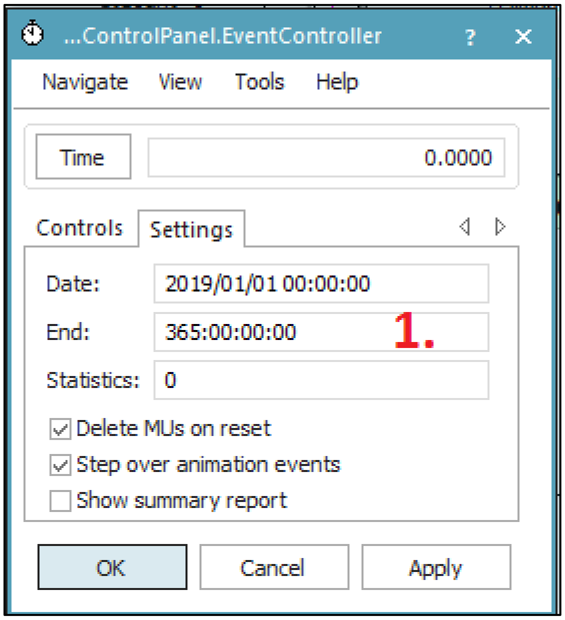

FIGURE 5-17: EVENTCONTROLLER – RUN LENGTH

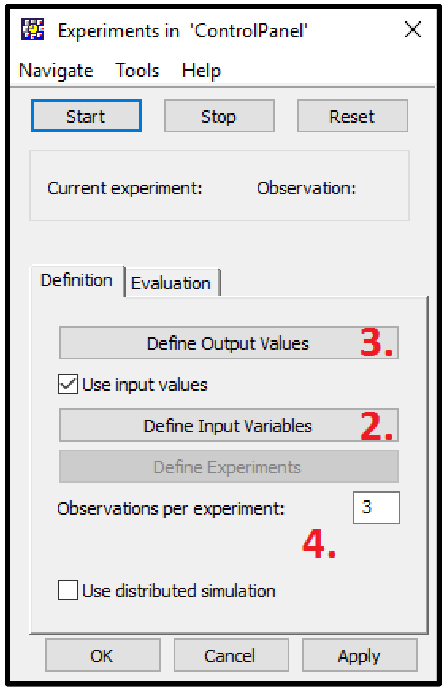

FIGURE 5-18: EXPERIMENT MANAGER

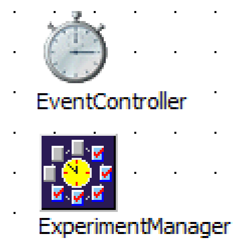

FIGURE 5-19: PLANT SIM ICONS

1. Run Length & Warm – Up Period

To ensure that the simulation represents reality in a reliable manner, the run length needs to be determined. The run length equals the time until the end of one simulation run. Since this research case integrating the new warehouse is based upon the long-term, the decision is made to simulate one year per simulation run. Within one year, a good measure upon the performance indicators can be done. Stochastic behavior and variability within the data can thereby be eliminated as much as possible.

However, the simulation is due to its stochastic behavior rather uncertain, especially at the beginning. Within terminating simulations, the principle of a *warm-up period* is integrated. This warm-up period is taken into account during analysis to ensure that after this period the simulation enters a *steady-state* in which its behavior is representable and reliable. Based upon the run length of one year, the warm-up period is considered to be one week. So during simulation, this week is used to configure the simulation, and especially prevent unexpected and highly variable behavior from happening within the starting phase.

2. Input Factors – Interactive Dashboard

By means of the simulation, the possibility of creating an interactive dashboard in which the user can apply his/her wishes and simulate different situations is opted. In here, multiple situations are derived where the possibilities and impact can be analyzed. Varying these input parameters is based primarily upon the bottleneck framework of Chapter 4 to check if transportation upon the Company X site can happen more efficiently when certain elements are adjusted or removed within the simulation.

The following instants are investigated within this dashboard, where the results upon varying the parameters are computed in Chapter 6:

- **Replacing Z5 Supply** – recall that the manual supply of Product X for production facility Z5 is crossing the AGV track multiple times. These crossings can interrupt the AGV and therefore the option of replacing this manual supply by automatic supply via pipelines (as is the case with the other product X supplies) is investigated. To do so, a *Boolean Expression* is used where the replacement can take on the values *true* and *false*, indicating if replacement via pipelines is put in place.
- **Relocating Company Y Activities –** here the same *Boolean Expression* is used, but now the option of relocating the Company Y activities towards the other side of the Location X site is opted. This is part of the master plan of Company X and therefore the influence that this relocation has upon the fluency of the network needs to be investigated.
- **Relocating Pallet Supplementing –** the pallets that need to be supplemented from the storage area at the production facilities are transported by means of forklift trucks. These transports cross the AGV tracks as well and therefore a *Boolean Expression* is used again to indicate if these pallet transports might be performed from another place. If the value for this relocation is *true* than the pallet supplementing is performed from another side, preventing the crossings of the AGV track.
- **Waiting System Expedition X Transports –** there is a huge difference between allowing the truck drivers of the *F3* department to do what they want or to regulate their behavior. This has especially impact upon the functionality of the AGV. By regulating, we mean that the drivers are stopped by means of traffic lights or traffic barriers if the AGV is in the neighborhood. Meaning that the AGV always has priority ruling and the truck drivers have to wait until it passed by. Such a waiting system needs to be investigated whether or not it has a positive influence upon the logistical network.
- **Processing Time Porter's Lodge –** the processing time of the new porter's lodge is highly variable, especially in the beginning. This is due to all the safety rules and regulations that ought to be provided to the new truck drivers arriving at the Company X site. Therefore, distinctions between the processing times of new truck drivers and known truck drivers is made. The known truck drivers, whom will be expanding with time (since they get acquainted with the rules), are able to compel to the safety rules and know exactly what to do on the site of Company X. Furthermore, automating certain activities at the Porter's Lodge by for example using Automatic Number Plate Recognition as we saw earlier in Chapter 4.5. might reduce the processing times. To test the consequences of the processing times, three scenarios are analyzed. The minimum processing time on average is 2.5 minutes here, whereas the maximum processing time of a truck is set at 12.5 minutes. To test this adequately, uniform ranges are created where the processing times vary between the upper and the lower bounds. Based on these ranges, Company X can gain insights in future impacts and whether to choose for automation of certain activities in order to reduce processing times. The uniform ranges of the processing times in minutes, with slight overlaps, are: **1** – U [2.30;7:30], **2** – U [5.00;10.00] and **3** – U [7.30;12.30].
- **Velocity AGV –** as we described earlier, the AGV has an average speed of 6 km/h based upon market perspective. However, variations are possible. Increasing the velocity might result in more AGV transports on a daily basis. But safety is a major concern of Company X and when for example the AGV drives around with 20-25 km/h on the Company X site this could result in dangerous situations. Therefore, a trade-off between velocity and safety needs to be made. To test this, four input values are considered for the AGV velocity: 4,6,8 and 10 km/h.

During experimentation, all the previously mentioned factors are tested within a full-factorial design. Since there are two options for the first four parameters, three options for the fifth parameter and four options for the last one, we have a $2^4 * 4^1 * 3^1 = 2^4 * 2^2 * 3^1 = 2^6 * 3^1$ = **192-factorial design**. Meaning that 192 experiments are required to check upon the performance indicators that are explained in Section 5.3. Overall, the following alternations for the input parameters are tested:

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The exact configurations among these alternations and corresponding best outcomes are handled in Chapter 6 where the results are analyzed.

3. Experimental Output

Recall that we made an overview of the KPIs throughout this research. These KPIs are used as output, to check what the impact upon the network is. First of all, AHP is performed with help of dedicated Company X employees, to categorize the KPIs. Hereafter, data is gathered for all the KPIs but the emphasis lies upon the outcomes of the AHP analysis. If required, more output factors might be evaluated as well to check for every instance what the consequences are by means of the model.

4. #Replications

The number of replications/observations per run is set at three. So every experiment is simulated three times to prevent inconsistencies and extreme variances from happening. In a later stage the averages of these three replications are computed, to be able to obtain results with an as high as possible level of confidence.

5.5. Conclusion

Within this chapter an outline of the modelling approach is provided. First of all, the *Technomatix PlantSimulation* model is described, where elements like the *ControlPanel, Frames, MUs*, *Table Files* and corresponding *Logic* are explained. Furthermore, the Key Performance Indicators (KPIs) for this specific case study are elaborated per logistical process: (1) Inbound Logistics, (2) AGV Transportation, (3) Outbound Logistics and (4) The Porter's Lodge. These KPIs can be seen as the output of the simulation runs. Besides the outline and the KPIs, the applicability of the input data is discussed. The integration of CAD models, the discrete empirical distribution fitting amongst the transportation frequencies and the different dimensions regarding the vehicles and facilities are described. Moreover, the experimental setup and accompanying factors are discussed. The decision has been made to make use of six different input factors: (1) Replacement Z5 Supply, (2) Relocation Company Y Activities, (3) Relocation Pallet Supplementing, (4) Waiting System Expedition X Transports, (5) Processing Time Porter's Lodge and (6) Velocity AGV. These can be configured in such a way that a $2^6 * 3^1$ = 192 full factorial experimental design is fulfilling all the different options. The experiments are running for one year with every experiment consisting out of three replications in order to reduce variability in the output.

6. Results and Interpretations

Throughout this chapter the obtained results are discussed. First of all, the AHP analysis that is performed internally at Company X is described in Section 6.1. Thereafter, the experimental output of the simulation is addressed in Section 6.2. By means of the results upon AHP and simulation, the bottleneck analysis can be performed and quantified in Section 6.3. Furthermore, impacts upon the porter's lodge are derived in Section 6.4. Moreover, the limitations that arise during the computations and experiments are discussed in Section 6.5. Lastly, the aspects of model validation and verification are explained for this research.

6.1. Analytical Hierarchical Process (AHP)

To perform an AHP analysis, we recall the literature that has been studied in Section 3.5. Such an approach is also used for this case, where we take a look at five specific indicators for a thorough analysis upon the functioning of the AGV and the porter's lodge. These indicators are: (1) *AGV Utilization*, (2) *Porter's Utilization*, (3) *AGV Crossings*, (4) *Congestion Rate* and (5) *Interrupted AGV Transports*. These provide Company X with significant insights regarding future impacts upon the logistical network. Based on the AHP literature, we make use of a pairwise comparison matrix where we compare the indicators with each other and check for importance. Since we make use of five indicators, we need:

$$Number\ of\ Pairwise\ Comparisons = \frac{5*4}{2} = 10$$

To perform the AHP analysis, a tool is developed in which scaling amongst the indicators can be done. This means that we are able to let the participants analyze the indicators for themselves and see what they think is more important. The decision is made to make use of a scaling from 1 till 18, where 9 means that both the indicator on the left as on the right are of equal importance. The arrows are put in place to drag and assign a performance score. Values ranging between 1-8 indicate that the criterium on the left side is more important, whereas values ranging between 10-18 indicate that the criterium on the right side is more important. An example of a filled-out AHP tool is shown in Figure 6-1 underneath:

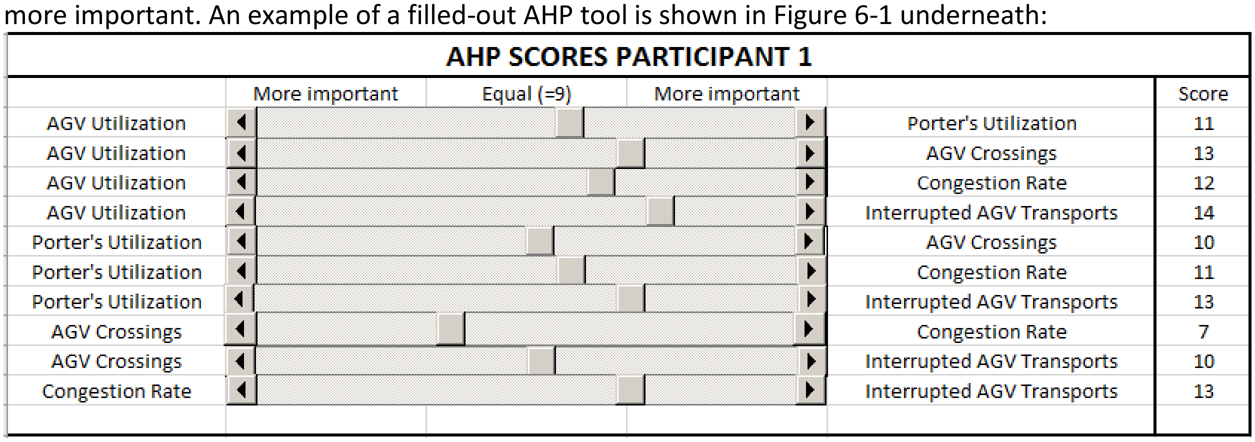

FIGURE 6-1: EXAMPLE OF THE FILLED OUT AHP CRITERIA TOOL - PAIRWISE COMPARISON MATRIX

Within this example, the participant showed that the *AGV Utilization* is somewhat less important than all the other indicators. Furthermore, we can see that the indicator *Interrupted AGV Transports* is considered most important by this specific participant, since it scores the highest within the pairwise comparisons (14, 13,10 and 13 compared to the others). To ensure that the AHP is filled out correctly, a description of the ranking is given to the participants as well. Five key Company X end-users are approached to indicate their visions within the tool. To ensure that the results are representable for future purposes, the managing employees of different logistical divisions of Company X are asked to fill the tool out. The ones who are asked are: (1) Expedition Y Manager, (2) Transport Planning Manager, (3) Manager F1 Logistics, (4) Safety Manager and (5) Senior Project Manager.

Furthermore, a small recap of the definitions of the criteria is given to let the user know what we exactly mean by a specific criterium and to what extent it is measured within the model:

- **AGV Utilization** – the utilization of the AGV focuses on the percentage of time that it is actually operating. Therefore, utilization can be calculated like:
$$\frac{[Driving\ Time\ AGV + (Un) - Loading\ Time\ AGV]}{Simulation\ Time}$$
- **Porter's Lodge Utilization** – the utilization of the porters at the future porter's lodge provides insights into the need for automating certain activities. This is highly dependent upon the degree and sorts of automation that are used here, which can be tested in the simulation by means of varying the processing times of the weightings and other functionalities at the porter's lodge.
- **AGV Crossings** – this criterium focuses on the number of times that the AGV track is **crossed** by other vehicles. During crossing, there is a possibility of interrupting the AGV transports. These crossings are calculated on an average daily basis and can provide insights for Company X related to the vehicles that cross the track the most frequently and thus cause possible problems in the future.
- **Congestion Rate** – the congestion rate is calculated at the porter's lodge. Every time a truck needs to wait, its waiting time is calculated and the average congestion rate on a daily basis caused due to the waiting trucks is derived. Due to this indicator, future impacts at the porter's lodge are evaluated by means of the simulation study.
- **Interrupted AGV Transports** – unlike the AGV crossings, this indicator looks solely at the number of AGV transports that are **interrupted** by another vehicle on an average daily basis. Therefore, this indicator checks if the number of interruptions is extraordinary and if measures should be taken in advance to prevent this from happening in the future.

The overall results of the performed AHP with the Company X employees are visualized and reviewed in the next section. After that, the emphasis is put upon the best scoring indicators for further experimentation. The individual results of the participants are attached in Appendix C1.

6.1.1. AHP Results

The obtained results of the tool are visualized per indicator and participant. These results are depicted in Figure 6-2, where percental importance of the indicators is computed based upon the assigned scores.

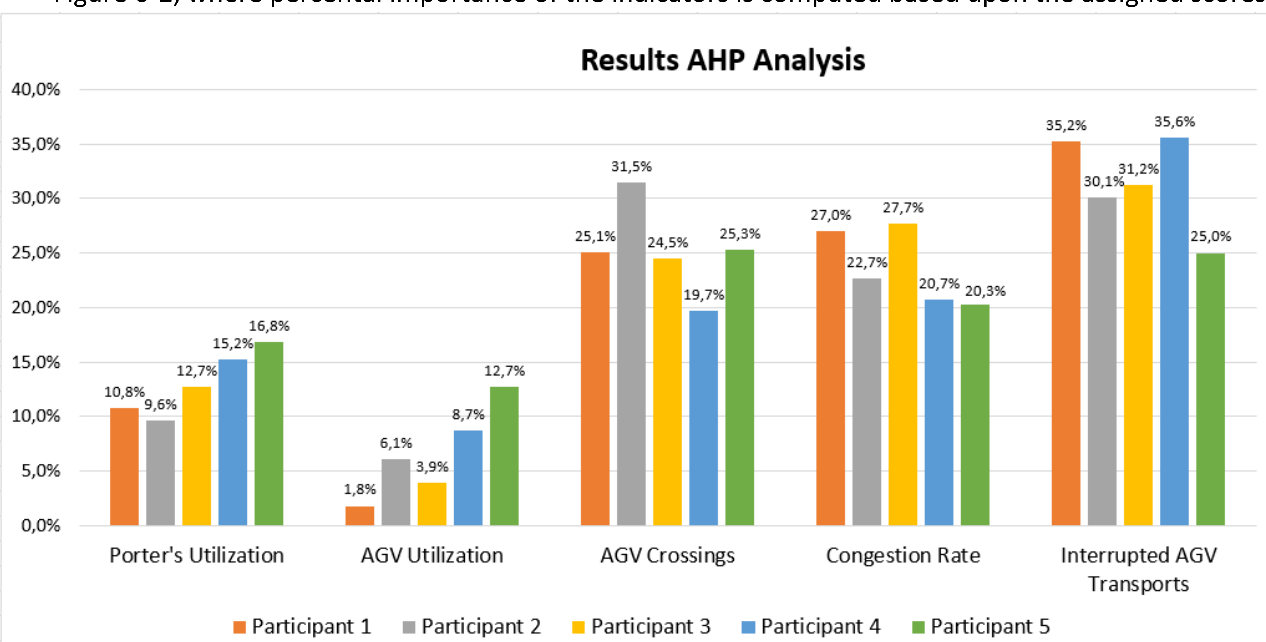

FIGURE 6-2: RESULTS OF THE PERFORMED AHP - ANALYSIS FOR 5 PARTICIPANTS

At first sight already some indicators stand out. The *Interrupted AGV Transports* are considered the most important by almost all participants, followed by the *AGV Crossings* and the *Congestion Rate* at the Porter's Lodge. Both utilizations at the Porter's Lodge and for the AGV are considered somewhat less important to emphasize during experimentation. The actual output emphasis is shortly discussed in the next section.

6.1.2. AHP Output Emphasis

Based on the performed AHP analysis, the most important criteria are *AGV Crossings*, *Interrupted AGV Transports* and *Congestion Rate* at the porter's lodge. After discussions it turned out that both the utilization of the porter's lodge as well as the AGV are considered important. They do not strive for a utilization of 99% or higher. However, there is not much to be worried about yet. Especially for the AGV, because when a high utilization is reached at certain moments the possibility is present to just drive some extra transports manually. Of course this is not preferable, but as a matter of problem solving this could be done when needed. Throughout the following sections regarding the experimental output, the emphasis lies upon the three most important criteria. Especially further analysis with regards to AGV-routing and the functioning of the porter's lodge is explained. In such a way, Company X can gain insights through simulation in the possible effects upon their logistical network with the AGV and the porter's lodge as critical contributors.

6.2. Experimental Output

Within this section, the output of the different experiments is discussed. Based upon a full-factorial design, the 192 experiments that are performed are analyzed. From these, the three best and the three worst experiments are retrieved for further analysis to see which values of the input factors have the best and worst scores upon the output factors. Where we showed that the output factors are the established KPIs for the different logistical processes.

6.2.1. Full-Factorial Design

Recall that we decided upon multiple input factors to be varied within the experiments. The input factors and their variation determine the 192 experiments:

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Furthermore, the run length of one experiment is determined to be one year. This year ought to give a significant insight into the impacts that the different scenarios can have on a daily basis. Thereby, the decision is made to test all the different configurations resulting in a full-factorial experimental design. Next to that, as mentioned beforehand, the data of the different weekdays deviates a lot from each other in both the inbound and outbound transports. Therefore, we perform different analyses for each day:

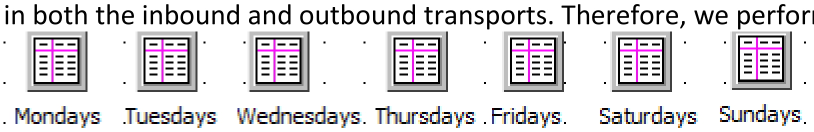

FIGURE 6-3: EXPERIMENTAL OUTPUT FILES PLANTSIMULATION COMPUTED ON A DAILY BASIS

In all of the daily tables, the 13 KPIs are stored for further analysis. We especially focus on the KPIs that score the highest via AHP, but the others are not neglected since they contribute to the validity of the model. Checking upon these per experiment ensures the correctness of the data and the ability to analyze the scenarios. In this way, the routing within the logistical network of Company X can be determined on a weekly basis incorporating average daily patterns. An example is now demonstrated.

Example Simulated Experiment

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In here, the configuration for this specific experiment 125 is assuming that two of the possible preventions of the previously mentioned AGV-bottlenecks are performed in the future. In this case, the "TRUE" values indicate that the Z5 Supply is replaced with pipelines and that the Pallet Supplementing is performed at another location. This experiment can be tested based upon the experimental output. The output of this experiment is shown in Table 6-3 underneath.

Table 6-3: Output Computed for the Example Experiment of Table 6-2 – Experiment 125

Day	ExpNr	PU	AU	AC	CR	IA	TP	PT	ST	FT	FrT	DT	PaT
Monday	125	49,1627%	93,9985%	93	95,5	4	169	56	0	38	66	8	0
Tuesday	125	49,4522%	93,9642%	85	96,5	3	166	50	0	34	72	7	0
Wednesday	125	49,5455%	94,0277%	91	70	2	156	44	0	35	65	9	0
Thursday	125	49,5750%	93,9988%	85	89	3	158	54	0	32	60	9	0
Friday	125	49,6221%	94,0058%	85	138	3	193	48	0	30	101	11	0
Saturday	125	46,8312%	93,9797%	29	14	1	74	53	0	2	8	11	0
Sunday	125	49,4516%	91,0506%	49	19,5	2	84	51	0	14	10	9	0

The different abbreviations that are used here as columns represent the indicators. Recall that we explained the following indicators in Chapter 5:

- **PU** = *Average Daily Porter's Utilization*
- **AU** = *Average Daily AGV Utilization*
- **AC** = *Average Daily AGV Crossings*
- **CR** = *Average Daily Congestion Rate*
- **IA** = *Average Daily Interrupted AGV Transports*
- **TP** = *Average Daily Transports at the Porter's Lodge*
- **PT** = *Average Daily F1 Transports*
- **ST** = *Average Daily Z5 Transports*
- **FT** = *Average Daily F3 Transports*
- **FrT** = *Average Daily F2 Transports*
- **DT** = *Average Daily Company Y Transports*
- **PaT** = *Average Daily Pallet Transports*

Within the example experiment the porter's utilization is rather low, whereas the AGV utilization is already quite high. Peaks amongst the crossings of the AGV track and interruptions of the AGV are present on Mondays. Whereas a large traffic congestion happens on Fridays. Given the full-factorial design, in total 192 experiments in different configurations are performed. The computations are done like experiment 125 to obtain an average weekly pattern based upon a one-year simulation run per experiment. Appendix B2 contains the configurations, where the input factors are varied. Now we want to zoom in on the experiments and check which configurations yield the best and worst possible outcomes.

6.2.2. Best Experiments vs. Worst Experiments

Based upon the full-factorial design we need to deal with 192 experiments, all with varying outputs. Here, we focus on the best and worst performing experiments to identify the experimental output range. First of all, we made use of three replications within the experiments to diminish variability as much as possible. Therefore, after the full-factorial design is computed, the averages of the replications are calculated to gain one value for each of the KPIs per experiment. To identify the best and worst experiments of this simulation study we need to make a distinction amongst the indicators. As we already deployed the three most important indicators during the AHP analysis, we can identify the three best and the three worst experiments on a daily basis. Logically, Company X wants to reduce the *AGV Crossings, Congestion Rate* and *Interrupted AGV Transports* as much as possible. Therefore, regarding the best experiments we seek to identify the experiments that score the lowest upon these indicators. However, the *AGV Utilization* and *Porter's Lodge Utilization* are not neglected. The desire is that these utilizations are not at a maximum (95%-100%) such that Company X still has some room for possible errors and unexpected behavior in the future. To identify the three best experiments, the following desired outcome is filtered:

TABLE 6-4: DESIRED FILTER CRITERIA FOR COMPANY X TO OBTAIN THE BEST EXPERIMENTS

Indicator	Desired Value
AGV Crossings	⬇
Congestion Rate	⬇
Interrupted AGV Transports	⬇
AGV Utilization	✖ [95%-100%]
Porter's Lodge Utilization	✖ [95%-100%]

Eventually the following configurations for the three best experiments are obtained based on the filtered outputs:

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This is a rather logical outcome, since all the bottlenecks are prevented and the processing time at the porter's lodge equals the lowest possible uniform range. Furthermore, there is one aspect that can be derived from the three best experiments, namely that varying the velocity of the AGV does not have a significant influence upon the performance of the KPIs. Since varying the velocity still results in the three best outcomes, where the prevention of the bottlenecks is performed and the processing time at the porter's lodge is as low as possible. The experimental output that corresponds to the configurations is visualized in Table 6-6 on the next page. As said, these experiments score the best upon the *AGV Crossings*, *Congestion Rate* and *Interrupted AGV Transports*. A short analysis of these three indicators is described here:

- *AGV Crossings* – the AGV track is crossed multiple times, but due to the alternations regarding the bottleneck, only the Expedition X trucks are crossing it within these experimental settings. Resulting in way less crossings with a minimum of only 5 on average on Saturdays and maximum of 77 on Mondays.
- *Congestion Rate* – the congestion rate at the porter's lodge is still seemingly high throughout the week. However, on Saturdays and Sundays only a congestion rate of 6 and 9 is reached.
- *Interrupted AGV Transports* – on average, for every day, there are **no** interrupted AGV transports, which is a very interesting result for Company X since the AGV can function effectively and efficiently.

The low input for the processing time at the porter's lodge results furthermore in an extremely low utilization at the porter's lodge with as minimum value 22.83% on average on Mondays. Furthermore, the AGV utilization does not reach the critical level of 95% and the lowest is achieved on average on Tuesdays with 93.94%. Lastly, the Z5 Supplies, Company Y Transports and Pallet Transports within the logistical network are 0 in their output. Since the configurations show that prevention is in place for these three transport modes, it is logical that they are 0 in this case. However, the *Expedition X* transports are not 0, because they are making use of a waiting system as we explained earlier. So these transports are still present in the network, but take the AGV into account and wait if it is in the neighborhood.

TABLE 6-6: EXPERIMENTAL OUTPUT CORRESPONDING TO THE THREE BEST EXPERIMENTS BASED ON COMPANY X DESIRES

Day	ExpNr	PU	AU	AC	IA	TP	CR	PT	ST	FT	FrT	DT	PaT
Monday	181	22,8298%	94,0463%	77	0	161	46,50	56	0	38	66	0	0
Monday	184	22,8298%	93,9985%	77	0	161	46,50	56	0	38	66	0	0
Monday	187	22,8298%	93,9746%	77	0	161	46,50	56	0	38	66	0	0
Tuesday	181	22,9900%	94,0120%	69	0	158	47,00	50	0	34	72	0	0
Tuesday	184	22,9900%	93,9642%	69	0	158	47,00	50	0	34	72	0	0
Tuesday	187	22,9900%	93,9403%	69	0	158	47,00	50	0	34	72	0	0
Wednesday	181	23,0187%	94,0755%	71	0	146	36,00	44	0	35	65	0	0
Wednesday	184	23,0187%	94,0277%	71	0	146	36,00	44	0	35	65	0	0
Wednesday	187	23,0187%	94,0038%	71	0	146	36,00	44	0	35	65	0	0
Thursday	181	23,0322%	94,0466%	65	0	148	44,00	54	0	32	60	0	0
Thursday	184	23,0322%	93,9988%	65	0	148	44,00	54	0	32	60	0	0
Thursday	187	23,0322%	93,9749%	65	0	148	44,00	54	0	32	60	0	0
Friday	181	23,0610%	94,0536%	61	0	181	65,00	48	0	30	101	0	0
Friday	184	23,0610%	94,0058%	61	0	181	65,00	48	0	30	101	0	0
Friday	187	23,0610%	93,9819%	61	0	181	65,00	48	0	30	101	0	0
Saturday	181	23,1665%	94,0275%	5	0	56	6,00	53	0	2	0	0	0
Saturday	184	23,1665%	93,9797%	5	0	56	6,00	53	0	2	0	0	0
Saturday	187	23,1665%	93,9558%	5	0	56	6,00	53	0	2	0	0	0
Sunday	181	22,9741%	94,0984%	29	0	68	9,00	51	0	14	1	0	0
Sunday	184	22,9741%	94,0506%	29	0	68	9,00	51	0	14	1	0	0
Sunday	187	22,9741%	94,0267%	29	0	68	9,00	51	0	14	1	0	0

Let us know look at the three worst performing experiments to see what the range of the experimental output is and furthermore identify what could be the future outcome if Company X decides to do nothing just let the AGV and porter's lodge function inefficiently. The three worst experiments of the 192-full factorial design, with corresponding configurations, are shown underneath.

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Logically, high *AGV Crossings, Congestion Rates* and *Interrupted AGV Transports* are reached when nothing is done about the prevention of the AGV bottlenecks and the processing time at the porter's lodge. When we take a look at the experimental output, we see that the highest number of AGV-track crossings by other vehicles is 148 on Wednesdays. Comparing that to the best experiments, these crossings are more than doubled. Furthermore, the AGV is interrupted frequently with a maximum of 8 interruptions on average on Friday. Besides that, the congestion rate occurring at the porter's lodge takes on extraordinary levels with a maximum of 181 trucks waiting on Fridays. Altogether, when no AGV bottleneck prevention is performed and the processing time of the porter's lodge remains high, then we can say that this has severe consequences for the logistical network. Therefore, we need to find opportunities for Company X to adjust their logistical network in an efficient way to diminish complications arising for the AGV and the porter's lodge.

TABLE 6-8: EXPERIMENTAL OUTPUT CORRESPONDING TO THE THREE WORST EXPERIMENTS

Day	ExpNr	PU	AU	AC	IA	TP	CR	PT	ST	FT	FrT	DT	PaT
Monday	3	76,2974%	94,0463%	145,5	4	171	148,00	54	5	38	65	7	12
Monday	6	76,2974%	93,9985%	145,5	5	171	148,00	54	5	38	65	7	12
Monday	9	76,2974%	93,9746%	145,5	4	171	148,00	54	5	38	65	7	12
Tuesday	3	76,6518%	94,0120%	136,5	5	165	144,00	46	4	34	71	7	11
Tuesday	6	76,6518%	93,9642%	136,5	5	165	144,00	46	4	34	71	7	11
Tuesday	9	76,6518%	93,9403%	136,5	5	165	144,00	46	4	34	71	7	11
Wednesday	3	76,7212%	94,0755%	148	4	172	150,50	51	5	36	68	11	12
Wednesday	6	76,7212%	94,0277%	148	4	172	150,50	51	5	36	68	11	12
Wednesday	9	76,7212%	94,0038%	148	5	172	150,50	51	5	36	68	11	12
Thursday	3	76,8808%	94,0466%	137	6	159	144,00	51	5	32	60	9	11
Thursday	6	76,8808%	93,9988%	137	5	159	144,00	51	5	32	60	9	11
Thursday	9	76,8808%	93,9749%	137	5	159	144,00	51	5	32	60	9	11
Friday	3	76,9242%	94,0536%	126,5	8	181	187,00	44	5	28	94	8	12
Friday	6	76,9242%	94,0058%	126,5	7	181	187,00	44	5	28	94	8	12
Friday	9	76,9242%	93,9819%	126,5	7	181	187,00	44	5	28	94	8	12
Saturday	3	77,1313%	94,0275%	96,5	3	96	36,00	61	4	5	7,5	16	2
Saturday	6	77,1313%	93,9797%	96,5	3	96	36,00	61	4	5	7,5	16	2
Saturday	9	77,1313%	93,9558%	96,5	3	96	36,00	61	4	5	7,5	16	2
Sunday	3	76,7296%	94,0984%	102	1	82	31,00	51	3	14	1	9	12
Sunday	6	76,7296%	94,0506%	102	2	82	31,00	51	3	14	1	9	12
Sunday	9	76,7296%	94,0267%	102	1	82	31,00	51	3	14	1	9	12

Future Feasibility

Although the three best experiments provide Company X with the desired outcomes, their future feasibility is very difficult. Since the three best experiments are configured on the basis that all the four bottlenecks with regards to the AGV are prevented, huge investments are required to achieve that. Furthermore, achieving a low processing time at the porter's lodge requires automation of activities which again incurs investments. Therefore, within the short-term, the feasibility of these experiments is difficult to achieve. If Company X decides to do nothing, the worst-case scenario results in high *AGV-Crossings, Congestion Rates* and *Interrupted AGV Transports*. This is also not desired, because within the long-term a fluent and efficient network is preferable. Thus different scenarios need to be investigated to come to a near-optimal solution in which the required alternations to the Company X site are bounded and investments are limited. Therefore, the impacts upon the AGV and its routing and the impacts upon the porter's lodge and its functioning need to be investigated separately to check which of the input factors has the most influence. The highest impact results in the need for Company X to do something about this and therefore for example consider prevention of certain (not all!) activities on the Company X site.

6.3. AGV - Bottleneck Analysis

The impact of the bottlenecks regarding the AGV is computed based on the experimental output. Recall that we came up with six bottlenecks in Chapter 4: (1) Transports Expedition X, (2) Manual Supply Z5, (3) Company Y Activities, (4) Pallet Supplementing, (5) Pedestrians and (6) External Transport Streams. The latter two are not modelled, because they are highly stochastic and unpredictable bottlenecks. Therefore, safety rules and regulations need to be put in place to deal with the pedestrians and the external transport streams like the parcel vans on the Company X site. The impact of the other four is calculated based upon the output of the KPIs. Furthermore, an AGV strategy with accompanying (safety) measures on the Company X site is proposed for efficient routing.

6.3.1. Impacts

To derive the impacts upon the bottlenecks for the AGV functioning, the experimental output is analyzed. Furthermore, the indicators considered most important regarding the AGV-routing are criticized closely. As we pointed out, these indicators are the *AGV Crossings* and *Interrupted AGV Transports*. Mainly the percental reductions upon these are identified to check the impact of the bottlenecks upon AGV transportation. For each of the four bottlenecks, an analysis with accompanying quantified data is performed and explained. To do so, we need to obtain the right configurations for these bottlenecks. To identify the impact of one bottleneck, an unique situation is required. Since we want to analyze the situation incorporating only **one** change upon the input factors, the other factors are kept constant. Otherwise the impact is not only caused due to one of the AGV bottlenecks, but the velocity of the AGV might for example influence the result as well. Therefore, the velocity of the AGV is kept constant at a 6km/h (prescribed velocity by AGV supplier Götting). Moreover, we make use of a processing time at the porter's lodge which is uniformly distributed between 5 and 10 minutes. Based on these settings, the impact of each bottleneck can be tested. The following four experiments are analyzed:

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In here, the value "TRUE" indicates that the bottleneck is not present and relocation/replacement or other measures have taken place. Therefore, when looking at the four experiments, we simulate the following:

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However, before testing the impact, we need to have an initial configuration to test and compare with. The initial configuration is the one where all the input factors are "FALSE", which means that the current situation at the site of Company X is kept the same. This yields the following configuration:

TABLE 6-11: INITIAL CONFIGURATION TO COMPUTE THE IMPACT REDUCTIONS OF THE BOTTLENECKS

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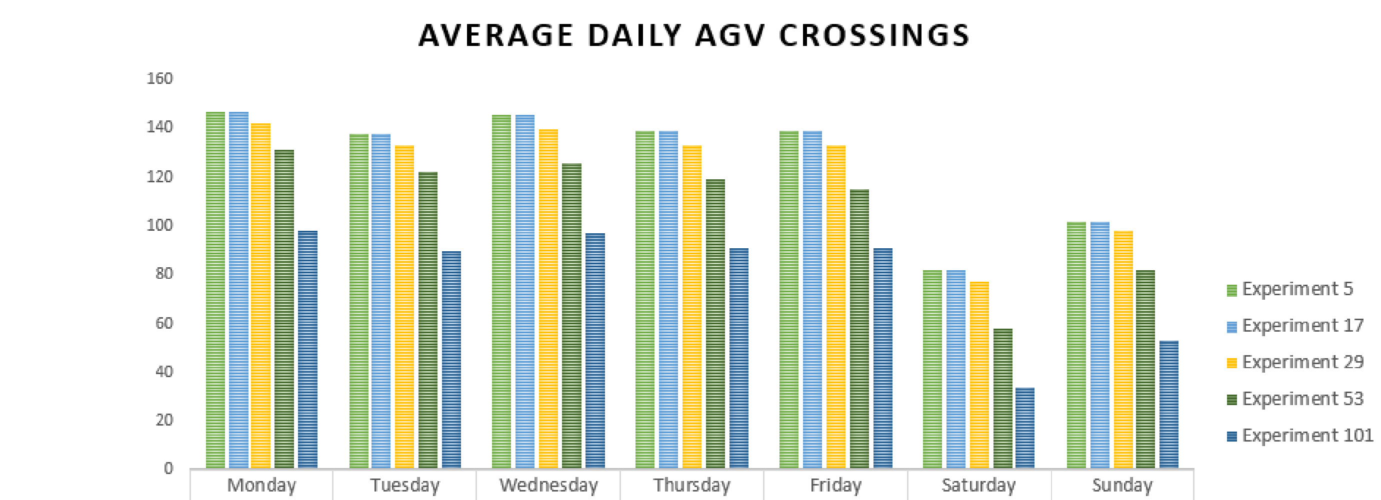
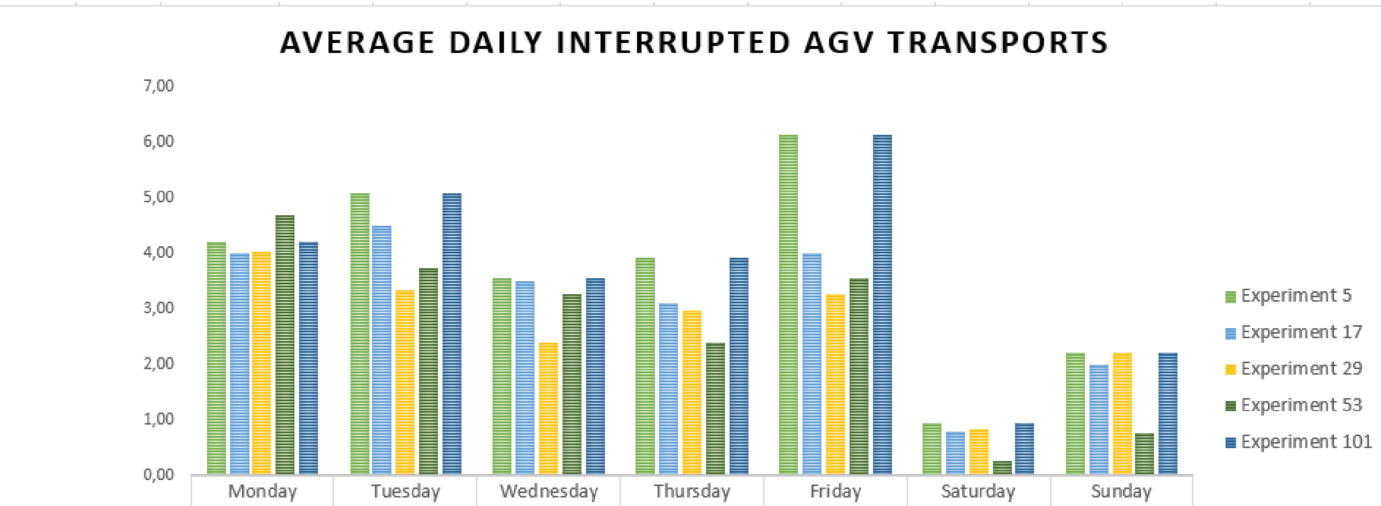
As has been explained, the transportation patterns deviate highly amongst the different days. Therefore, for the seven days of the week, separate impact reduction analyses are computed per bottleneck. Based upon the AGV crossings, insights can be derived upon the possiblities of interrupting AGV routing. Therefore, these are analysed per experiment as described in Table 6-8. The *AGV Crossings* on a daily basis per bottleneck experiment are computed and visualized in Figure 6-4.



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Experiment 5	147	138	146	139	139	82	102
Experiment 17	147	138	146	139	139	82	102
Experiment 29	142	133	140	133	133	77	98
Experiment 53	131	122	126	119	115	58	82
Experiment 101	98	90	97	91	91	34	53

FIGURE 6-4: AVERAGE DAILY AGV CROSSINGS THAT ARE COMPUTED PER BOTTLENECK EXPERIMENT

The actual impact of each bottleneck regarding the AGV crossings is elaborated in the following paragraphs. Based on the crossings, interruptions for the AGV might occur. Since not all the crossings indicate an interruption, this indicator is analyzed separately by means of the *Interrupted AGV Transports:*



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Experiment 5	4,22	5,08	3,55	3,93	6,14	0,96	2,21
Experiment 17	4,00	4,50	3,50	3,10	4,00	0,80	2,00
Experiment 29	4,03	3,36	2,40	2,97	3,26	0,86	2,21
Experiment 53	4,70	3,74	3,26	2,40	3,55	0,29	0,77
Experiment 101	4,22	5,08	3,55	3,93	6,14	0,96	2,21

FIGURE 6-5: AVERAGE DAILY INTERRUPTED AGV TRANSPORTS THAT ARE COMPUTED PER BOTTLENECK EXPERIMENT

However, the *AGV Crossings* provide Company X with an idea of future transport behavior and especially major “crossers” that ought to be regulated or prevented. Therefore, both indicators are reflected in the next paragraphs where the percental impact reduction that could be gained due to prevention or regulation of the bottleneck is calculated. We analyze the four AGV bottlenecks separately:

AGV Bottleneck 1: Transports Expedition X

For this bottleneck we compare experiment 17, where the waiting system for the *Expedition X* transports is incurred, with the initial configuration of experiment 5. The outcome of these calculations is depicted in Table 6-12. The impact upon the crossings is not reduced by means of the forced waiting system for the transports of Expedition X. This is rather logical, because they are forced to wait if the AGV is in the neighborhood, but cross the track afterwards if they receive a signal that they are allowed to drive.

FIGURE 6-6: AGV BOTTLENECK 1 ON THE COMPANY X SITE: EXPEDITION X TRUCKS (COMPANY X SITE, 2018)

With regards to the interruptions of the AGV transports we see some improvement potential. Especially on Tuesdays, Thursdays and Fridays, the interruption rate of the AGV is improved significantly. So, the forced waiting system by means of traffic lights or traffic barriers has a significant and positive influence upon this bottleneck.

TABLE 6-12: IMPACT ANALYSIS OF AGV BOTTLENECK 1: TRANSPORTS EXPEDITION X

Transports Expedition Fresh	#Crossings	Impact Reduction Crossings	#Interruptions	Impact Reduction Interrupted Transports
Mondays	147	0,00%	4,00	5,19%
Tuesdays	138	0,00%	4,50	11,46%
Wednesdays	146	0,00%	3,50	1,35%
Thursdays	139	0,00%	3,10	21,15%
Fridays	139	0,00%	4,00	**34,82%**
Saturdays	82	0,00%	0,80	16,57%
Sundays	102	0,00%	2,00	9,32%

AGV Bottleneck 2: Manual Supply Z5

The manual supplies are not occurring that frequently on a daily basis, but recall that a lot of maneuvering is required to be able to dock the product X trailers at the designated area for unloading. These two unloading docks are depicted in Figure 6-7. Therefore, some reduction upon both the crossings of the AGV track and the interruptions of the AGV transports can be achieved here. One of the most important things to consider is that whenever a Z5 supply needs to happen, the probability of interrupting the AGV is high due to the extensive maneuvering. As we take a look at the impacts we can see that the crossings do not reduce that much because of the Z5 supplies, simply because of the low number of transports.

FIGURE 6-7: AGV BOTTLENECK 2 ON THE COMPANY X SITE: MANUAL SUPPLY LOCATION X 5 (COMPANY X SITE, 2018)

However, when the Z5 supplies are replaced by the pipelines, the interruption of the AGV transports can be reduced significantly. Especially on Fridays, a significant reduction is established when we take a look at Table 6-13. Therefore, an investment into the pipelines could be beneficial for stimulating fluent AGV behavior.

TABLE 6-13: IMPACT ANALYSIS OF AGV BOTTLENECK 2: MANUAL SUPPLY LOCATION X 5

Steenderen 5 Supply	#Crossings	Impact Reduction Crossings	#Interruptions	Impact Reduction Interrupted Transports
Mondays	142	3,40%	4,03	4,55%
Tuesdays	133	3,62%	3,36	33,96%
Wednesdays	140	4,12%	2,40	32,43%
Thursdays	133	4,32%	2,97	24,39%
Fridays	133	4,32%	3,26	**46,88%**
Saturdays	77	**6,10%**	0,86	10,00%
Sundays	98	3,92%	2,21	0,00%

AGV Bottleneck 3: Company Y Activities

Unlike the Z5 supplies, the Company Y activities occur more frequently during the days. However, these trucks do not require that much maneuvers. But the experimental output indicates that both the crossings and the interruptions could be improved significantly if the Company Y activities are relocated. On Saturdays, a reduction of crossings of 29.27% can be achieved. When looking at the interruptions, throughout the weekdays significant reductions can be achieved by relocation of the Company Y activities. Again, this is all compared to the initial configuration where we do not alter anything and remain using the activities of the current situation.

FIGURE 6-8: AGV BOTTLENECK 3 ON THE COMPANY X SITE: COMPANY Y ACTIVITIES (COMPANY X SITE, 2018)

Furthermore, when performing a relocation of the Company Y activities, extra space becomes available around the AGV track and thus the detection error margin decreases. With this error margin we refer to the detection radius of the AGV. In the model the assumption is made that whenever an object is moving within a 5-meter radius, the AGV is interrupted. Since the Company Y trucks are performing their activities on and around the future AGV-track, this can have serious consequences with regards to detection by the AGV.

TABLE 6-14: IMPACT ANALYSIS OF AGV BOTTLENECK 3: COMPANY Y ACTIVITIES

Duynie Activities	#Crossings	Impact Reduction Crossings	#Interruptions	Impact Reduction Interrupted Transports
Mondays	131	10,88%	4,70	11,36%
Tuesdays	122	11,59%	3,74	26,42%
Wednesdays	126	13,75%	3,26	8,11%
Thursdays	119	14.39%	2,40	39,02%
Fridays	115	17,27%	3,55	42,19%
Saturdays	58	**29,27%**	0,29	**70,00%**
Sundays	82	19,61%	0,77	65,22%

AGV Bottleneck 4: Pallet Supplementing

The pallet supplements are crossing the AGV track frequently on an average daily basis. Therefore, when the storage is transferred to another location (outside AGV perimeters) this bottleneck has a significant impact reduction, which is shown in Table 6-15. Reasons for that could be that pallets need to be supplemented on a seven-day basis, because production is happening 24/7. Thus, unlike the other bottlenecks, there is no decline in pallet transports in the weekends. Therefore, the impact reduction when comparing it with the initial situation is somewhat higher.

FIGURE 6-9: AGV BOTTLENECK 4 ON THE COMPANY X SITE: PALLET SUPPLEMENTING (COMPANY X SITE, 2018)

Since supplementing is performed by Company X employees on a fork-lift truck, the AGV is not interrupted. Because the Company X employees are all known with the AGV in the future and know that they should wait and especially not interrupt the AGV. In coordination with Company X this decision has been made and therefore no impact upon the interrupted transports is caused due to the pallet supplementing. Of course, a traffic light or traffic barrier could be put into place to make entirely sure that no interruptions with the fork-lift trucks occur. The impact analysis of this bottleneck is shown in Table 6-15.

TABLE 6-15: IMPACT ANALYSIS OF AGV BOTTLENECK 4: PALLET SUPPLEMENTING

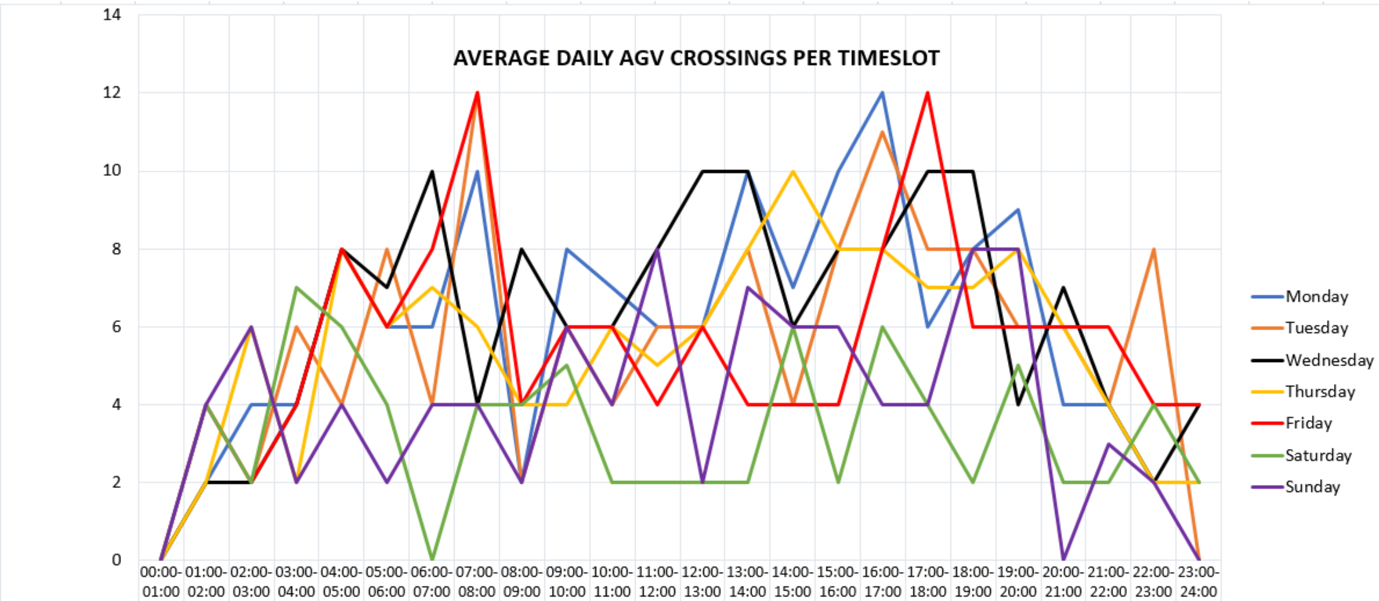
Pallet Supplementing	#Crossings	Impact Reduction Crossings	#Interruptions	Impact Reduction Interrupted Transports
Mondays	98	33,33%	4,22	0,00%
Tuesdays	90	34,78%	5,08	0,00%
Wednesdays	97	33,33%	3,55	0,00%
Thursdays	91	34,53%	3,93	0,00%
Fridays	91	34,53%	6,14	0,00%
Saturdays	34	**58,54%**	0,96	0,00%
Sundays	53	48,04%	2,21	0,00%

Future Feasibility Bottleneck(s) Prevention

Within this section, the different impact reductions upon the prevention of certain bottlenecks are described. They are all analyzed separately, meaning that the impact and possible reduction upon the bottlenecks is tested independently. When we look at future feasibility, this is something which is suitable for Company X. Unlike the three best experiments (where we prevented all the bottlenecks), these experiments make use of only one bottleneck prevention. Where especially the replacement of Z5 supply and the relocation of Company Y Activities contribute to reducing the impact upon both the *AGV Crossings* and *Interrupted AGV Transports*. Meaning that the AGV might drive way more efficient throughout the entire week when one of these adjustments is performed. Furthermore, the waiting system for the trucks of *Expedition X* does not require a significant preventive measure and thus no big investments are incurred for that. Overall, the bottlenecks can all be prevented, but when we look at feasibility it is unadvisable to perform all the prevention methods since the investments are high. Therefore, decisions based upon the results need to be made to determine which investment is suitable and affordable given the circumstances.

6.3.2. AGV Strategy

Based on the bottlenecks and the experimental output upon the indicators, an AGV strategy can be proposed. As we look at the crossings on an hourly basis throughout one entire week, without preventing any of the other transport processes, several aspects are interesting to take into account. The crossings are computed and plotted per day. These crossings represent an average daily basis per timeslot of 1 hour throughout the entire week, where we again made use of a run length of the simulation of 1 year. The visualization of these crossings is depicted underneath:



	00:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00	04:00-05:00	05:00-06:00	06:00-07:00	07:00-08:00	08:00-09:00	09:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00
Monday	0	2	4	4	8	6	6	10	2	8	7	6	6	10	7	10	12	6	8	9	4	4	2	2
Tuesday	0	2	2	6	4	8	4	12	2	6	4	6	6	8	4	8	11	8	8	6	6	4	8	0
Wednesday	0	2	2	4	8	7	10	4	8	6	6	8	10	10	6	8	8	10	10	4	7	4	2	4
Thursday	0	2	6	2	8	6	7	6	4	4	6	5	6	8	10	8	8	7	7	8	6	4	2	2
Friday	0	4	2	4	8	6	8	12	4	6	6	4	6	4	4	4	8	12	6	6	6	6	4	4
Saturday	0	4	2	7	6	4	0	4	4	5	2	2	2	2	6	2	6	4	2	5	2	2	4	2
Sunday	0	4	6	2	4	2	4	4	2	6	4	8	2	7	6	6	4	4	8	8	0	3	2	0

FIGURE 6-10: COMPUTED AVERAGE DAILY AGV CROSSINGS PER DAY & SPREAD OUT PER HOURLY TIMESLOT

The graph indicates that throughout the 168 timeslots of a week, a significant number of crossings are taking place. However, when looking at a suitable AGV strategy to perform the transports from production towards the new warehouse, some interesting opportunities arise here. To be able to integrate the computed data of the simulation model regarding the crossings of the AGV track, a more detailed analysis is required to analyze the functioning of the AGV more closely. To do so, the average number of transports per timeslot for a given day is computed and shown in Table 6-16. Based on that, the peaks and off-peaks regarding the AGV crossings and the possibility of having an interruption can be derived.

TABLE 6-16: AVERAGE DAILY AGV CROSSINGS PER DAY

Day	Average Crossings
Monday	5.96
Tuesday	5.54
Wednesday	6.17
Thursday	5.50
Friday	5.58
Saturday	3.29
Sunday	4.00

When analyzing the data and checking whether the values on a given day are underneath (possible off-peak) or above (possible peak) the average number, results in one rough off-peak interval and two rough peak moments of traffic upon the Company X site. Based on these (off)-peaks, opportunities for designing an efficient AGV driving strategy can be obtained. Thereby looking at the number of transports in these hours and checking whether the AGV is able to make the transports on time and ensure that production output is transported.

Off-peak hours

- *[22:00-03:00]* → at the end of the evening and beginning of the night, less traffic is present on the site. Therefore, opportunities for the AGV arise here. The AGV could transport more frequently in these hours, because the possibility of interrupted behavior is lower. Furthermore, within the weekends, opportunities for even more transports arise.

Peak hours

- *[04:00-08:00]* → this is one of the highest peaks within traffic movements at the Company X site. Especially on Monday until Friday a lot of transport movements are happening and thus it is a good idea to not use the AGV within these time frames. However, since production is happening 24/7 the finished products need to be stored for 4 hours at the *Expedition Y* area when the AGV is inactive.
- *[12:00-19:00]* → in these five hours more transports than on average occur, these can be seen as peak hours compared to the rest of the timeslots. However, the AGV cannot be stopped entirely for nine hours (both peaks) in total, since it will not be able to transport all produced goods. Therefore, the other transport streams need to be regulated to ensure AGV efficiency within this peak.

Furthermore, the possibility of having some of the bottlenecks replaced provides opportunities for the AGV. Because of that, less crossings ought to take place and therefore the efficiency of the AGV increases. As we saw earlier, the four AGV-bottlenecks do have significant influence on the routing of the AGV via the crossings of the AGV track and thereby the possibility of interruption. So choices upon the prevention of the bottlenecks need to be made. Moreover, within an AGV strategy, the following should be taken into account:

- **Priority Ruling** – whatever happens on the site is variable, as we saw via the simulation model that a huge number of movements are present at every instance. Thus, the AGV should be programmed as such that it has priority ruling to ensure that it functions as efficient as possible.
- **Transportation of Full-Truck Loads** – it is wise to always transport Full-Truck Loads, to be able to transport efficiently and thereby diminish the number of AGV transports needed. As we saw already, the possibility of interrupting the movements is quite high and therefore the AGV transports should be the least as possible.
- **Incorporate Charging** – decisions about the question whether to use an electrical or diesel truck for the AGV need to be made. Both variants need charging/refueling and therefore this should be incorporated in the strategy of the AGV. When for example the electrically driven AGV needs to charge via a similar charger as depicted in Figure 6-11, these charging moments can be integrated in the strategy. The decision could for example be made to charge every time the AGV is back at its original position.

FIGURE 6-11: ELECTRICAL VEHICLE 2 GRID CHARGING (BROOKS AND THESEN, 2007)

- **Pedestrians** – the pedestrians are not modelled, but they should be regulated since they can also cause interruptions of the AGV.
- **External Transports** – the external transports, that are a bottleneck as well, are refrained from this case study due to its high variability. However, rules and regulations need to be made for them to prevent more crossings and accompanying AGV interruptions from happening.

6.4. Porter's Lodge - Impacts

Within this section the impact upon the porter's lodge is evaluated. Obtained from the AHP analysis and accompanying Company X perspective, the congestion rate caused at the porter's lodge due to several reasons can result in future problems. One of the reasons for a high congestion rate includes the processing time that is required to process an incoming truck. Therefore, recall that we vary the processing time between the minimum time required (2.30 minutes) and the maximum time required (12.30 minutes) for handling a truck in three different intervals. The impact of a specific interval is tested for the congestion rate with accompanying waiting times. Moreover, the impact upon the utilization of the porter's lodge is measured based upon both the incoming and outgoing transports since both require activities performed by the porters. Therefore, the impact of varying the processing time is also tested for that indicator. To be able to perform a concise analysis for the porter's lodge, the following configurations are investigated:

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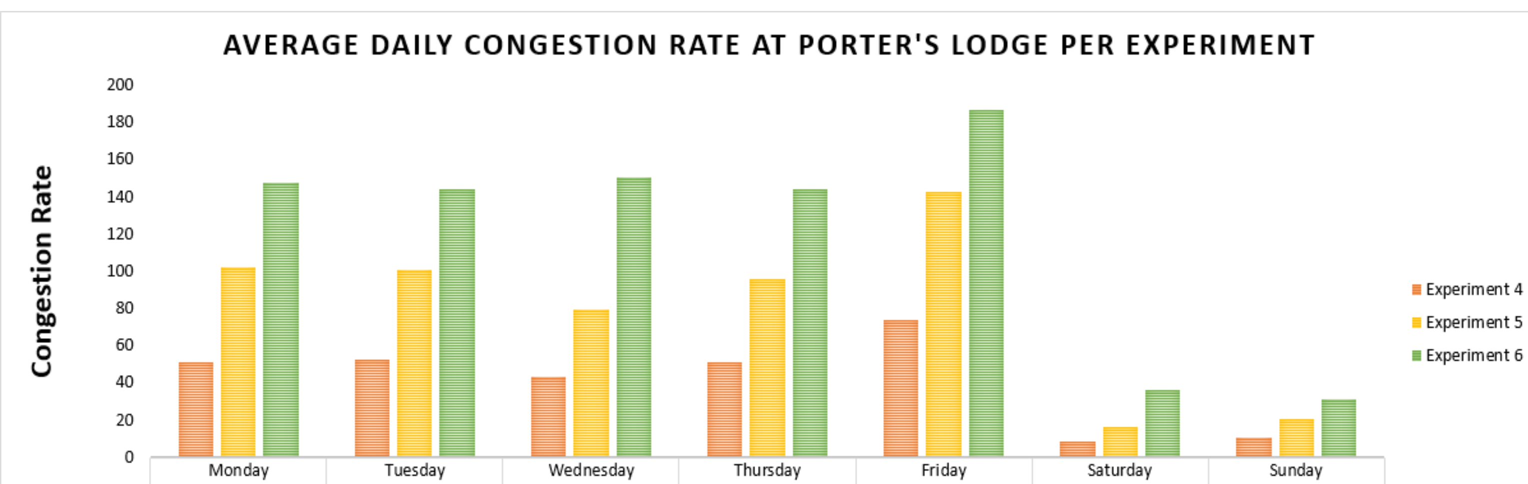
These experiments are chosen since nothing is replaced or relocated from the possible AGV bottlenecks, meaning that all the transports still pass the future porter's lodge. Furthermore, the input factor regarding the velocity of the AGV is kept constant at 6 km/h such that this does not have influences upon the porter's lodge impact computations. First of all, the impact upon the congestion rate is analyzed in Section 6.4.1., followed by the impact upon the porter's utilization in Section 6.4.2. In both cases, the three scenarios for the processing time are analyzed and the possible degree of automation is discussed.

6.4.1. Congestion Rate vs. Degree of Automation

As described previously, we vary amongst three scenarios regarding the processing time of the porter's lodge. These processing times take on values within uniform time intervals. The results regarding the congestion rate, for each time interval respectively, are visualized in Figure 6-12.



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Experiment 4	51	52,5	43	51	74	8,5	11
Experiment 5	102	101	79,5	96	143	16	20,5
Experiment 6	148	144	150,5	144	187	36	31

FIGURE 6-12: AVERAGE DAILY CONGESTION RATE OF THE CONFIGURATIONS OF TABLE 6-17

When we zoom in and compare the experiments with each other, it is possible to derive future impact reductions. The fundamental idea is to start with the worst input factor which is U[7:30, 12:30]. Here, the decrease in congestion rates is computed on an average daily basis. The different impact reductions are shown in Table 6-18 underneath.

TABLE 6-18: COMPUTED IMPACT REDUCTIONS FOR THE KPI: CONGESTION RATE AT PORTER'S LODGE

Day	Value Exp 4	Value Exp 5	Value Exp 6	Reduction Exp 6 - Exp 5	Reduction Exp 5 - Exp 4	Reduction Exp 6 - Exp 4
Monday	51	102	148	31,08%	50,00%	65,54%
Tuesday	52,5	101	144	29,86%	48,02%	63,54%
Wednesday	43	79,5	150,5	47,18%	45,91%	71,43%
Thursday	51	96	144	33,33%	46,88%	64,58%
Friday	74	143	187	23,53%	48,25%	60,43%
Saturday	8,5	16	36	55,56%	46,88%	76,39%
Sunday	11	20,5	31	33,87%	46,34%	64,52%

As we can see here, significant congestion rate reductions are achieved by decreasing the processing times. This could for example be achieved via automating certain activities like the Automatic Number Plate Recognition mentioned in Section 4.5.

The congestion rate caused at the porter's lodge is an important measure for Company X to check if a lot of trucks are waiting on an average daily basis. However, the waiting times corresponding to the waiting trucks are important as well to derive the problems that might arise for the truck drivers. Long waiting times are logically not desired here. Therefore, the waiting times corresponding to the different processing times at the porter's lodge are investigated and computed by means of the simulation model. The results are shown in Table 6-19 underneath.

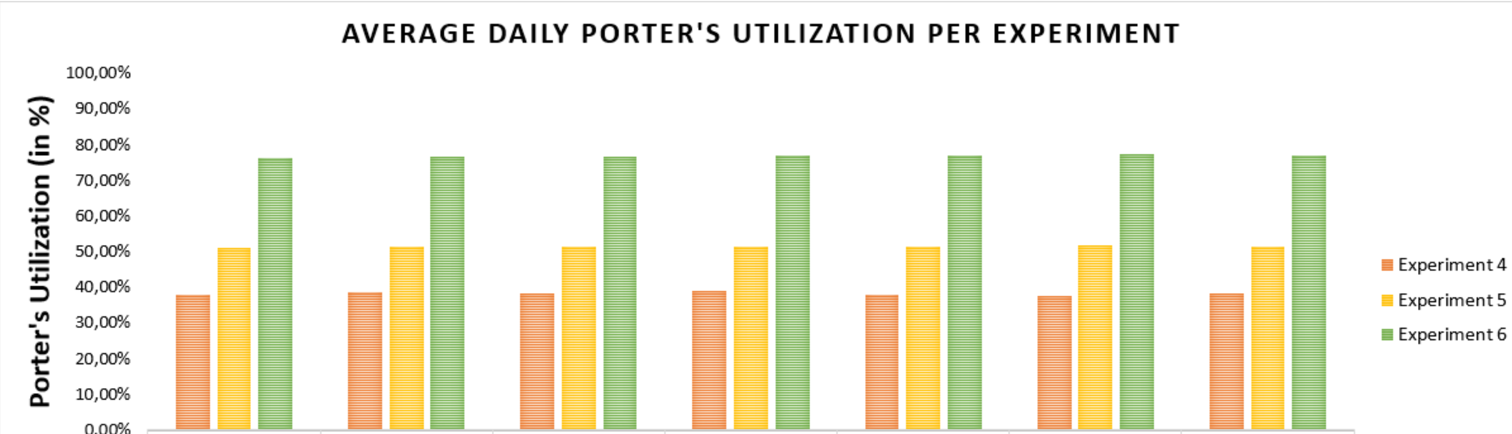
TABLE 6-19: WAITING TIMES CORRESPONDING TO THE PROCESSING TIMES AT THE PORTER'S LODGE

Day	Waiting Time U[2:30,7:30]	Waiting Time U[5:00,10:00]	Waiting Time U[7:30,12:30]
Monday	11.38 minutes	33.51 minutes	39.90 minutes
Tuesday	17.47 minutes	34.77 minutes	39.66 minutes
Wednesday	15.98 minutes	32.98 minutes	41.41 minutes
Thursday	16.64 minutes	32.21 minutes	39.61 minutes
Friday	18.31 minutes	39.78 minutes	49.90 minutes
Saturday	6.98 minutes	22.12 minutes	30.10 minutes
Sunday	8.67 minutes	26.15 minutes	28.18 minutes

From these results we see that rather long processing times have a negative effect upon the waiting times. When we take the waiting times on an average Friday as an example, we see a significant and drastic change in the waiting times. Recall that we saw that on an average Friday, in the best-case scenario 74 trucks need to wait throughout the entire day and in the worst-case scenario 187 trucks need to wait. The accompanying waiting times are 18.31 minutes and 49.90 minutes respectively. This means that, on average, a truck needs to wait 31.59 minutes longer when long processing times are attained. Queueing theory shows that if long queues (in essence congestion rates here) are created, the waiting times increase significantly. Regarding these waiting times, one could say that an average waiting time of 49.90 minutes to be processed at the porter's lodge is way too long. Decreasing the processing times can thereby have significant influence upon waiting time reductions as we can see from Table 6-19.

6.4.2. Porter's Utilization vs. Degree of Automation

Besides the congestion rate, the processing times also have impacts upon the porter's lodge utilization. Since long waiting times caused due to relatively long processing times result into high porter's lodge utilizations, the utilizations on an average daily basis for the three experiments are visualized similarly as the congestion rate. The results are depicted in Figure 6-13 underneath:



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Experiment 4	37,92%	38,58%	38,38%	38,90%	38,02%	37,55%	38,29%
Experiment 5	50,91%	51,19%	51,29%	51,32%	51,37%	51,59%	51,21%
Experiment 6	76,30%	76,65%	76,72%	76,88%	76,92%	77,13%	76,73%

FIGURE 6-13: AVERAGE DAILY PORTER'S UTILIZATION OF THE CONFIGURATIONS OF TABLE 6-17

TABLE 6-20: COMPUTED IMPACT REDUCTIONS FOR THE KPI: PORTER'S UTILIZATION

Day	Value Exp 4	Value Exp 5	Value Exp 6	Reduction Exp 6 - Exp 5	Reduction Exp 5 - Exp 4	Reduction Exp 6 - Exp 4
Monday	37,92%	50,91%	76,30%	33,27%	25,52%	50,30%
Tuesday	38,58%	51,19%	76,65%	33,21%	24,65%	49,67%
Wednesday	38,38%	51,29%	76,72%	33,15%	25,17%	49,97%
Thursday	38,90%	51,32%	76,88%	33,24%	24,21%	49,41%
Friday	38,02%	51,37%	76,92%	33,22%	25,99%	50,58%
Saturday	37,55%	51,59%	77,13%	33,12%	27,20%	51,31%
Sunday	38,29%	51,21%	76,73%	33,26%	25,23%	50,10%

Again, the impact reductions are computed and shown in Table 6-20. From that perspective we can see that the impacts upon the porter's utilization are significant as well. When again looking at the worst-case scenario U[7:30,12:30] and the best-case scenario U[2:30,7:30] we see that an impact reduction of approximately 50% can be achieved for the porter's utilization. Within the worst-case scenario, when no automation of activities is performed, utilizations of 76-77% for the porter's lodge are present. Although this is not rather high, this might give complications for Company X. Namely, if the utilization of the porter's lodge decreases significantly, the porters have the opportunity to fulfill other tasks instead of solely helping and instructing the truck drivers. This is a desire of Company X, since a lot of paperwork and registration activities need to be performed and furthermore the porters can be seen as safety guardians for the Company X site. Therefore, when the porters are approximately 25% of their time busy with the arriving trucks (best-case) they have way more time for other activities.

Thus, matters of automation should be taken into account to eventually be able to decrease processing times and positively affect both the congestion rate and the porter's utilization at the porter's lodge.

6.5. Limitations

During the creation of the model, the computations and the eventual experimentation phase, several limitations came along. The most important ones, that are limiting certain aspects to make the results of this research completely realistic, are explained here:

- **Inconsistent behavior AGV –** the AGV is modelled based upon the characteristics provided by potential supplier Götting. Thereby, the AGV moves along the AGV-track based on the described RFID-transponders. However, there are a lot of other possibilities for AGV maneuvering. Also, there are multiple other suppliers of AGVs and corresponding technology that might suit Company X. In this research the characteristics and moving behavior of the AGV is limited to Götting perspective.
- **Unpredictable behavior –** the simulation makes use of multiple random number streams that for example make up the processing times at different stations. Since these times can deviate a lot, the random number streams are used for distribution purposes. For example within the case of the processing times of the porter's lodge we made use of a uniform distribution taking on values between lower and upper bounds. Logically, the best experiment in this case turned out to be the one with the lowest range in minutes: U[2:30,7:30]. In here, random number streams are used to cover up unpredictable behavior. We also made use of more replications to diminish variances, but still unpredictable behavior might come along. Therefore, one can never be a 100% sure that the simulation reflects future reality.
- **Rules and regulations** – within a lot of instances the model is based on common sense. Especially regarding the routing of the AGV this is of importance. Multiple traffic lights and traffic barriers could be put into place in the future, and the simulation model takes this into account. Therefore, the interruptions of the AGV can be somewhat lower than in reality. Because when one of the drivers or pedestrians does not take the traffic rules into consideration, the AGV might be hindered and delayed in its transport.
- **Forecasting transports -** due to the current absence of transports regarding the new warehouse, forecasting is applied for these transportation modes. As explained, historical data has been used to model all the transports within the logistical network based on hourly time intervals. But in the future, for the customer transports meant for product retrieval, an increase of transports might be present. Since the warehouse is able to store 40,700 pallets, the customers arriving on the Company X site increase and thus these forecasts are not completely realistic.

6.6. Model Validation & Verification

As we saw earlier, the new warehouse is not finished by the end of this research. The goal of Company X is to have the warehouse completely operational by the end of 2019 and thus the results of this research ought to be implemented and integrated into the logistical network by then. Retrieved from literature, multiple forms of validation and verification techniques are applicable. In here, the focus of validation and verification lies upon the created simulation model. Certain aspects of model validation are not applicable because of the fact that parts of the logistical network are not operational yet. However, multiple parts of the model can be validated. Furthermore, verification based upon the data, logic and the performed experiments is certainly possible. Therefore, both validation and verification are discussed here.

6.6.1. Simulation Model Validation

Within the literature review of Chapter 3, five kinds of validating techniques are analyzed: (1) Internal Validity, (2) Animation, (3) Historical Data Validation, (4) Event Validity and (5) Operational Validity. These validation techniques are shortly discussed and their applicability and influence within this research is identified:

- **Internal Validity** – the internal validity deals with the variability within a model by making three replications to prevent stochastic behavior as much as possible. Multiple replications (three per experiment) are performed to decrease variability. However, the stochastic behavior is not tackled completely, because the future planning is very variable. Truck drivers might for example need to deal with traffic jams and weather conditions which are not accounted for in the simulation model.
- **Animation –** a graphical representation is presented to convince the end-users of the results of the simulation. Therefore, due to animating behavior the model moves through time and the user can validate if the right movements and processes happen consistently and adequately at each discrete event.
- **Historical Data Validation** – the main historical data that is used concerns the modes of transport. Especially the *Z1*, *Company Y* and *Expedition X* transports are completely modelled based on historic data. To apply validation here, the transports are tracked throughout the simulation on a yearly basis and stored to compare the simulation data with the historic data. Multiple iterations are performed to ensure that in the end the right number of transports at each moment are integrated in the simulation model.
- **Event Validity** – this type of validation technique compares the events of the simulation with the events in real life. For example the described scenario where trucks have to wait if the AGV is in the neighborhood. These types of events are not possible to test yet and are hard to validate in the future. Since there are lots of occurrences on a daily basis, Company X should pay close attention to the key contributors within the logistical network on their site.
- **Operational Validity** – this technique is not possible to perform, since critical elements of the simulation model like the AGV, the porter's lodge and the new warehouse are not operational yet. Therefore, the output behavior of the simulation cannot be tested based upon operationality.

Overall, several validation techniques are applied to ensure that the simulation model is representing reality. Especially through animation and usage of historical data, validating turned out that the transports and accompanying visualization are modeled correctly. However, due to absence of the new warehouse, the AGV and the porter's lodge matters of event validity and operational validity are not applicable. Therefore, multiple assumptions have been made to be able to make use of a simulation model and gain insights in future processes. Stochastic behavior is diminished due to the usage of multiple replications per experiment where the variability in the output is decreased, but since we make use of simulation model for future purposes lots of variability is still present.

6.6.2. Simulation Model Verification

The verification of the simulation is primarily based upon the data, the used logic and experimentation, as has been retrieved from literature in Chapter 3. Especially the data and data model errors that can occur during modelling are of importance here. Several decisions have been made to be able to model important parts of this research. Since the entire logistical network is made up from scratch in the simulation model, the processing times and waiting times are also incorporated. Thereby, statistical distributions are used. Mainly uniform and normal distributions are used to fit the actual processes of Company X. However, variations in real world definitely occur. Therefore, the statistical distributions give an as good as possible approach to reality, but do not reflect the actual processes completely.

With regards to the logic and algorithms of the simulation model we refer to:

- **The AGV**: its routing and the crossings and interruptions by other vehicles.
- **The Porter's Lodge**: the functioning, the processing times, the waiting times and possible congestion rates due to the waiting.
- **The New Warehouse**: the processes at the warehouse regarding both ingoing (AGV) as outgoing (customers) transports.
- **Other transports**: their entering time slots, their routing and behavior upon the Company X site.
- **The Experimental Design**: the varying of input factors, the right settings and the output computations.

In addition to the data model errors and the integrated logic, errors in experimentation can cause the research to be incomplete or even unusable. The major cause for this is misinterpreting the results. Since we have to deal with 192 experiments with each experiment consisting out of three replications and multiple output values on a daily basis, generating the results as described in Section 6.2. required several computations. Thus small errors might be made here, but the results regarding the best experiments for the seven days are quite similar and significant. Indicating that prevention of activities benefits the behavior from especially the AGV, something that Company X expected beforehand and turned out to be true by means of the model.

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Overall there are some minor flaws regarding the data distribution and experimental setup, but based on the simulation, Company X can get insights in future impacts and act accordingly. Which would not be possible with any other model. Where we tried to approach the future situation incorporating the logistics surrounding the new warehouse as depicted in Figure 6-14 as reliable as possible.

6.7. Results - Conclusion

Throughout this chapter the obtained results of this research with corresponding interpretations are outlined. First of all, the results of the performed AHP analysis are discussed. The results are ranked and scored per participant and indicator. It turned out that the *AGV Crossings*, the *Congestion Rate* and the *Interrupted AGV Transports* are considered most important for detailed analysis. Secondly, the 192-full factorial design regarding the simulation model is explained. Based on that, the three best and three worst experiments are highlighted. These experiments emphasize the significant differences and the opportunities for Company X to create a more efficient logistical network.

An AGV-bottleneck analysis considering the impact of each bottleneck separately is performed for the AGV and its functioning. In here, the four major bottlenecks: (1) Transports Expedition X, (2) Z5 Supplies, (3) Company Y Activities and (4) Pallet Supplementing are analyzed and their impact upon the logistical network and especially the AGV is discussed. The two important indicators that are emphasized here are the *AGV Crossings* and the *Interrupted AGV Transports*. The replacement of Z5 Supply and the relocation of Company Y Activities have significant impact reductions on both indicators. Whereas the waiting system for the Expedition X truck drivers results in an impact reduction upon the interruptions. On the other hand, the transferring of the Pallet Supplementing has primarily positive influences upon the number of AGV Crossings.

In the future, Company X can easily improve the AGV functioning by only implementing the waiting system for the Expedition X trucks. On average, these trucks cause 4 interruptions of the AGV per day and these can be avoided due to a waiting system. The investment costs are low and the implementation time is short. However, when Company X wants to integrate the AGV in the most efficient way possible, investments for Company Y and the Z5 Supplies are required. These investments encompass the relocation of the Company Y activities and the replacement of the manual Z5 supplies via underground pipelines. In addition to the elimination possibilities of the AGV bottlenecks, an AGV strategy is proposed to keep the off-peak and peak hours into account. The off-peak hours are on average between 22:00-03:00 and two peak intervals can be found at 04:00-08:00 and 12:00-19:00.

Moreover, the porter's lodge and the impacts of the experiments upon the *Congestion Rate* and the *Porter's Utilization* are tested. We varied the processing time at the porter's lodge to check for impacts and possible reductions. Regarding the congestion rate, significant reductions are achieved when the processing time is reduced. Furthermore, the waiting times increase drastically when high processing times are attained. Lowering the processing time at the porter's lodge can be done by automating certain functionalities, via for example the usage of Automatic Number Plate Recognition. Furthermore, the impact upon the porter's lodge utilization decreases as well. However, the maximum utilization with the worst accompanying processing time of U[7:30,12:30] has a value of 77.13% which is still not a problem for Company X. But when they want the porters to perform other functionalities like safety guarding and registration, a lower utilization provides opportunities for the porters to fulfill the other activities as well during their workdays.

Besides the analysis upon the future impacts, the limitations regarding the creation and usage of the simulation model are discussed. Lastly, model validation and verification are explained where the techniques suitable for this research are elaborated. Several aspects of both the validation and verification techniques found in literature are applicable for this research. Within the next chapter, the conclusions and recommendations that can be withdrawn from this case study with accompanying results are discussed.

7. Conclusion and Recommendations

Based upon this research and the accompanying model, there are several factors worth considering and these require attention in the future. First of all, the conclusions that can be drawn from this research are explained in Section 7.1. Furthermore, a list of recommendations for Company X with accompanying explanations is provided in Section 7.2. Moreover, an interactive dashboard Company X been created as final delivery for Company X in which they are able to simulate multiple configurations in the future to see what kind of consequences certain aspects might have. This dashboard is shortly discussed in Section 7.3. Lastly, aspects for further research, an eventual future implementation plan and a roadmap are discussed in Section 7.4.

7.1. Conclusion

Due to the introduction of a new warehouse, the logistical network of Company X changes drastically. The new warehouse results in a more efficient way of transportation, since lots of the external storage locations are no longer needed and thus these storage transportations are happening internally on the Company X site. By the introduction of a single Automatic Guided Vehicle (AGV), these storage transportations are taken care of. This AGV is responsible for the storage transportations of finished products, retrieved from the production area, and transported to the new warehouse in the future. However, the logistical network of Company X becomes more complex, because the transportation frequencies increase and the number of foreign and unknown truck drivers on-site increase as well. A porter's lodge at the new warehouse is responsible for the regulation of these transports. Therefore, this new porter's lodge can be seen as the centralized entrance of the future network and requires investigation as well to derive possible complications and prevent them from happening.

The new warehouse and the accompanying increased transportation rates, the AGV and the porter's lodge result in a complex logistical network. Company X's desire is to obtain a fluent and efficient network to deal with all the activities in a proper and timely way. Therefore, this research focused on efficient routing upon the Company X site to prevent future complications and problems from happening. So, within this research we tried to come up with answers regarding the main research question:

How can the routing and planning, i.e. (1) the incoming supply of raw material, (2) the inter-warehouse transportation, (3) the AGV transportation and (4) the outbound logistics on the site of Company X be arranged in such a way that the situation incorporating the new warehouse functions efficiently?

Multiple aspects are investigated to come up with solutions for an efficient situation incorporating the new warehouse. We saw that several transportation flows make up the rather crowded network. In total, six bottlenecks could interrupt future AGV behavior. Tackling these bottlenecks as much as possible is the ultimate goal, but preventing all of them is hardly possible since that would require huge investments and drastic changes to the Company X site. Therefore, an AGV bottleneck analysis is performed to check the impacts upon AGV functioning for the following bottlenecks: (1) *Transports Expedition X*, (2) *Manual Supply Z5*, (3) *Company Y Activities*, (4) *Pallet Supplementing*, (5) *Pedestrians* and (6) *External Transports*. Since the latter two are highly variable and unpredictable, these are not taken into account during modelling. Preventing the first four bottlenecks is investigated throughout this research to come up with a good and efficient routing for the AGV.

To be able to analyze future impacts and test different scenarios, a simulation model is constructed. Based on that, the entire future situation incorporating the new warehouse is modelled to derive an animated version of future reality. Throughout the simulation, multiple Key Performance Indicators (KPIs) are tracked and analyzed. The ones considered the most important for a thorough analysis are: (1) *Average Daily AGV Crossings*, (2) *Average Daily AGV Utilization*, (3) *Average Daily Interrupted AGV Transports*, (4) *Average Daily Porter's Lodge Utilization* and (5) *Average Daily Congestion Rate*. We tried to analyze the KPIs based on different configurations. Where the prevention possibilities regarding the AGV bottlenecks and the performance of the porter's lodge are critical aspects. Conclusions for the functioning of the AGV and the porter's lodge can be withdrawn from the simulation-testing of the different scenario's in a 192-full factorial design.

7.1.1. AGV

The functioning of the AGV is primarily based upon the bottlenecks that are present along its track. For the AGV, we looked at the number of crossings, the AGV utilization and the number of interrupted AGV transports in particular. Based on the simulation runs, it turned out that the highest impact reduction upon AGV behavior are achieved by:

- **Replace Manual Supply Z5**
    - Highest impact reduction upon the crossings of the AGV track of 6.1% on Saturdays.
    - Highest impact reduction upon the interrupted AGV transports of 46.88% on Fridays.
- **Relocate Company Y Activities**
    - Highest impact reduction upon the crossings of the AGV track of 29.27% on Saturdays.
    - Highest impact reduction upon the interrupted AGV transports of 70.00 % on Saturdays.

Pallet Supplementing and the Expedition X transports do have significant impacts upon the AGV. However, they need to be regulated instead of being replaced/relocated. The pallet supplementing is performed by internal Company X employees and they need to be informed about the priority of the AGV. Whereas the Expedition X transports make up the core business of Company X and they cannot be prevented. Therefore, adequate monitoring and safety regulating is needed to ensure that the number of interrupted AGV transports is as low as possible regarding this bottleneck. Lastly, it can be concluded that increasing the velocity of the AGV does not have significant effects upon the functioning of the AGV. The velocity is varied between 4,6,8 and 10 km/h per hour, but no significant differences in the number of AGV transports and accompanying interruptions by other vehicles are found. This is rather logical, because the number of crossings by other vehicles remains the same regardless of the velocity of the AGV.

7.1.2. Porter's Lodge

The activities at the porter's lodge are modelled and we saw that its centralized location results in complications regarding the congestion rates at the waiting area and the utilization rate of the porters. When the processing time is distributed U[7:30,12:30], high congestion rates arise, with a maximum of 151 trucks waiting on Wednesdays. Therefore, automating activities like the usage of automatic number plate recognition and an interactive waiting system for the truck drivers could decrease the processing times. The simulation showed that decreasing the processing times at the porter's lodge to U[5:00,10:00] or even U[2:30,7:30] has significant impact reductions on the congestion rate and accompanying waiting times. Besides that, we looked at the porter's utilization. This utilization does not reach levels higher than 78% for each scenario. Which is good for Company X since this means that the porters are able to perform the work and even have time left for other activities for example.

7.1.3. Final Concluding Words

Finally, we can conclude that the created simulation model looked at the future logistical network of Company X and derived possible complications. However, the new warehouse is operational at the beginning of 2020 and therefore decisions need to be made beforehand for both the AGV and the porter's lodge to ensure that the network functions as efficient as possible.

7.2. Recommendations

Based on the performed research and corresponding analyses, several critical points and accompanying solutions can be recommended. Eventually, efficient routing and planning within the complex logistical network of Company X ought to be obtained. The key aspects, listed underneath, are recommended to Company X to ensure an efficient logistical network in the future. These are based upon the simulation and conducted investigation, to ensure fluent transportation on and around the Company X site:

- **Prevention/Elimination AGV Bottleneck(s)** – two of the bottlenecks should be eliminated to ensure fluent AGV behavior. These are circled in red in Figure 7-1:
    - **Replacement Z5 Supply** – the maneuvering at the docks results in high chances of interruption of the AGV and thus pipelines for these supplies are advisable.
    - **Relocation Company Y Activities** – the Company Y trucks hinder the AGV frequently and therefore a transferal to another location should be put into place for these transports.
- **Regulate AGV Bottlenecks –** some of the bottlenecks should be regulated to ensure fluent AGV behavior. These are circled in black in Figure 7-1:
    - **Regulate Expedition X** – make use of traffic lights and barriers for these trucks.
    - **Regulate Pallet Supplementing** make use of traffic lights and barriers for these trucks.

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- **AGV Timeslot Strategy –** hourly timeslot strategy for the AGV functioning, bearing in mind:
    - Prevent driving in the peak hours as much as possible ≈ [04:00-08:00] & [12:00-19:00].
    - Drive frequently in off-peak hours ≈ [22:00-03:00].
    - Transport more frequently in the weekends, since the chance of interruptions is lower.
    - Incorporate AGV charging to ensure that the AGV is able to transport when needed.
- **AGV Priority Ruling** – the AGV should always have priority over the other vehicles, such that it can perform its transports as fast and as efficient as possible.

- **Manual Takeover AGV –** especially in the beginning, lots of errors might occur. Manual takeover should **always** be possible and is advisable to incur at the start of AGV operationality.
- **Visualize AGV track** – the AGV track should be visualized in reality to ensure that people know that the AGV is travelling on that specific track and they are alerted due to the visualization.
- **Inform Truck Drivers** – truck drivers should also be aware of the fact that an AGV is driving on Company X terrain, therefore informing them by the entrance at the porter's lodge is advisable.
- **Reduce Pedestrian Crossings** – the pedestrians are not modelled in this research, but since they are crossing the track as well, their crossings should be reduced as much as possible.
- **Automating Porter's Lodge Activities** – automating activities of the porter's lodge is advisable, because the processing times are likely to decrease based on these automation techniques. Furthermore, within the long-term this might result in a reduction of employees needed in the future. However, the reliability of the automation should be checked and verified before integration.

7.3. Interactive Dashboard

To be able to make use of the simulation tool in the future, an interactive dashboard is created where the input factors can be altered according to the user's wishes to see what the consequences for Company X will be. These consequences focus primarily on the AGV and its routing efficiency. However, the option to deviate amongst the processing times of the porter's lodge is also possible. An overview of this dashboard is depicted in Figure 7-2 underneath, where we took a screenshot of a possible configuration.

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Within the dashboard, we created the opportunity for Company X to test the configurations for themselves. Testing means simulating the model for a certain period of time. First of all, recall that we investigated the handling of four AGV-bottlenecks. Their impact is reflected within this research via the so-called "tick-boxes". A  indicates that prevention is put in place. Whereas a  indicates that no prevention is performed, like with the pallet supplementing in the example configuration used in the dashboard of Figure 7-4. By simply ticking the boxes, Company X can alter the value of the prevention possibilities and see what the impacts are and furthermore zoom in on the complications. Moreover, the drop-down menus give the opportunity of altering the AGV velocity (4,6,8,10 km/h) and the processing times at the porter's lodge (U[2:30,7:30], U[5:00,10:00], U[7:30,12:30]). Eventually, the table files represent the experimental output. First of all, the data is stored on an average daily basis throughout the simulation run. Furthermore, the data of all the mentioned KPIs of this research are stored. Based on that, Company X is able to perform simulations with the constructed model. Lastly, a short manual is written for Company X to ensure that they are able to make use of the simulation model in the future.

7.4. Future Implementation & Further Research

Based on the conducted research, several possibilities for further research arise here. First of all, we take a look at opportunities for Company X to ensure an even better routing and planning within the logistical network in addition to this research. Furthermore, to be able to integrate the outcomes and recommendations of this research in the future, multiple implementations are required. These future implementations with accompanying roadmap of the suitable timeslots for implementation are described.

7.4.1. Further Research

Further research is required to develop a more efficient network, since a lot of aspects of the complex network still need to be investigated. In total, four possibilities for further research regarding the logistical network of Company X are explained:

- **AGV Charging Strategy** – the AGV could both be a diesel or an electrically driven truck. Recall that we looked at the (dis)-advantages, but no concise decision is made yet. Regardless whether refueling or recharging is needed, adequate and especially efficient moments for charging the AGV need to be found. Therefore, further research into possibilities and opportunities for Company X needs to be done here.
- **Number of AGVs –** although one AGV is able to perform three transportations within an hour in the ideal scenario, the number of AGVs might be increased to two in the long-term. When doing so, production could for example increase as well. All the pros and cons of introducing an extra AGV should be evaluated thoroughly to check whether it could be beneficiary for Company X in a couple of years after the introduction of the first AGV. Simulation could be a helpful tool here for decision-making.
- **Overall integration into an ERP system** – a lot of planning and routing is currently in play, but the software is not integrated throughout the different departments of Company X. Therefore, not all the data is gathered and stored in an efficient way. When data is stored in an integrated ERP system by every department, extensive analysis is possible to eventually improve several processes encompassing the logistical network.
- **Simulating Inner-Logistics & Consequences Logistical Network** – besides simulating the logistical network regarding the transportations, inner-processes and accompanying consequences are also interesting factors to consider. For example the order picking within the new warehouse. Within this research this aspect is considered constant, but of course this process ought to be done efficiently as well in the future. Therefore, further research might give Company X some more thought of the opportunities that arise at other departments rather than the logistical network incorporating mainly the transportations.

7.4.2. Future Implementation - Roadmap

To eventually implement pieces of this research, a roadmap is created and depicted in Figure 7-3. This roadmap focuses on the described recommendations encompassing the new warehouse. In here, the activities needed for both the AGV and the porter's lodge are central aspects. To specify the range of time, we make use of short-term (1-year), mid-term (3-years) and long-term (5-years) time horizons. Where complete operationality of the warehouse is assumed to be at the 1st of January 2020. So starting at 2019 with the short-term time horizon, the following roadmap is designed for possible implementation of several activities:

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The activities are categorized within four major projects: *Company X Site, AGV, Porter's Lodge* and *New Warehouse*. The colors indicate the different categories. When Company X decides to perform one of the activities, the color indicates which project is affected the most. Overall, it is recommended to perform all the activities within the upcoming 5 years to ensure efficient routing and planning upon the Company X site. Since several investments are required to implement all the activities, this roadmap might be altered a bit in the future due to costs and time constraints. But based on this research and the accompanying simulation model and results, these activities are emphasized for future purposes.

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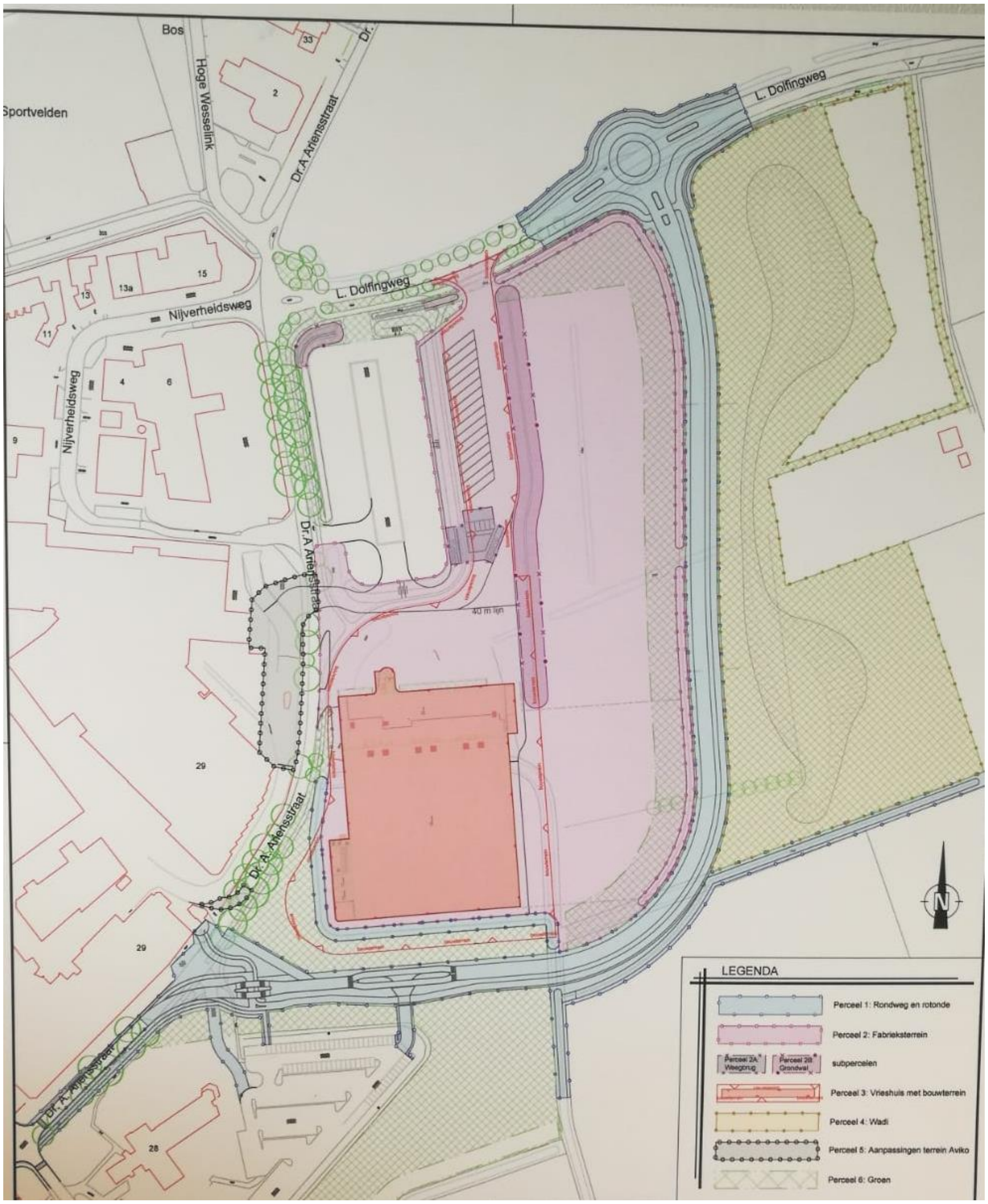
Appendices

A1. The New Warehouse

Underneath a drawing of the situation incorporating the new warehouse is shown.



Red = Warehouse

Pink = Factory site

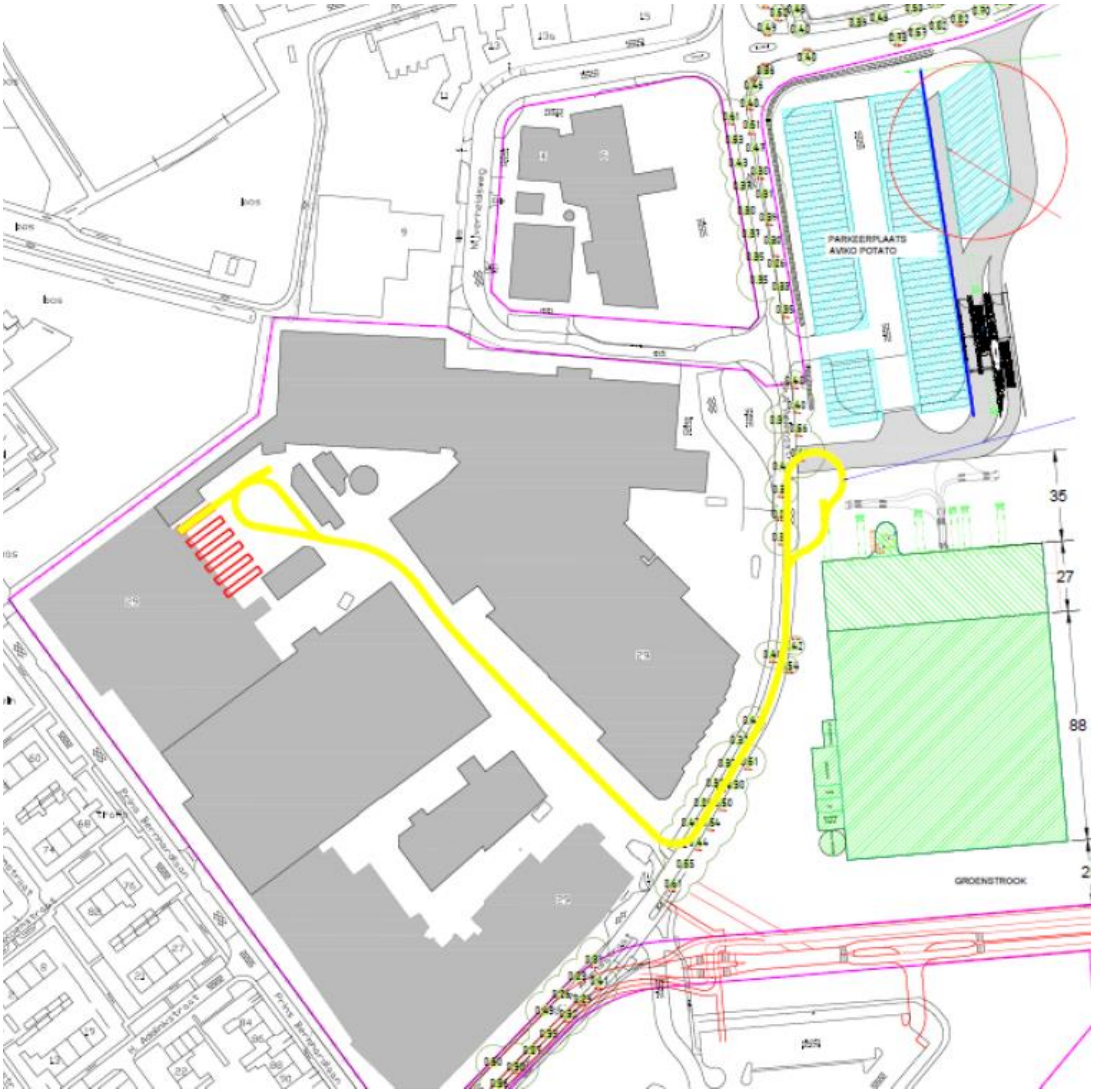
Blue = Driveways and roundabout

Black = Adjustments current site Company X

Green **=** Surroundings

A2. The AGV Track

In the picture underneath the track of the AGV leading from the current production facilities to the new warehouse is shown in yellow. Eventually, one AGV will be driving on this track. So it is a one-way track that the AGV can travel in both directions. Legally it is not allowed to drive on public highways and therefore, a separate track for the AGV will be made. The existing roads are shifted to underneath the new warehouse to ensure that the AGV can safely cross the road between the current terrain and the new warehouse.



A3. Layout Facilities

The different facilities present on the site of Company X are addressed in the figure underneath. In here, the locations of the current buildings are shown:

1. Supply → F1
2. Production → Z1, Z4 and Z5
3. Storage and Retrieval → Expedition Y and Expedition X

Furthermore, the location of the new warehouse is indicated to define the future situation. This CAD-model includes the actual sizes of the facilities, scaled to the extent that it is representable as an image within this document.

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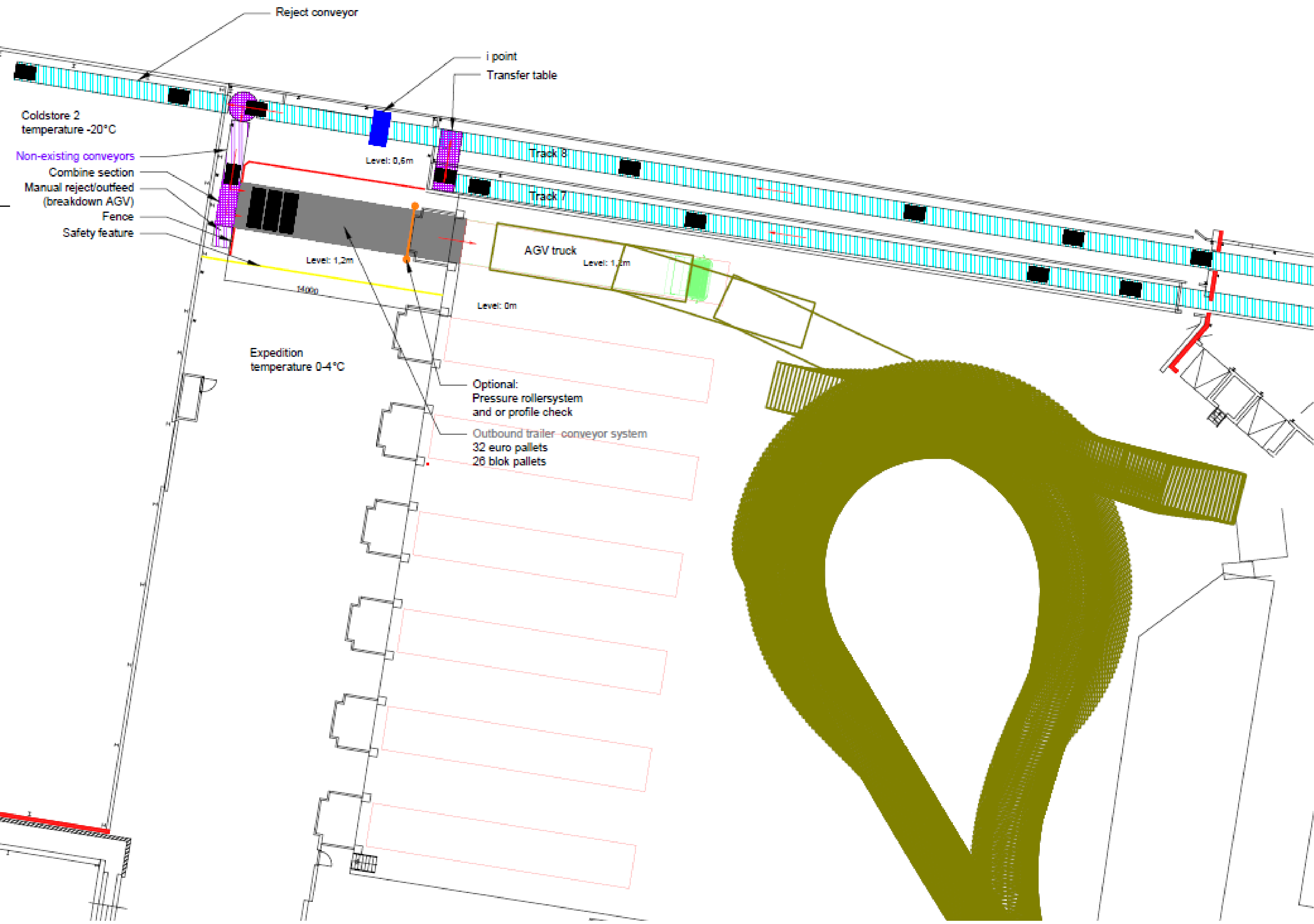
A4. Expedition Y – including AGV

In the picture underneath the current layout of the Expedition Y facility is shown, where the alternations required for the AGV and its track are also visualized. The AGV will dock backwards at one of the current docks of Expedition Y and load the produced pallets two by two. Then, it will drive to the new warehouse to unload.



A5. Functionalities & Required FTEs – Porter's Lodge

nr	Omschrijving	Korte toelichting taak/activiteit	Portier			
	Huidige activiteiten portier		Min/act /dag	# dgn /wk	Tot # min/wk	# FTE / wk
1	Bewaking bedrijfsterrein binnen gegeven kaders	Sleutelronde, afsluiten KD, controle hekken en poorten	90	5	450	0,19
2	Signaleert en treedt op bij afwijkingen op de huis- en veiligheidsregels	Bij afwijkingen, bij stop weken meer werk	30	7	210	0,09
3	Controleert en registreert weeg- en basisgegevens ingaande en uitgaande goederenstromen		300	7	2100	0,88
		Vet	90	7		
		Duynie	90	7		
		Potato (2 weging)	90	7		
		Overige	30	7		
4	Voert administratieve werkzaamheden uit		60	7	420	0,18
5	Maakt toegangsbadges aan	Bij stopweken zitten ze wegens piekbelasting van 06:00 - 10:00 met 2 medewerkers	75	5	375	0,16
6	Ontvangt en verwijst bezoekers door en informeert de betrokken afdeling	VCA check, uitgifte flyers en instructies	30	5	150	0,06
7	Informeert bezoekers, leveranciers en overige externen over huisregels	VCA check, uitgifte flyers en instructies Bij projectperioden is dit in de ochtend zoveel werk dat er twee zitten	180	5	900	0,38
8	Geeft parkeervergunningen uit	Bij projectperioden is dit veel meer werk	60		0	0,00
9	Coördineert de communicatie in geval van calamiteiten	Aleen trainen als BHV	30		0	0,00
10	Fungeert als telefooncentrale ten behoeve van de productie buiten kantoortijden	Buiten de diensturen komt de telefoon bij ploegleider de ploegleider die het eerst oppakt handlet het telefoontje af	15	7	105	0,04
11	Heeft dagelijks contact met verschillende afdelingen en extern met expediteurs	Portier heeft veel contact met Vers, diepvries, buitendienst en magazijn maar ook met diverse projectleiders	150	7	1050	0,44
12	Spreekt dagelijks elementair Engels en Duits				0	0,00
13	waarborgt onder voorwaarden de veiligheid op het terrein		30	7	210	0,09
14	Beheert (reserve) sleutels en documenten ten behoeve van calamiteiten		15	7	105	0,04
15					0	0,00
					0	0,00
		Totaal			6075	2,53

A6. Layout Simulation Model

The layout of the simulation model is depicted underneath. In here, all the logistical transport modes upon the site of Company X and its surroundings are modelled on scale.

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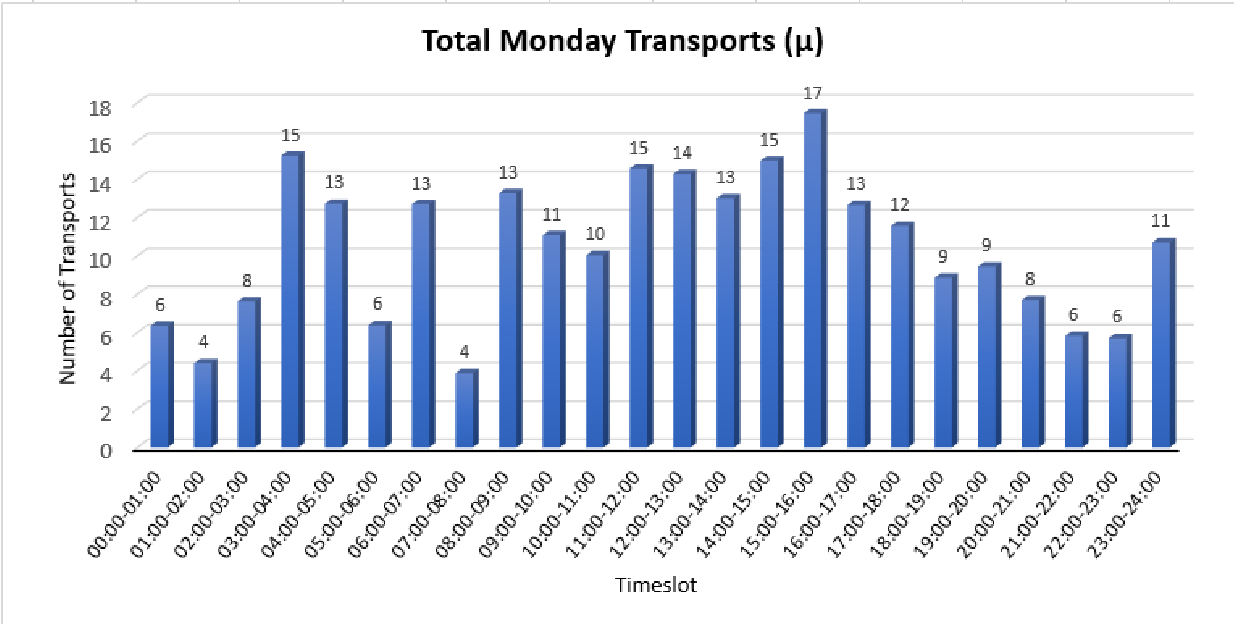
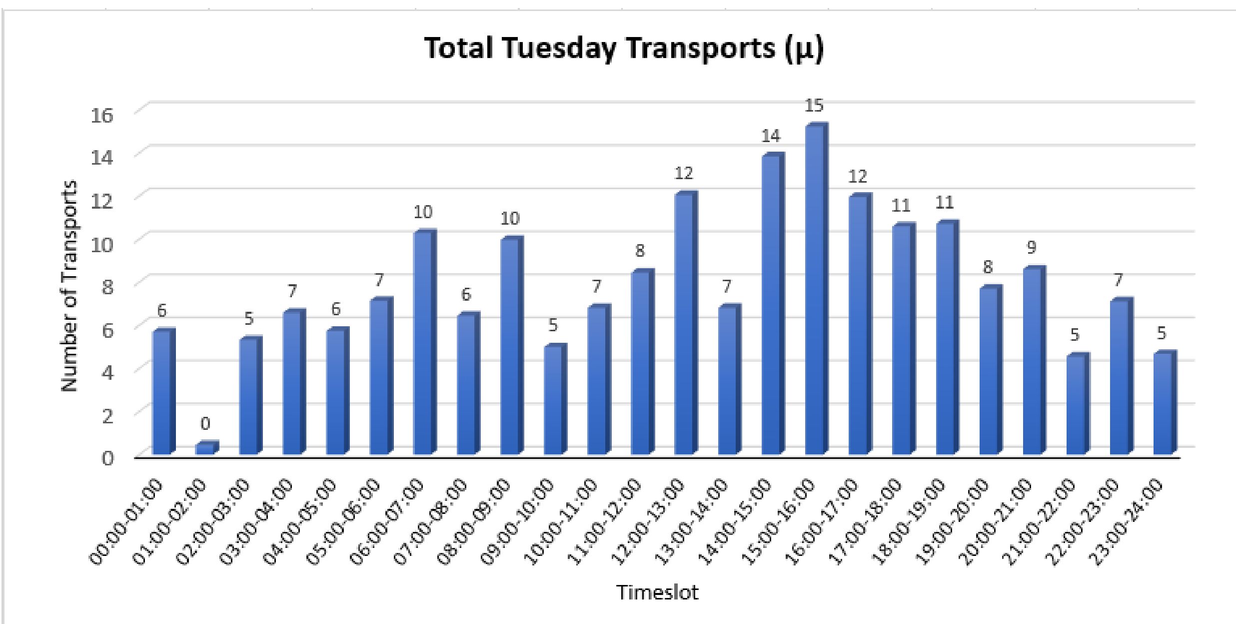
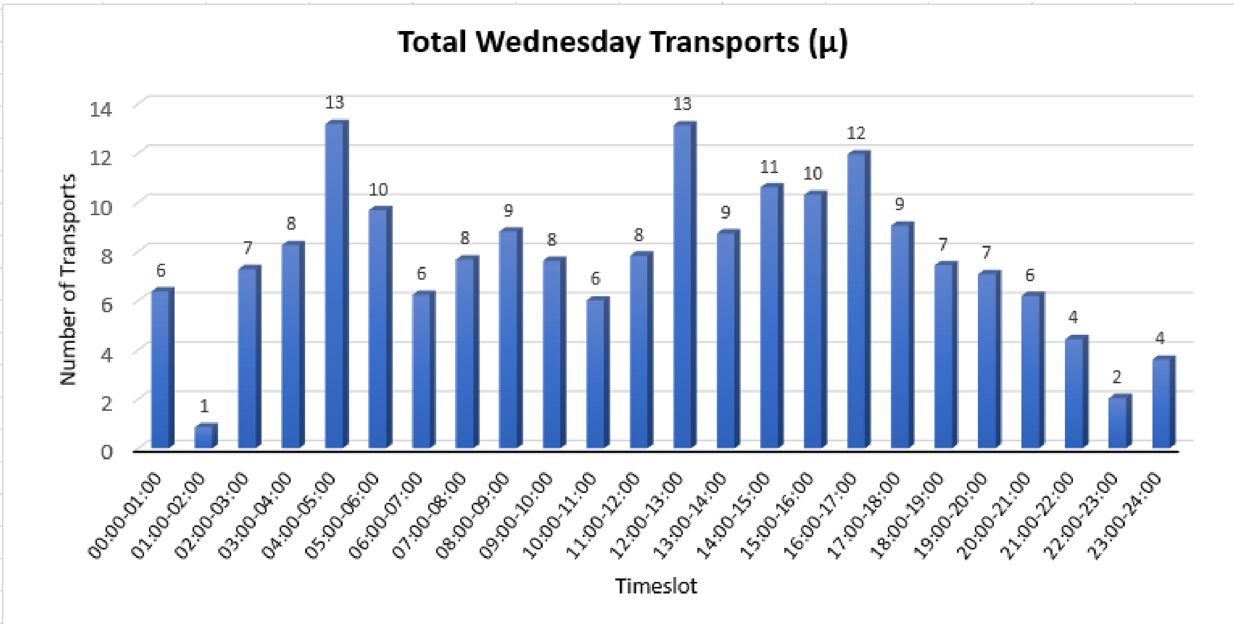
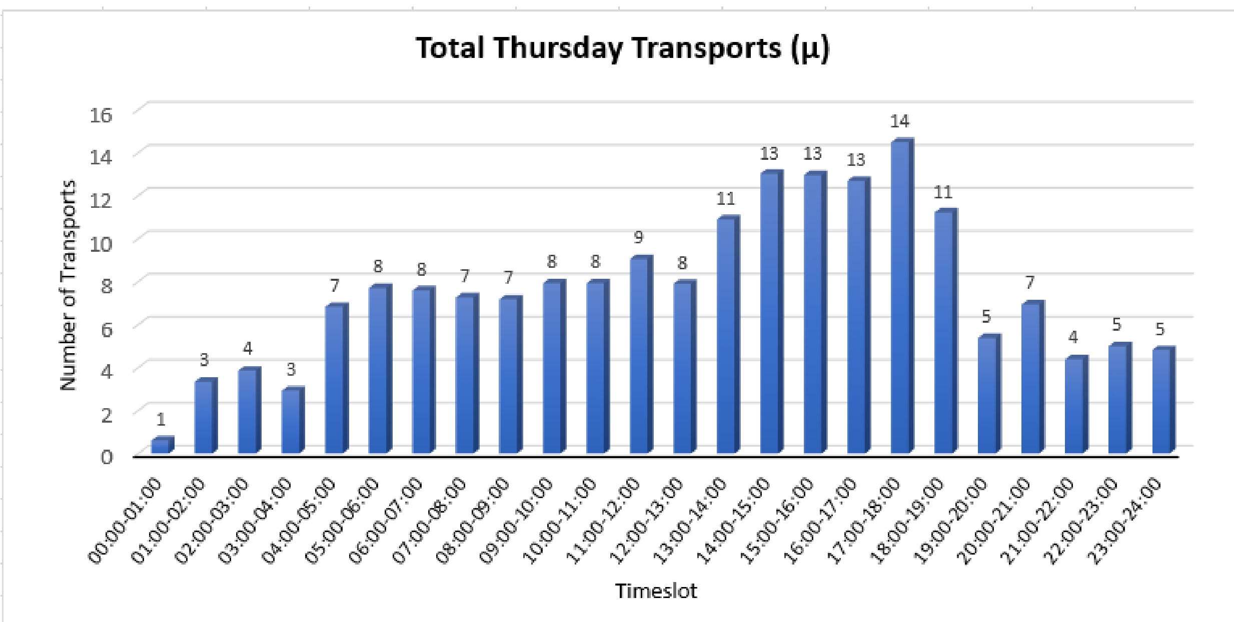
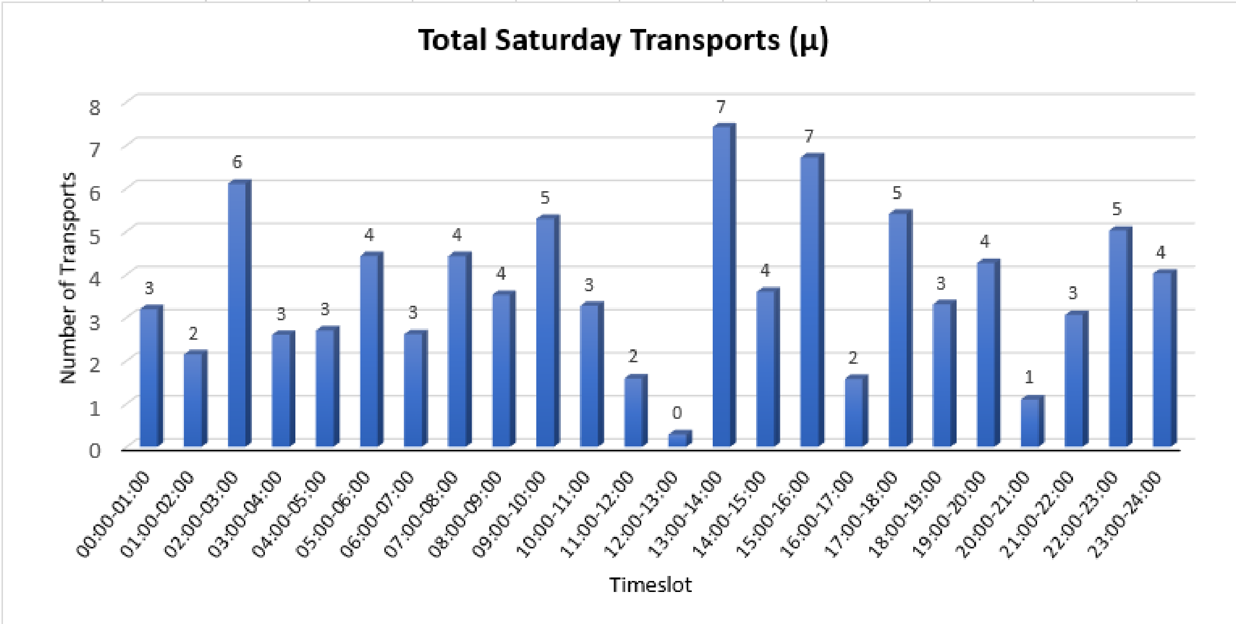
B1. Analysis Transport Frequencies



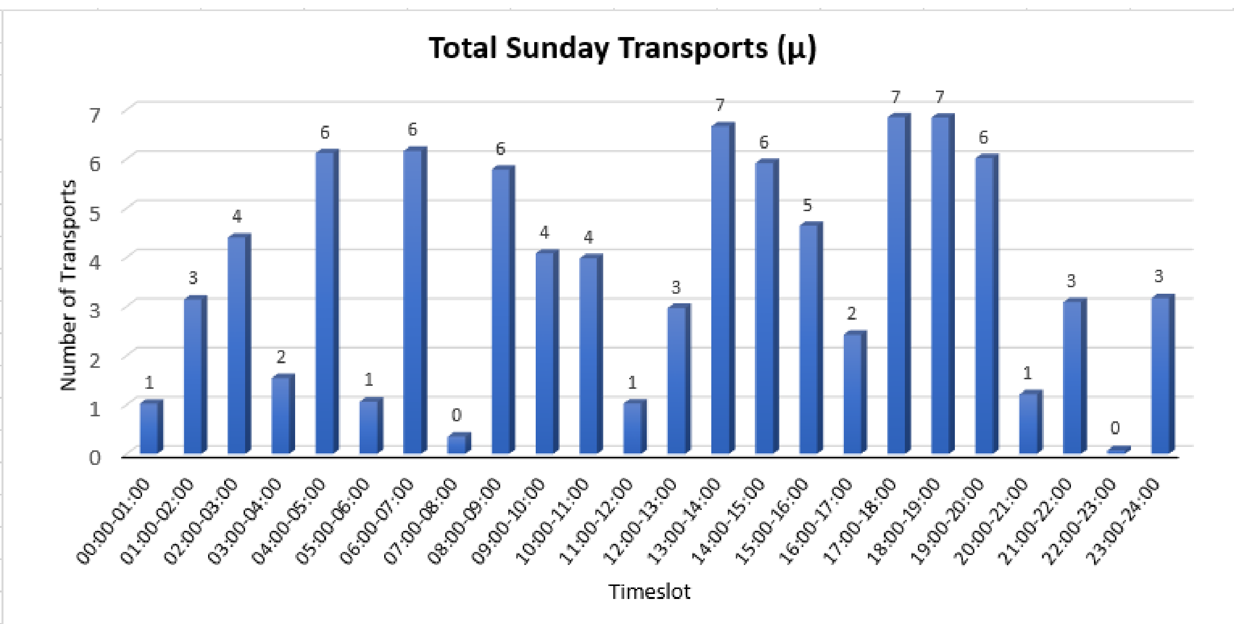



Total Wednesday Transports (μ)
Number of Transports
Timeslot
0
2
4
6
8
10
12
14
6
1
7
8
13
10
6
8
9
8
6
8
13
9
11
10
12
9
7
7
6
4
2
4
00:00-01:00
01:00-02:00
02:00-03:00
03:00-04:00
04:00-05:00
05:00-06:00
06:00-07:00
07:00-08:00
08:00-09:00
09:00-10:00
10:00-11:00
11:00-12:00
12:00-13:00
13:00-14:00
14:00-15:00
15:00-16:00
16:00-17:00
17:00-18:00
18:00-19:00
19:00-20:00
20:00-21:00
21:00-22:00
22:00-23:00
23:00-24:00


Total Thursday Transports (μ)
Number of Transports
Timeslot
0
2
4
6
8
10
12
14
16
1
3
4
3
7
8
8
7
7
8
8
9
8
11
13
13
13
14
11
5
7
4
5
5
00:00-01:00
01:00-02:00
02:00-03:00
03:00-04:00
04:00-05:00
05:00-06:00
06:00-07:00
07:00-08:00
08:00-09:00
09:00-10:00
10:00-11:00
11:00-12:00
12:00-13:00
13:00-14:00
14:00-15:00
15:00-16:00
16:00-17:00
17:00-18:00
18:00-19:00
19:00-20:00
20:00-21:00
21:00-22:00
22:00-23:00
23:00-24:00



Total Saturday Transports (μ)
Number of Transports
Timeslot
3
2
6
3
3
4
3
4
4
5
3
2
0
7
4
7
2
5
3
4
1
3
5
4
00:00-01:00
01:00-02:00
02:00-03:00
03:00-04:00
04:00-05:00
05:00-06:00
06:00-07:00
07:00-08:00
08:00-09:00
09:00-10:00
10:00-11:00
11:00-12:00
12:00-13:00
13:00-14:00
14:00-15:00
15:00-16:00
16:00-17:00
17:00-18:00
18:00-19:00
19:00-20:00
20:00-21:00
21:00-22:00
22:00-23:00
23:00-24:00



Total Sunday Transports (μ)
Number of Transports
Timeslot
1
3
4
2
6
1
6
0
6
4
4
1
3
7
6
5
2
7
7
6
1
3
0
3
00:00-01:00
01:00-02:00
02:00-03:00
03:00-04:00
04:00-05:00
05:00-06:00
06:00-07:00
07:00-08:00
08:00-09:00
09:00-10:00
10:00-11:00
11:00-12:00
12:00-13:00
13:00-14:00
14:00-15:00
15:00-16:00
16:00-17:00
17:00-18:00
18:00-19:00
19:00-20:00
20:00-21:00
21:00-22:00
22:00-23:00
23:00-24:00

C1. Results AHP Analysis

AHP SCORES PARTICIPANT 1

	More important	Equal (=9)	More important		Score
AGV Utilization				Porter's Utilization	11
AGV Utilization				AGV Crossings	13
AGV Utilization				Congestion Rate	12
AGV Utilization				Interrupted AGV Transports	14
Porter's Utilization				AGV Crossings	10
Porter's Utilization				Congestion Rate	11
Porter's Utilization				Interrupted AGV Transports	13
AGV Crossings				Congestion Rate	7
AGV Crossings				Interrupted AGV Transports	10
Congestion Rate				Interrupted AGV Transports	13

AHP SCORES PARTICIPANT 2

	More important	Equal (=9)	More important		Score
AGV Utilization				Porter's Utilization	8
AGV Utilization				AGV Crossings	11
AGV Utilization				Congestion Rate	11
AGV Utilization				Interrupted AGV Transports	12
Porter's Utilization				AGV Crossings	13
Porter's Utilization				Congestion Rate	12
Porter's Utilization				Interrupted AGV Transports	13
AGV Crossings				Congestion Rate	8
AGV Crossings				Interrupted AGV Transports	11
Congestion Rate				Interrupted AGV Transports	12

AHP SCORES PARTICIPANT 3

	More important	Equal (=9)	More important		Score
AGV Utilization				Porter's Utilization	8
AGV Utilization				AGV Crossings	11
AGV Utilization				Congestion Rate	9
AGV Utilization				Interrupted AGV Transports	12
Porter's Utilization				AGV Crossings	11
Porter's Utilization				Congestion Rate	10
Porter's Utilization				Interrupted AGV Transports	11
AGV Crossings				Congestion Rate	12
AGV Crossings				Interrupted AGV Transports	13
Congestion Rate				Interrupted AGV Transports	12

AHP SCORES PARTICIPANT 4

	More important	Equal (=9)	More important		Score
AGV Utilization				Porter's Utilization	12
AGV Utilization				AGV Crossings	10
AGV Utilization				Congestion Rate	9
AGV Utilization				Interrupted AGV Transports	10
Porter's Utilization				AGV Crossings	11
Porter's Utilization				Congestion Rate	9
Porter's Utilization				Interrupted AGV Transports	11
AGV Crossings				Congestion Rate	8
AGV Crossings				Interrupted AGV Transports	9
Congestion Rate				Interrupted AGV Transports	10

AHP SCORES PARTICIPANT 5

	More important	Equal (=9)	More important		Score
AGV Utilization				Porter's Utilization	11
AGV Utilization				AGV Crossings	10
AGV Utilization				Congestion Rate	11
AGV Utilization				Interrupted AGV Transports	12
Porter's Utilization				AGV Crossings	10
Porter's Utilization				Congestion Rate	9
Porter's Utilization				Interrupted AGV Transports	11
AGV Crossings				Congestion Rate	10
AGV Crossings				Interrupted AGV Transports	10
Congestion Rate				Interrupted AGV Transports	11

C2. 192-Full Factorial Experimental Configurations

Experiment	Replacement Z5 Supply	Relocation Company Y Activties	Relocation Pallet Supplementing	Waiting System Non-AGV Trucks	Velocity AGV	Processing Time Porter's Lodge
Exp 001	FALSE	FALSE	FALSE	FALSE	4 km/h	U [2:30,7:30]
Exp 002	FALSE	FALSE	FALSE	FALSE	4 km/h	U [5:00,10:00]
Exp 003	FALSE	FALSE	FALSE	FALSE	4 km/h	U [7:30,12:30]
Exp 004	FALSE	FALSE	FALSE	FALSE	6 km/h	U [2:30,7:30]
Exp 005	FALSE	FALSE	FALSE	FALSE	6 km/h	U [5:00,10:00]
Exp 006	FALSE	FALSE	FALSE	FALSE	6 km/h	U [7:30,12:30]
Exp 007	FALSE	FALSE	FALSE	FALSE	8 km/h	U [2:30,7:30]
Exp 008	FALSE	FALSE	FALSE	FALSE	8 km/h	U [5:00,10:00]
Exp 009	FALSE	FALSE	FALSE	FALSE	8 km/h	U [7:30,12:30]
Exp 010	FALSE	FALSE	FALSE	FALSE	10 km/h	U [2:30,7:30]
Exp 011	FALSE	FALSE	FALSE	FALSE	10 km/h	U [5:00,10:00]
Exp 012	FALSE	FALSE	FALSE	FALSE	10 km/h	U [7:30,12:30]
Exp 013	FALSE	FALSE	FALSE	TRUE	4 km/h	U [2:30,7:30]
Exp 014	FALSE	FALSE	FALSE	TRUE	4 km/h	U [5:00,10:00]
Exp 015	FALSE	FALSE	FALSE	TRUE	4 km/h	U [7:30,12:30]
Exp 016	FALSE	FALSE	FALSE	TRUE	6 km/h	U [2:30,7:30]
Exp 017	FALSE	FALSE	FALSE	TRUE	6 km/h	U [5:00,10:00]
Exp 018	FALSE	FALSE	FALSE	TRUE	6 km/h	U [7:30,12:30]
Exp 019	FALSE	FALSE	FALSE	TRUE	8 km/h	U [2:30,7:30]
Exp 020	FALSE	FALSE	FALSE	TRUE	8 km/h	U [5:00,10:00]
Exp 021	FALSE	FALSE	FALSE	TRUE	8 km/h	U [7:30,12:30]
Exp 022	FALSE	FALSE	FALSE	TRUE	10 km/h	U [2:30,7:30]
Exp 023	FALSE	FALSE	FALSE	TRUE	10 km/h	U [5:00,10:00]
Exp 024	FALSE	FALSE	FALSE	TRUE	10 km/h	U [7:30,12:30]
Exp 025	FALSE	FALSE	TRUE	FALSE	4 km/h	U [2:30,7:30]
Exp 026	FALSE	FALSE	TRUE	FALSE	4 km/h	U [5:00,10:00]
Exp 027	FALSE	FALSE	TRUE	FALSE	4 km/h	U [7:30,12:30]
Exp 028	FALSE	FALSE	TRUE	FALSE	6 km/h	U [2:30,7:30]
Exp 029	FALSE	FALSE	TRUE	FALSE	6 km/h	U [5:00,10:00]
Exp 030	FALSE	FALSE	TRUE	FALSE	6 km/h	U [7:30,12:30]
Exp 031	FALSE	FALSE	TRUE	FALSE	8 km/h	U [2:30,7:30]
Exp 032	FALSE	FALSE	TRUE	FALSE	8 km/h	U [5:00,10:00]
Exp 033	FALSE	FALSE	TRUE	FALSE	8 km/h	U [7:30,12:30]
Exp 034	FALSE	FALSE	TRUE	FALSE	10 km/h	U [2:30,7:30]
Exp 035	FALSE	FALSE	TRUE	FALSE	10 km/h	U [5:00,10:00]
Exp 036	FALSE	FALSE	TRUE	FALSE	10 km/h	U [7:30,12:30]
Exp 037	FALSE	FALSE	TRUE	TRUE	4 km/h	U [2:30,7:30]

Exp 038	FALSE	FALSE	TRUE	TRUE	4 km/h	U [5:00,10:00]
Exp 039	FALSE	FALSE	TRUE	TRUE	4 km/h	U [7:30,12:30]
Exp 040	FALSE	FALSE	TRUE	TRUE	6 km/h	U [2:30,7:30]
Exp 041	FALSE	FALSE	TRUE	TRUE	6 km/h	U [5:00,10:00]
Exp 042	FALSE	FALSE	TRUE	TRUE	6 km/h	U [7:30,12:30]
Exp 043	FALSE	FALSE	TRUE	TRUE	8 km/h	U [2:30,7:30]
Exp 044	FALSE	FALSE	TRUE	TRUE	8 km/h	U [5:00,10:00]
Exp 045	FALSE	FALSE	TRUE	TRUE	8 km/h	U [7:30,12:30]
Exp 046	FALSE	FALSE	TRUE	TRUE	10 km/h	U [2:30,7:30]
Exp 047	FALSE	FALSE	TRUE	TRUE	10 km/h	U [5:00,10:00]
Exp 048	FALSE	FALSE	TRUE	TRUE	10 km/h	U [7:30,12:30]
Exp 049	FALSE	TRUE	FALSE	FALSE	4 km/h	U [2:30,7:30]
Exp 050	FALSE	TRUE	FALSE	FALSE	4 km/h	U [5:00,10:00]
Exp 051	FALSE	TRUE	FALSE	FALSE	4 km/h	U [7:30,12:30]
Exp 052	FALSE	TRUE	FALSE	FALSE	6 km/h	U [2:30,7:30]
Exp 053	FALSE	TRUE	FALSE	FALSE	6 km/h	U [5:00,10:00]
Exp 054	FALSE	TRUE	FALSE	FALSE	6 km/h	U [7:30,12:30]
Exp 055	FALSE	TRUE	FALSE	FALSE	8 km/h	U [2:30,7:30]
Exp 056	FALSE	TRUE	FALSE	FALSE	8 km/h	U [5:00,10:00]
Exp 057	FALSE	TRUE	FALSE	FALSE	8 km/h	U [7:30,12:30]
Exp 058	FALSE	TRUE	FALSE	FALSE	10 km/h	U [2:30,7:30]
Exp 059	FALSE	TRUE	FALSE	FALSE	10 km/h	U [5:00,10:00]
Exp 060	FALSE	TRUE	FALSE	FALSE	10 km/h	U [7:30,12:30]
Exp 061	FALSE	TRUE	FALSE	TRUE	4 km/h	U [2:30,7:30]
Exp 062	FALSE	TRUE	FALSE	TRUE	4 km/h	U [5:00,10:00]
Exp 063	FALSE	TRUE	FALSE	TRUE	4 km/h	U [7:30,12:30]
Exp 064	FALSE	TRUE	FALSE	TRUE	6 km/h	U [2:30,7:30]
Exp 065	FALSE	TRUE	FALSE	TRUE	6 km/h	U [5:00,10:00]
Exp 066	FALSE	TRUE	FALSE	TRUE	6 km/h	U [7:30,12:30]
Exp 067	FALSE	TRUE	FALSE	TRUE	8 km/h	U [2:30,7:30]
Exp 068	FALSE	TRUE	FALSE	TRUE	8 km/h	U [5:00,10:00]
Exp 069	FALSE	TRUE	FALSE	TRUE	8 km/h	U [7:30,12:30]
Exp 070	FALSE	TRUE	FALSE	TRUE	10 km/h	U [2:30,7:30]
Exp 071	FALSE	TRUE	FALSE	TRUE	10 km/h	U [5:00,10:00]
Exp 072	FALSE	TRUE	FALSE	TRUE	10 km/h	U [7:30,12:30]
Exp 073	FALSE	TRUE	TRUE	FALSE	4 km/h	U [2:30,7:30]
Exp 074	FALSE	TRUE	TRUE	FALSE	4 km/h	U [5:00,10:00]
Exp 075	FALSE	TRUE	TRUE	FALSE	4 km/h	U [7:30,12:30]
Exp 076	FALSE	TRUE	TRUE	FALSE	6 km/h	U [2:30,7:30]

Exp 077	FALSE	TRUE	TRUE	FALSE	6 km/h	U [5:00,10:00]
Exp 078	FALSE	TRUE	TRUE	FALSE	6 km/h	U [7:30,12:30]
Exp 079	FALSE	TRUE	TRUE	FALSE	8 km/h	U [2:30,7:30]
Exp 080	FALSE	TRUE	TRUE	FALSE	8 km/h	U [5:00,10:00]
Exp 081	FALSE	TRUE	TRUE	FALSE	8 km/h	U [7:30,12:30]
Exp 082	FALSE	TRUE	TRUE	FALSE	10 km/h	U [2:30,7:30]
Exp 083	FALSE	TRUE	TRUE	FALSE	10 km/h	U [5:00,10:00]
Exp 084	FALSE	TRUE	TRUE	FALSE	10 km/h	U [7:30,12:30]
Exp 085	FALSE	TRUE	TRUE	TRUE	4 km/h	U [2:30,7:30]
Exp 086	FALSE	TRUE	TRUE	TRUE	4 km/h	U [5:00,10:00]
Exp 087	FALSE	TRUE	TRUE	TRUE	4 km/h	U [7:30,12:30]
Exp 088	FALSE	TRUE	TRUE	TRUE	6 km/h	U [2:30,7:30]
Exp 089	FALSE	TRUE	TRUE	TRUE	6 km/h	U [5:00,10:00]
Exp 090	FALSE	TRUE	TRUE	TRUE	6 km/h	U [7:30,12:30]
Exp 091	FALSE	TRUE	TRUE	TRUE	8 km/h	U [2:30,7:30]
Exp 092	FALSE	TRUE	TRUE	TRUE	8 km/h	U [5:00,10:00]
Exp 093	FALSE	TRUE	TRUE	TRUE	8 km/h	U [7:30,12:30]
Exp 094	FALSE	TRUE	TRUE	TRUE	10 km/h	U [2:30,7:30]
Exp 095	FALSE	TRUE	TRUE	TRUE	10 km/h	U [5:00,10:00]
Exp 096	FALSE	TRUE	TRUE	TRUE	10 km/h	U [7:30,12:30]
Exp 097	TRUE	FALSE	FALSE	FALSE	4 km/h	U [2:30,7:30]
Exp 098	TRUE	FALSE	FALSE	FALSE	4 km/h	U [5:00,10:00]
Exp 099	TRUE	FALSE	FALSE	FALSE	4 km/h	U [7:30,12:30]
Exp 100	TRUE	FALSE	FALSE	FALSE	6 km/h	U [2:30,7:30]
Exp 101	TRUE	FALSE	FALSE	FALSE	6 km/h	U [5:00,10:00]
Exp 102	TRUE	FALSE	FALSE	FALSE	6 km/h	U [7:30,12:30]
Exp 103	TRUE	FALSE	FALSE	FALSE	8 km/h	U [2:30,7:30]
Exp 104	TRUE	FALSE	FALSE	FALSE	8 km/h	U [5:00,10:00]
Exp 105	TRUE	FALSE	FALSE	FALSE	8 km/h	U [7:30,12:30]
Exp 106	TRUE	FALSE	FALSE	FALSE	10 km/h	U [2:30,7:30]
Exp 107	TRUE	FALSE	FALSE	FALSE	10 km/h	U [5:00,10:00]
Exp 108	TRUE	FALSE	FALSE	FALSE	10 km/h	U [7:30,12:30]
Exp 109	TRUE	FALSE	FALSE	TRUE	4 km/h	U [2:30,7:30]
Exp 110	TRUE	FALSE	FALSE	TRUE	4 km/h	U [5:00,10:00]
Exp 111	TRUE	FALSE	FALSE	TRUE	4 km/h	U [7:30,12:30]
Exp 112	TRUE	FALSE	FALSE	TRUE	6 km/h	U [2:30,7:30]
Exp 113	TRUE	FALSE	FALSE	TRUE	6 km/h	U [5:00,10:00]
Exp 114	TRUE	FALSE	FALSE	TRUE	6 km/h	U [7:30,12:30]
Exp 115	TRUE	FALSE	FALSE	TRUE	8 km/h	U [2:30,7:30]

Exp 116	TRUE	FALSE	FALSE	TRUE	8 km/h	U [5:00,10:00]
Exp 117	TRUE	FALSE	FALSE	TRUE	8 km/h	U [7:30,12:30]
Exp 118	TRUE	FALSE	FALSE	TRUE	10 km/h	U [2:30,7:30]
Exp 119	TRUE	FALSE	FALSE	TRUE	10 km/h	U [5:00,10:00]
Exp 120	TRUE	FALSE	FALSE	TRUE	10 km/h	U [7:30,12:30]
Exp 121	TRUE	FALSE	TRUE	FALSE	4 km/h	U [2:30,7:30]
Exp 122	TRUE	FALSE	TRUE	FALSE	4 km/h	U [5:00,10:00]
Exp 123	TRUE	FALSE	TRUE	FALSE	4 km/h	U [7:30,12:30]
Exp 124	TRUE	FALSE	TRUE	FALSE	6 km/h	U [2:30,7:30]
Exp 125	TRUE	FALSE	TRUE	FALSE	6 km/h	U [5:00,10:00]
Exp 126	TRUE	FALSE	TRUE	FALSE	6 km/h	U [7:30,12:30]
Exp 127	TRUE	FALSE	TRUE	FALSE	8 km/h	U [2:30,7:30]
Exp 128	TRUE	FALSE	TRUE	FALSE	8 km/h	U [5:00,10:00]
Exp 129	TRUE	FALSE	TRUE	FALSE	8 km/h	U [7:30,12:30]
Exp 130	TRUE	FALSE	TRUE	FALSE	10 km/h	U [2:30,7:30]
Exp 131	TRUE	FALSE	TRUE	FALSE	10 km/h	U [5:00,10:00]
Exp 132	TRUE	FALSE	TRUE	FALSE	10 km/h	U [7:30,12:30]
Exp 133	TRUE	FALSE	TRUE	TRUE	4 km/h	U [2:30,7:30]
Exp 134	TRUE	FALSE	TRUE	TRUE	4 km/h	U [5:00,10:00]
Exp 135	TRUE	FALSE	TRUE	TRUE	4 km/h	U [7:30,12:30]
Exp 136	TRUE	FALSE	TRUE	TRUE	6 km/h	U [2:30,7:30]
Exp 137	TRUE	FALSE	TRUE	TRUE	6 km/h	U [5:00,10:00]
Exp 138	TRUE	FALSE	TRUE	TRUE	6 km/h	U [7:30,12:30]
Exp 139	TRUE	FALSE	TRUE	TRUE	8 km/h	U [2:30,7:30]
Exp 140	TRUE	FALSE	TRUE	TRUE	8 km/h	U [5:00,10:00]
Exp 141	TRUE	FALSE	TRUE	TRUE	8 km/h	U [7:30,12:30]
Exp 142	TRUE	FALSE	TRUE	TRUE	10 km/h	U [2:30,7:30]
Exp 143	TRUE	FALSE	TRUE	TRUE	10 km/h	U [5:00,10:00]
Exp 144	TRUE	FALSE	TRUE	TRUE	10 km/h	U [7:30,12:30]
Exp 145	TRUE	TRUE	FALSE	FALSE	4 km/h	U [2:30,7:30]
Exp 146	TRUE	TRUE	FALSE	FALSE	4 km/h	U [5:00,10:00]
Exp 147	TRUE	TRUE	FALSE	FALSE	4 km/h	U [7:30,12:30]
Exp 148	TRUE	TRUE	FALSE	FALSE	6 km/h	U [2:30,7:30]
Exp 149	TRUE	TRUE	FALSE	FALSE	6 km/h	U [5:00,10:00]
Exp 150	TRUE	TRUE	FALSE	FALSE	6 km/h	U [7:30,12:30]
Exp 151	TRUE	TRUE	FALSE	FALSE	8 km/h	U [2:30,7:30]
Exp 152	TRUE	TRUE	FALSE	FALSE	8 km/h	U [5:00,10:00]
Exp 153	TRUE	TRUE	FALSE	FALSE	8 km/h	U [7:30,12:30]
Exp 154	TRUE	TRUE	FALSE	FALSE	10 km/h	U [2:30,7:30]

Exp 155	TRUE	TRUE	FALSE	FALSE	10 km/h	U [5:00,10:00]
Exp 156	TRUE	TRUE	FALSE	FALSE	10 km/h	U [7:30,12:30]
Exp 157	TRUE	TRUE	FALSE	TRUE	4 km/h	U [2:30,7:30]
Exp 158	TRUE	TRUE	FALSE	TRUE	4 km/h	U [5:00,10:00]
Exp 159	TRUE	TRUE	FALSE	TRUE	4 km/h	U [7:30,12:30]
Exp 160	TRUE	TRUE	FALSE	TRUE	6 km/h	U [2:30,7:30]
Exp 161	TRUE	TRUE	FALSE	TRUE	6 km/h	U [5:00,10:00]
Exp 162	TRUE	TRUE	FALSE	TRUE	6 km/h	U [7:30,12:30]
Exp 163	TRUE	TRUE	FALSE	TRUE	8 km/h	U [2:30,7:30]
Exp 164	TRUE	TRUE	FALSE	TRUE	8 km/h	U [5:00,10:00]
Exp 165	TRUE	TRUE	FALSE	TRUE	8 km/h	U [7:30,12:30]
Exp 166	TRUE	TRUE	FALSE	TRUE	10 km/h	U [2:30,7:30]
Exp 167	TRUE	TRUE	FALSE	TRUE	10 km/h	U [5:00,10:00]
Exp 168	TRUE	TRUE	FALSE	TRUE	10 km/h	U [7:30,12:30]
Exp 169	TRUE	TRUE	TRUE	FALSE	4 km/h	U [2:30,7:30]
Exp 170	TRUE	TRUE	TRUE	FALSE	4 km/h	U [5:00,10:00]
Exp 171	TRUE	TRUE	TRUE	FALSE	4 km/h	U [7:30,12:30]
Exp 172	TRUE	TRUE	TRUE	FALSE	6 km/h	U [2:30,7:30]
Exp 173	TRUE	TRUE	TRUE	FALSE	6 km/h	U [5:00,10:00]
Exp 174	TRUE	TRUE	TRUE	FALSE	6 km/h	U [7:30,12:30]
Exp 175	TRUE	TRUE	TRUE	FALSE	8 km/h	U [2:30,7:30]
Exp 176	TRUE	TRUE	TRUE	FALSE	8 km/h	U [5:00,10:00]
Exp 177	TRUE	TRUE	TRUE	FALSE	8 km/h	U [7:30,12:30]
Exp 178	TRUE	TRUE	TRUE	FALSE	10 km/h	U [2:30,7:30]
Exp 179	TRUE	TRUE	TRUE	FALSE	10 km/h	U [5:00,10:00]
Exp 180	TRUE	TRUE	TRUE	FALSE	10 km/h	U [7:30,12:30]
Exp 181	TRUE	TRUE	TRUE	TRUE	4 km/h	U [2:30,7:30]
Exp 182	TRUE	TRUE	TRUE	TRUE	4 km/h	U [5:00,10:00]
Exp 183	TRUE	TRUE	TRUE	TRUE	4 km/h	U [7:30,12:30]
Exp 184	TRUE	TRUE	TRUE	TRUE	6 km/h	U [2:30,7:30]
Exp 185	TRUE	TRUE	TRUE	TRUE	6 km/h	U [5:00,10:00]
Exp 186	TRUE	TRUE	TRUE	TRUE	6 km/h	U [7:30,12:30]
Exp 187	TRUE	TRUE	TRUE	TRUE	8 km/h	U [2:30,7:30]
Exp 188	TRUE	TRUE	TRUE	TRUE	8 km/h	U [5:00,10:00]
Exp 189	TRUE	TRUE	TRUE	TRUE	8 km/h	U [7:30,12:30]
Exp 190	TRUE	TRUE	TRUE	TRUE	10 km/h	U [2:30,7:30]
Exp 191	TRUE	TRUE	TRUE	TRUE	10 km/h	U [5:00,10:00]
Exp 192	TRUE	TRUE	TRUE	TRUE	10 km/h	U [7:30,12:30]