August 2024

Bachelor Thesis

The Improvement of Twence's Bunker Management

Industrial Engineering & Management
University of Twente

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UNIVERSITY OF TWENTE.

Bachelor Thesis Industrial Engineering and Management

Improving Twence's Bunker Management

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August 20th, 2024

FACULTY
Behavioral, Management and Social Sciences

DATE
August 2024

VERSION
Version 2

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FILE NAME
BSc Thesis Industrial Engineering and Management

Preface

Dear reader,

This report illustrates the finalization of my study Industrial Engineering and Management at the University of Twente. I would like to grab the opportunity to express my gratitude towards Twence for offering me the chance to conduct my bachelor thesis and learn how to put the gained theory at the university into practice. My research aimed to improve Twence's bunker management.

First of all, I would like to thank my company supervisors at Twence for their very willing help and belief in me during the research assignment. Our weekly meetings, short talks and their high enthusiasm helped me give the right structure and approach to the research. Furthermore, their ability to bring me into contact with the right people within Twence has made a compelling impact on the quality of the research.

Second of all, I would like to say thank you to my first university supervisor, Alessio Trivella, for his guidance during the project. The offered feedback and supervision contributed to the thesis' progression. Also, I would like to thank my second university supervisor, Stephan Meisel, for his support during the end phase of the project. His competence and feedback led to a report of a higher quality.

Lastly, I would like to express my gratitude to all the people involved in the research assignment for their dedication and time. All participants have had their share and together are responsible for the foundation of this thesis assignment.

Yours sincerely,

Lars Oude Egberink

August, 2024

Management Summary

The topic addressed during this research is the improvement of the bunker management within the supply chain of Twence, a company operating in the waste-to-energy sector. An improved bunker management is essential to obtain higher supplier satisfaction, less unnecessary costs and a better operating company in general. A literature study found that the application of time slots and quantity restrictions to supplies could potentially form a solution to Twence's uncertain bunker management problem. A time slot is a period allocated to an entity in which something is about to happen. In this case, a time slot is allocated to a truck in which the truck should discard its waste at Twence. The quantity restriction in this case is a limitation to the number of discarded tons per week for every supplier. Through modeling the current situation in a DES (Discrete Event Simulation) and through modeling a situation in which the current situation is restricted by time slots and quantity restrictions in a DES, a conclusion could be drawn.

Problem

This research discusses Twence's bunker management, since Twence currently encounters challenges controlling their bunker level. Nine main causes for the challenging bunker level have been found including weather conditions, the elimination of deposits on pressure holders, lack of communication, the acquisition of more waste than can be put through, no human involvement during weekend days, a big competitor of Twence catching fire and going out of operation, the build-up of waste inventory at TOP during late summer, restricting licenses and last the mismatch between scheduled supplies and realized supplies. The deviations between scheduled supplies and realized supplies are judged to be the major cause for Twence's current bunker management, which results in the following research question being addressed in this report:

"How can Twence increase the predictability of waste supply in order to have a better-operating bunker management?"

Method

The Managerial Problem Solving Method functions as the basis for finding a solution to the core problem of this research assignment. First, a thorough analysis was conducted about the current supply chain operations of Twence including an overview of the supply chain and an overview of the current supply planning process. Subsequently, a literature study was completed to acquire knowledge regarding how to tackle uncertainty in supply, techniques matching supply to demand, supply planning factors and the effects of the application of time slots. Afterward, a discrete event simulation model of the current supply planning situation and a discrete event simulation model of the situation in which time slots are utilized were designed. During the experimentation phase, the two model's outputs were compared and additional analyses were executed to gather extra insights. Lastly, given the results advice was given to the company regarding the implementation of the solution.

Results

Comparing and contrasting the output of the two models yielded some intriguing results. Firstly, applying time slots in combination with quantity limits to supplier trucks leads to an improved division of waste supplies throughout the week. Additionally, it also results in more certainty concerning weekly supplies at the end of the week. Furthermore, due to more spread of supplier arrivals throughout the day, waiting times are massively reduced.

More experimenting resulted in finding out that a further fall in waiting time can be achieved by minimizing the size of the time slot. Reasons to believe that suppliers are willing to concede in flexibility and instead are rewarded with a lowered waiting time were both found in theory and in practice. Moreover, a smaller interval of the possible trucks arriving on a specific day further decreases the standard deviation of daily supplies. Thirdly, the probability of Temporary Storage Space (TOP) movements is reduced when assuming a fixed throughput. Lastly, it was discovered that by means of decreasing the failure rate and/or the recovery time a reduced waiting time is achieved. Here, the failure rate can be described as the rate at which a dump hole preceding the bunker is inaccessible due to malfunctioning bunker management and the recovery time is the time needed for Twence personnel to clear a dump hole before a new truck can unload the truck.

Conclusion

Coming back to the research question: "How can Twence increase planning predictability of waste supply in order to have a better operating bunker management?", it can be answered with the application of time slots and quantity restrictions. By means of the utilization of time slots, trucks are allocated one time slot in the week in which they need to deliver their waste. With the help of quantity restrictions, suppliers are not able to exceed their weekly maximum. Time slots and quantity restrictions yield a better build-up of supplies throughout the day and week, fewer big peaks and falls in supplies, a more constant end volume of supplies, a lower probability of going to TOP and reduced waiting times for trucks of suppliers. Overall, planning predictability for Twence is increased. An increased supply predictability leads to more certainty in the arrival of supplies and that in turn leads to more certainty in managing the bunker level.

Recommendation

It is being recommended to start using time slots and quantity restrictions in the short term as a solution to undertake measures against the difficult manageable bunker level. For now, a time slot with a size of two hours is set to be the best-fitting time slot size. However, it must be noted that the application of time slots and quantity restrictions generates a substantial impact on suppliers, as their level of flexibility is strictly reduced from delivering at any moment in the week to delivering within only two hours. Therefore, continuous monitoring of supplier opinions and supplier satisfaction is required and a slow introduction of the measures is required. A time slot of size two hours has proven to work out for both the supplier of waste and the receiver of waste for one of Twence's suppliers; the supplier values the reduced waiting time over the decrease in flexibility and the AEC benefits at all KPIs. However, since it is just one supplier's opinion, an assessment of the feasibility of the size of time slots must be performed in collaboration with the suppliers. Depending on the results, the size of the time slots should be modified.

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List of Abbreviations

AEB	Afval Energie Bedrijf Amsterdam (competitor of Twence)
AEC	Waste-to-energy plant
AVR	Afval Verwerking Rijnmond (competitor of Twence)
A&O	Twence's Department of Analysis and Optimization
BEC	Biomass Installation
BP	Yearly planning of supplies on the 1st of January
BPMN	Business Process Model & Notation
CAMAK	CO2 Capturer Installation
CCU	Carbon Capturer Utilization
CDF	Cumulative Distribution Function
DES	Discrete Event Simulation
KPI	Key Performance Indicator
MD	Maximum Deviation
MTP	Maximum Time Period
MU	Moving Unit
MVI	Manure Valorization Installation
OFAT	One Factor At a Time
RoO	Ratio of Outliers
SOI	Bottom Ashes Installation
SSD	Supply Standard Deviation
TAS	Twence Waste Sorting
TOP	Temporary Storage Space Outside
TPF	Theoretical Probability Function
TT	Terrain Time
U&L	Twence's Department of Execution and Logistics

1. Introduction

In this chapter, an overview is presented describing the relevance, background and execution of the identified problem. Section 1.1 addresses the company Twence and its main operations, whilst Section 1.2 focuses on the background of the problem including elements like the problem identification and the problem cluster. Moreover, Section 1.3 discusses the research design. Section 1.4 concentrates on the scope of the problem and the research's limitations.

1.1. About Twence

Twence is an energy and raw material company that produces energy out of waste by means of their waste-to-energy plant (AEC). Founded in 2001, Hengelo, Twence has established itself as the waste processing company of the region Twente in the Netherlands. Twence's main activities are attracting waste from commercial companies and municipalities nearby and processing the waste into usable energy and steam. These products are sold to industrial activities nearby and used for city district heating in Enschede (Twence, 2024). Twence's future aim is to collectively move towards a more sustainable existence.

1.2. Problem Explanation

Twence is a multi-diverse company operating as an energy-of-waste plant in the waste-to-energy sector for several waste streams such as residual waste, wood waste and composting waste. Twence's core business centers around the processing of residual waste and consists of weighing a (refuse) truck before it enters the terrain, allocating the truck to the right storage space to drop off the waste, weighing the empty truck before it leaves the terrain and processing the dumped waste into usable products. Income is generated both at the input and at the output by charging suppliers a fee per discarded tonnage of waste and by providing electricity and steam created by burning waste in Twence's energy-of-waste plant to local customers like Grolsch, Nobian and The University of Twente.

Twence has three options when managing the incoming supply of waste streams per incoming truck:

1. The waste can be dropped off in the bunkers that precede the burning installation.
2. The waste is temporarily stored outside on the so-called TOP, which has a licensed capacity of 40 kilotons.
3. The inflow of waste is restrained, meaning that specific clients temporarily cannot drop off their waste at Twence.

Preferably, waste is immediately transferred to the bunkers, as TOP and restraining waste are more costly and less efficient options. However, in the case that the bunkers are too full or in the occasion that there is a(n) (un)planned maintenance stop going on in the bunkers of the AEC, Twence has more leeway in having the options of storing waste due to TOP's existence and restricting clients to dump their waste.

Nevertheless, over the past year TOP has been used more often than before particularly due to a deviation between realized waste supply and scheduled waste supply, which is caused by the random arrival of supplier trucks. The random arrival of trucks causes structurally non-constant bunker levels. If incoming waste is transported to TOP, this is called a detour. This detour results in having to decide either baling the waste or not baling the waste. Baling waste costs money, but also guarantees the waste a maximum storage of three years at TOP, whilst not baling waste costs less money, offers a maximum stay of one year at TOP and increases fire hazard. Before the maximum storage time of the waste at TOP is reached, Twence needs to drive the waste internally to the AEC, which again costs money.

On the other hand, restricting clients from delivering their contractual waste also costs a lot of money. First, Twence misses out on the income per delivered ton of waste and second, the client must be compensated for the fact that it could not deliver the waste in the first instance. Figure 1.1 visualizes the decisions and actions that come with the inflow of waste. The double circle splits the process into two parts for readability purposes.

Given the preceding, the following problems arise:

- Employees are busy and frustrated with having to anticipate on the bunker levels and adjusting decisions several times a day.
- Profits go down as TOP is more often used than initially planned and/or clients are restrained from delivering their waste.
- Supplier satisfaction declines, because the reliability of the disposal of waste is not certain at Twence.

In general, a more controllable bunker level would provide more calmness among employees, fewer detours to TOP leading to bigger profits and a higher supply probability.

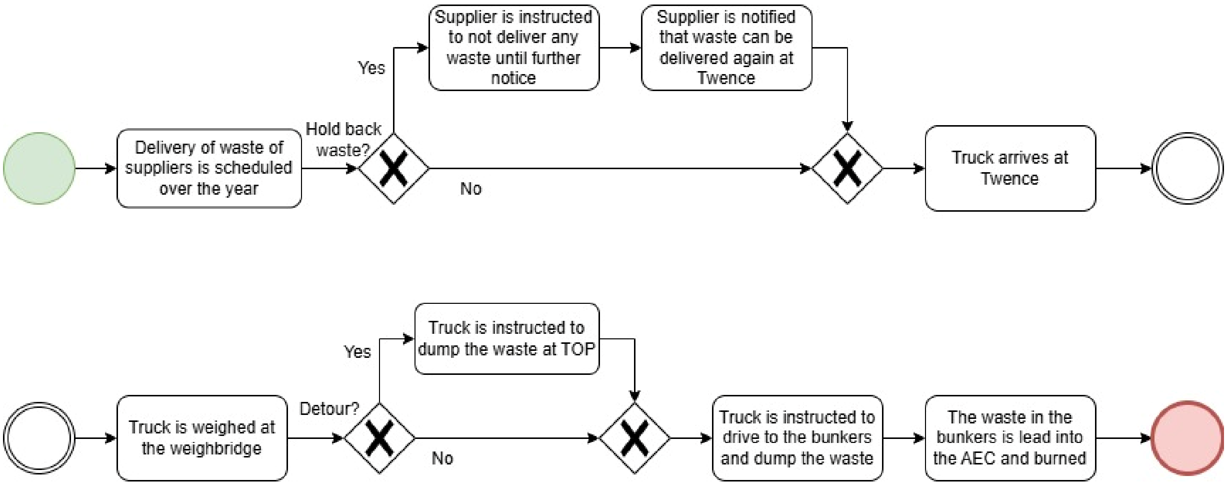

Figure 1.1 - Business Process Model of Problem Description

1.2.1. Problem Cluster

The problem cluster is visible in Figure 1.2, visualizing all connected problems to the end problem: big variations in the bunker level. The core problem being tackled in this research assignment is the weekly mismatch between scheduled and realized supplies. Other potential core problems regarding the action problem are:

- Weather conditions.
- Elimination of deposits on pressure holders.
- Lack of proper communication between operators and management.
- Twence's Sales department acquiring a quantity of waste that is close to the maximum capacity communicated by U&L.
- No human involvement during weekends.
- AVR catching fire, causing a division of waste among the remaining AECs in The Netherlands.
- Build-up of waste supplies at TOP in late summer.
- Licenses restricting the operations.

Now, a short explanation will follow as to why Twence should tackle the chosen core problem instead of one of the other potential core problems.

First of all, weather conditions cannot be influenced and is therefore not a suitable core problem. Weather conditions cause different densities of waste, which means that for a same number of tons the bunker can be full or only half full, causing bunker management difficulties. Secondly, the elimination of deposits on pressure holders is a decision made by the Dutch government and is therefore not influenceable as well. The result of the elimination of deposits is an increase in pressure holders being thrown in the residual waste. These pressure holders end up in the burning installation where they damage the oven through explosions. More unprojected maintenance stops are required to repair the burning installation, resulting in a reduced throughput.

Thirdly, the lack of proper communication between operators and management is especially felt on behalf of the operators as they feel that the information they provide is not considered higher up the ladder. This eventually leads to the operators not reporting everything they normally would, which can result in unnecessary harmful situations. In accordance with the company supervisors, it has been decided that solving such issue is not a suitable task. Fourthly, it is a common belief in the organization that the Sales department acquires more waste supplies than the maximum throughput. This is an issue that in theory can easily be changed, but in practice will remain an issue since both involved departments Sales and U&L are not willing to concede. In accordance with the company supervisors the decision has been made to not deepen into this topic, since it is more an issue between two parties.

Fifthly, no human involvement during the weekends is an informed decision by the management board that will not be adjusted in the short term. During weekend days, Twence is not open for the arrival of supplies. This means that Twence needs to accurately calculate the minimal bunker stock that the AEC requires to be able to run at full capacity during the weekend, because an unnecessary stop of the AEC caused by a shortage of waste stock costs a lot of money. Sixthly, the biggest competitor in the branch, Afval Verwerking Rijnmond (AVR), caught fire in September 2023 causing them to shut down (AVR, 2023). It is expected that AVR will become operational again in October 2024 (Kok, 2024). The result of the fire is that a part of the waste supply going to AVR had to be redivided over other AECs, under which Twence. This problem and its effects could not be prevented.

Seventhly, Twence builds up waste supplies at TOP during the late summer months, because waste supplies during autumn are lower, whilst throughput during autumn months and winter months is relatively high. To be able to run the AEC at full capacity during autumn an extra waste stock is being created at TOP for certainty reasons. However, the extra number of tons at TOP also causes fewer opportunities when TOP needs to be used for its original purpose, namely in the case of a structural oversupply. On the work floor, there are a lot of different opinions about the exact purpose of TOP and reasons when to use it and therefore for now this cause is considered not a top priority. Lastly, licenses are a problem as they mostly restrict Twence's operations. However, there are valid reasons for the licenses to exist. It is not expected that the conditions of the license change, nor that Twence could change them. Taking all of that into consideration, it is evident that the core problem to tackle is the planning of the waste supplies of suppliers.

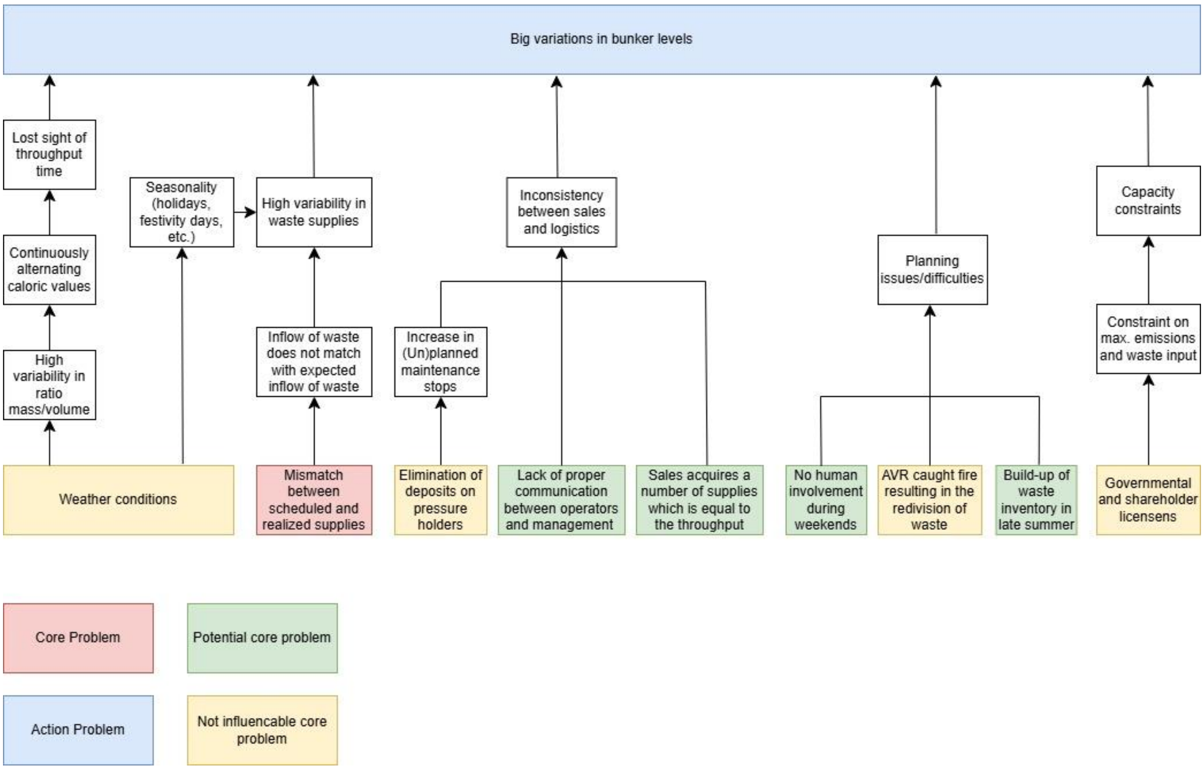

Figure 1.2 - Problem Cluster

1.2.2. Problem Context

Following the previous section, Twence's current action problem is the existence of an uncontrollable bunker level. After discussions with the company and its supervisors, it is decided that a numerical norm concerning the action problem is not relevant for the research, since in fact every possible improvement is praised. However, it must be said that this research aims for the optimal result. The current situation, the reality, is that there is a daily varying bunker level where it is not unusual for the planned bunker level to deviate more than one kiloton from the actual bunker level. As a reference value, a full bunker on average throughout the whole year of both Lijn 1+2 and Lijn 3 contains approximately eight kilotons. Twence has two operating bunkers called Lijn 1+2 (responsible for household waste) and Lijn 3 (responsible for industrial waste). As of the year 2024, Lijn 1+2 has a weekly average supplies standard deviation of 214 tons and Lijn 3 has a weekly average supplies standard deviation of 319 tons. Together, the two average 267 tons. Equation 1.1 calculates the standard deviation over a week of supplies, which consists of five days:

$$\sigma = \sqrt{\frac{1}{5} * \sum_{i=1}^{5} (x_i - \mu)^2} \qquad (1.1)$$

The weekly standard deviation of the bunker level for the year 2024 for Lijn 1+2 is 596 tons. Similarly, the weekly standard deviation of the bunker level for Lijn 3 is 536 tons. Given this, it is visible that the bunker level is not fully dependent on the number of supplies arriving as in that case a higher number than 596 would have been expected for the weekly standard deviation of the bunker level for Lijn 3 (since the weekly average supplies standard deviation for Lijn 3 is higher than for Lijn 1+2). The bunker level is also influenced by the factors of throughput and supply movements from TOP to the bunkers.
The norm is a controllable bunker, where the planned bunker level and actual bunker level (almost) coincide. An actual bunker level that on average is closer to the planned bunker level is an improvement of the situation and therefore an outcome of the research.

In the end, a solution to the action problem can only be found by first solving the existing core problem, namely the weekly mismatch between scheduled supply and realized supply of waste due to the random arrival of supplies. In reality, the weekly supply of waste is very volatile. The norm would be to have a constant supply of waste throughout the week, meaning a standard deviation of 0. However, such will never be achieved due to primarily operational deviations and seasonality factors. Therefore, the goal of the assignment is to get as close as possible to the constant supply of waste, where again every improvement is considered satisfactory. A more constant supply of waste could be realized with the help of allocating time slots and quantity restrictions to suppliers.

Figure 1.3 shows the fluctuations in waste supply (measured in tons) for successive weeks 2 and 3 of 2024. The fluctuations are caused by the random arrival of trucks throughout the week. The blue bars represent the constant planned supply of waste per day of the week, whereas the red bars represent the realized supply of waste per day. The green line shows the absolute difference between planned and realized waste in tons, whereas the purple line shows the related percentage of actual waste compared to the planned waste. This figure presents the mismatch in the supply of waste and therefore the existing variance in supply on day and week levels. The norm would be to have equally high red and blue bars.

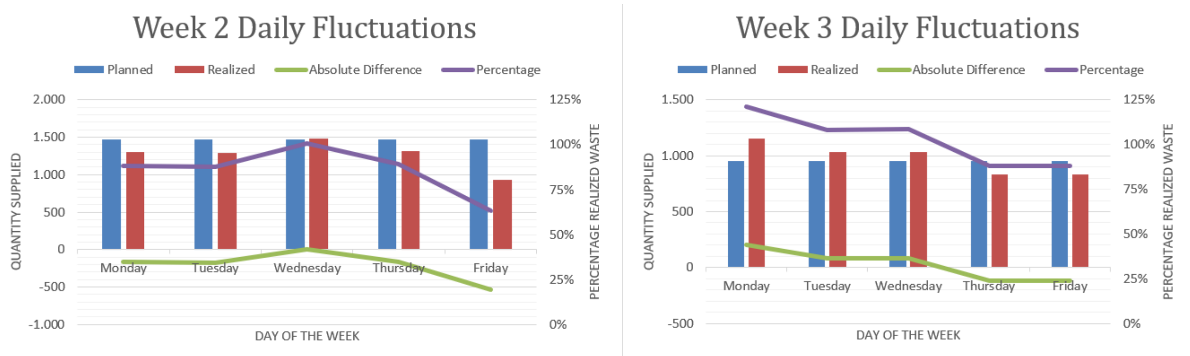

Figure 1.3 - Discrepancy between planned supply and realized supply in weeks 2 & 3 in 2024

1.3. Type of Research

1.3.1. Research Questions

Taking into consideration the core problem and action problem (See Problem Identification), leads to the general research question:

"How can Twence increase the predictability of waste supply in order to have a better-operating bunker management?"

This thesis describes five sub-research questions which together provide an answer to the general research question. The first question provides insight into the current situation of supply handling, whereas the second question evaluates relevant pieces of literature. Question three contributes to the final solution by describing the conceptual model, stating model assumptions, and experimenting with the simulation model. The results of the model and the drawn conclusions are demonstrated in question four. Lastly, sub-question five implements the conclusion to the current working process.

Sub-Research Question 1: How is the current planning of waste delivery and bunker management arranged?

This sub-question describes the main processes related to the existing supply chain, the current supply planning process, the arrival of supplies throughout the year, month and week and provides insight into the measurable KPIs. The following sub-questions have been defined:

1.1 What is the path that the waste must undertake from entering Twence's terrain up to being dumped?
1.2 What factors does the planning department take into consideration when scheduling waste deliveries?
1.3 How is the current arrival of supplies arranged?
1.4 How do Key Performance Indicators (KPIs) regarding the Supply Chain perform in the present situation?

Sub-Research Question 2: What information found in the literature is relevant to the optimization of the planning of waste supply?
A literature review will be conducted focusing on waste processing together with optimal planning. Planning techniques available from related industries will also be used, since preliminary literature research found out that the waste processing sector in general does not have a lot of information available. The following sub-questions have been defined:
2.1 How do other companies deal with uncertainty in supply?
2.2 What are general existing techniques to match supply to demand?
2.3 What are factors that need to be considered whilst planning supplies?
2.4 How does the application of time slots work?
2.5 What are the cases in which DES is used?

Sub-Research Question 3: How should the simulation model be designed?
Based on the found information in sub-questions one and two, a conceptual model is designed describing the existing relations. Subsequently, a model is developed in the form of a simulation model. The following sub-questions have been defined:
3.1 Why is simulation chosen as the means to solve the problem?
3.2 How is the simulation's system defined?
3.3 What does the model look like presented in a flow chart?
3.4 What types of data are used in the simulation?
3.5 How is the model translated into a simulation model?
3.6 How is the simulation model verified and validated?
3.7 What experiments and analyses are performed regarding the simulation model?

Sub-Research Question 4: What is the outcome given the application of the model?
The performance of the model is addressed by doing experiments. Based on the performances a conclusion can be drawn. The following sub-questions have been defined:
4.1 How do the Supply Chain KPIs perform?
4.2 What conclusions can be drawn from these results?
4.3 To what extent does the conclusion compare to earlier conducted research?

Sub-Research Question 5: How can the designed model best be implemented into the business?
A link is created between theory and practice. This sub-question aims to provide an answer to how the results from the model can be translated into practical solutions used by the working personnel. The following sub-questions have been defined:
5.1 What is the general recommendation?
5.2 What parties are involved regarding the model implementation?
5.3 How should time slots be implemented into the system?

1.4. Scope
The research solely focuses on the AEC and its supply chain problem. Although the same problem also occurs at Twence's biomass installation (BEC), it has been decided to prioritize the AEC as this installation is more profitable. Including the BEC would make the assignment too big due to different operations within the AEC and the BEC. However, if the suggested

solution works out for the AEC, a similar solution might be applied to the BEC by Twence themselves. Also, the improvement of the supply chain has been limited to the part from the weighbridge up to and including the bunker.

Figure 1.4 visualizes all Twence's entities from which the AEC is one. The part referred to as "Scope" is the part of Twence's operations which is assessed during this assignment. Although it seems like the AEC is only a small part of Twence's operations, the AEC is responsible for more than half of Twence's revenues. The green circles with the €-sign imply that at those steps in the chain, money is earned by Twence for the AEC. Figure C.1 in Appendix C provides an overview of Twence's terrain in Hengelo, where "Afvalenergiecentrale Lijn 1 en 2" and "Afvalenergiecentrale Lijn 3" together represent the AEC and "Stortlob" symbolizes TOP.

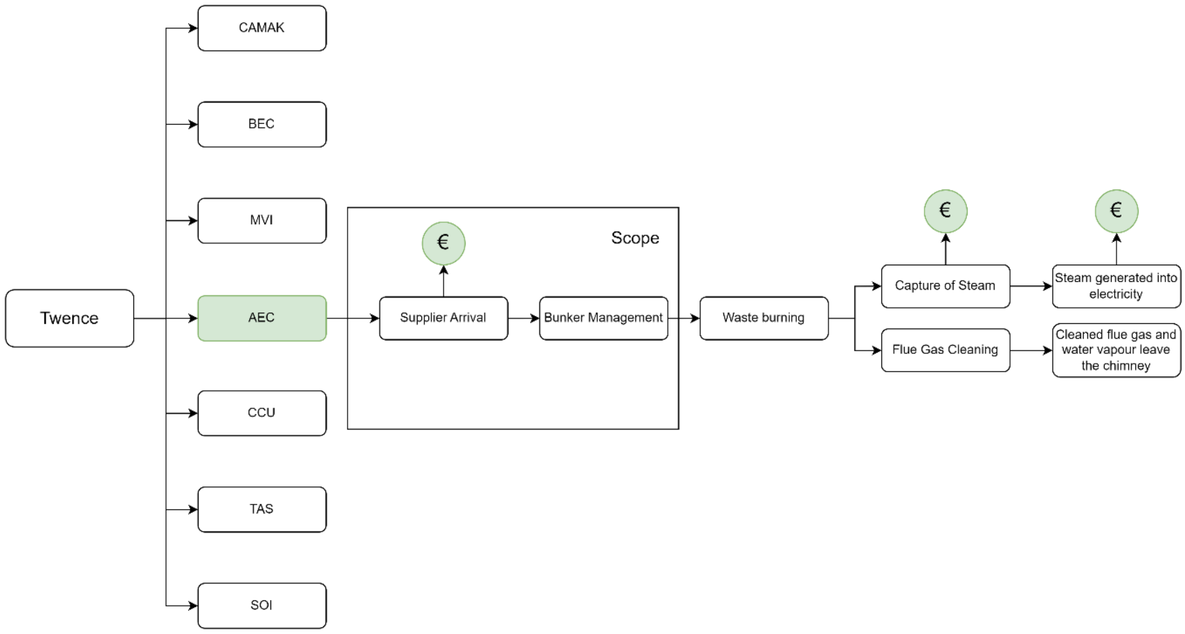

Figure 1.4 – Scope of the assignment

1.4.1. Limitations

Some limitations for this research have been established:

- Technical knowledge of installations is not included in the research. Exactly knowing what every installation contributes to the overall process is outside the scope of the research.
- Improving the throughput has not been investigated as a possible solution to this assignment, because that requires technical knowledge.
- The exact contractual agreements with clients are not completely respected during this research. The existing contracts include details which are too small to consider for the scope of the total research assignment.
- The rule that household waste is mainly deposited at Lijn 1+2 and industrial waste is mainly deposited at Lijn 3 is neglected, because of the many exceptions that exist (which would cost too much time to dig into).

2. Current Situation

This chapter aims to provide an answer to the sub-research question: "How is the current planning of waste delivery to the bunker arranged?"

The first section of this chapter seeks to offer an overview of the current flow of waste at Twence represented in a BPMN model and provided with a description of the supply chain processes. Section 2.2 gives insight into the current planning process including scheduling factors, again by means of a BPMN model and a related description. Section 2.3 covers the arrival of supplies throughout several time periods. In Section 2.4 KPIs will be defined and calculated. These KPIs will be used as the major tool to assess whether the proposed solution improves the current situation.

2.1. Current Supply Chain Operations

Twence's supply chain is a complex system of streams of raw material and waste. Figures 2.1 and 2.2 display the BPMN model of Twence's supply chain.

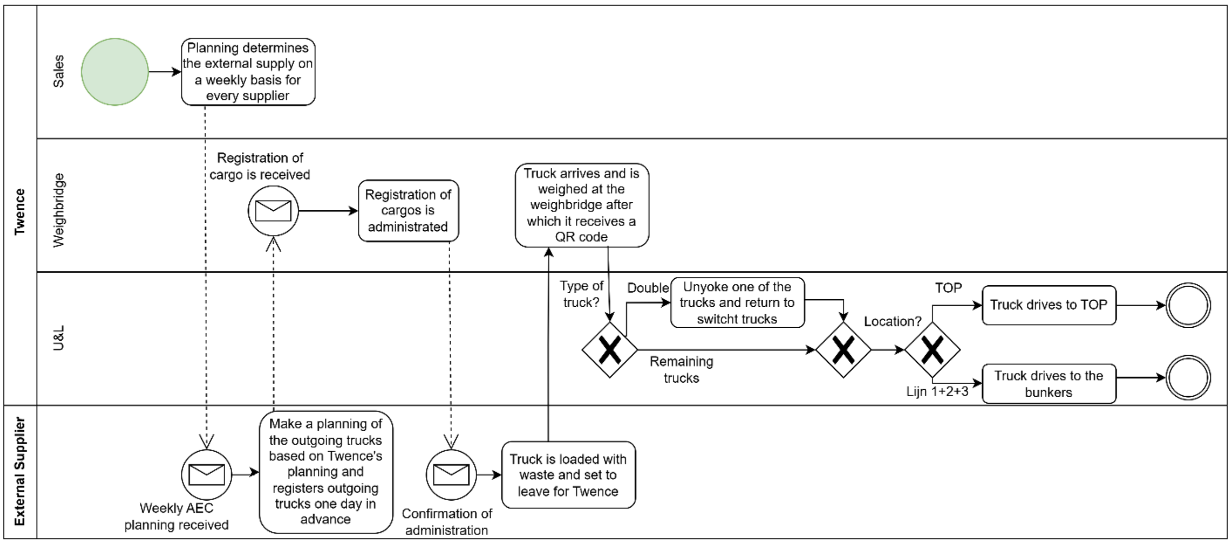

Figure 2.1 - Supply Chain Part 1

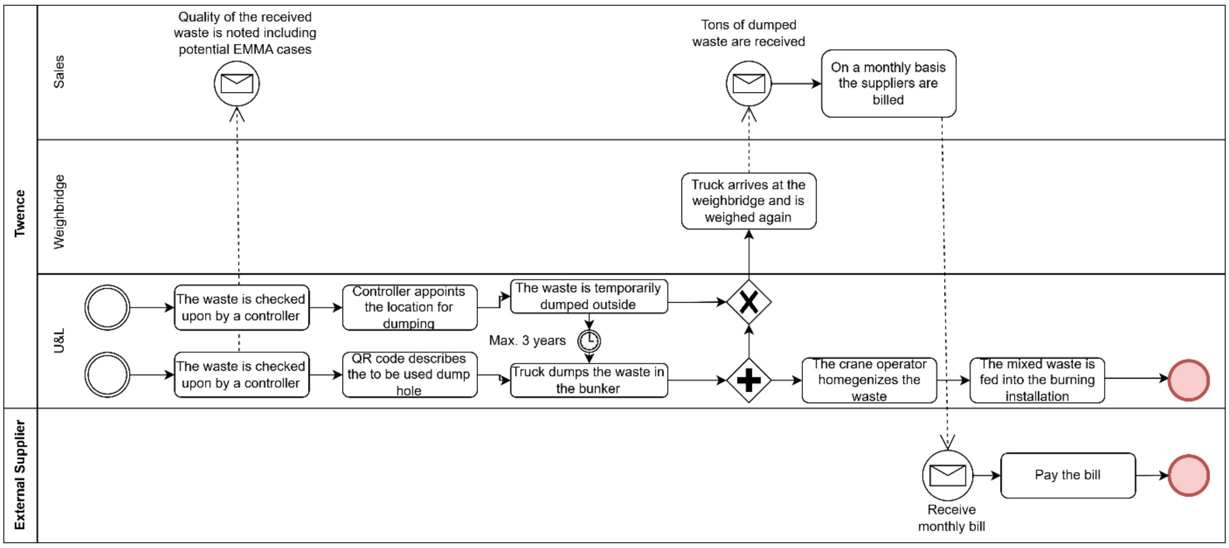

Figure 2.2 - Supply Chain Part 2

Before introducing Twence's supply chain, the terms supplier and truck must be explained within this context. A supplier is a company that has a contract with Twence to discard waste. A supplier has several trucks that separately drive their waste collection routes and discard their waste at Twence.
Twence's supply chain from the weighbridge up to the bunkers consists of two parties, namely Twence (split up into three departments) and their external suppliers of waste. The supply chain commences when Twence's planning department has determined the yearly external supplies per supplier on a weekly basis. Details about the creation of this planning of supplies are described in Section 2.2. Based on the allowed delivery of tons of waste per week, every supplier makes their own planning regarding outgoing trucks. One day before the arrival of a cargo at Twence, the supplier of that cargo registers itself in Twence's system including details like the name of the supplier and the type of cargo. Twence either accepts or denies the registration and in the case of an acceptation, confirms the potential dumping of waste.

The moment a truck arrives at Twence, it parks its truck in front of the gate and leaves the truck to hand over a filled-in file to the weighbridge personnel. Subsequently, the driver returns to the truck, the truck is weighed and before the gate opens the driver receives a printed paper with a QR code and information describing where on Twence's terrain the waste should be dropped off. Afterward, the composition of the truck determines whether the driver should pay a visit to the switch site; a truck with two trailers first must unyoke one of the trailers before making way for the waste platform or TOP. Then, the truck drives up the ramp towards the waste platform (for Lijn 1+2 and Lijn 3) or up the hill to TOP (in the case of a detour). At both locations, a controller is present that checks if the supplied waste corresponds to the registered waste supplies and the controller executes random samples of the quality of the waste. In the case of a complete mismatch between the requested waste stream and the delivered waste stream, the truck is demanded to return to its home depot. However, in the case of a slight difference in waste stream/quality or the case of an exact match of the waste stream, the truck is allowed to drive onto the waste platform to the allocated dump hole. Regarding TOP, the controller allocates a spot to temporarily store the waste. Within a period of maximum three years, the waste dropped at TOP must be internally driven back into the bunkers. The waste stream is noted down and the status of the waste is sent to Sales including "EMMA cases", which are situations when the waste stream is disapproved or when the waste stream deviates from the expected waste stream. These "EMMA cases" are used to notify the client of the quality of waste.

When the trucks have discarded the waste in their trucks, they go back to the weighbridge (or in the case of a double trailer go to the switch site and drive again to the bunker or TOP) and are weighed again. The gate opens and the truck starts the journey back to the home base of the supplier. The difference in tons at the weighbridge is the total amount of tons deposited. Every month, the client receives a bill for the services of Twence. Parallel to the truck making its way back, the dumped waste in the bunker is mixed with other types of waste to get a homogenized mix with a constant caloric value. After which, the mixed waste is fed into a big funnel which leads the waste into the AEC. A constant caloric value guarantees a sustained burning process of the AEC. Then, generated outputs include steam, electricity, bottom ashes and emissions from which the first two outputs are sold to customers.

2.2. Current Planning of Supplies

2.2.1. Flow Chart and Description of Planning

Twence's current planning of supplies regards three departments, namely U&L, Sales and A&O. The planning process is visualized with the help of BPMN and is shown in Figure 2.3 (Camunda, 2024).

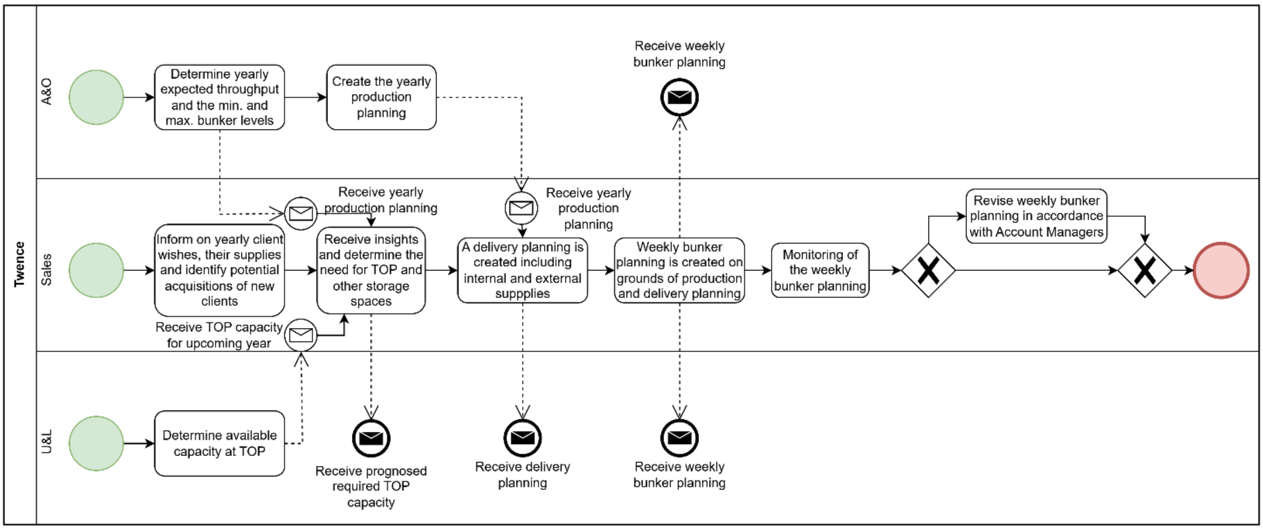

Figure 2.3 – Supply Planning Process

In August of every year, both U&L and A&O are supposed to submit essential information to Sales to develop a reliable planning. U&L hands over the expected available TOP capacity for the next year, whilst A&O communicates the maximal and minimal bunker levels for both bunkers for specific scenarios and the expected throughput per "Lijn" of the burning installation. At the same time, the account managers in the Sales department have contract negotiations for the next year and attempt to have a clear image of the contracted amounts of waste for the upcoming year. Also, on behalf of Sales, the need for TOP and other storage spaces is calculated, which are in turn delivered to U&L.

Subsequently, in November A&O determines the yearly production planning which considers the throughput and the demand of the AEC. This planning considers scheduled maintenance stops, the expected quality of waste, seasonality factors and the number of experiments conducted on waste. With the help of the production planning, Sales creates a delivery planning for waste supplies. The delivery planning includes a list of all the suppliers and their weekly supplies. In addition, the planning also incorporates internal transportation routes from TOP into the bunker. On grounds of the by A&O provided yearly production planning and the by Sales provided delivery planning, Sales builds a bunker planning. Knowing the incoming supplies in the bunker and what moves out of the bunker (throughput, determined in the production planning), a prognosis can be made describing the alternations in the bunker level. This step completes the yearly process of planning supplies.

Another element of the planning of supplies is monitoring whether the planning is followed by Twence's external suppliers. Monitoring is performed by watching and analyzing the proceedings of the bunker throughout the week and determining whether suppliers comply with their weekly delivery schedule. A monitoring tool is the provided data in QlikSense describing virtual bunker levels and supplier percentages of expected versus realized deliveries. Another monitoring tool is an actual monitor which shows several camera images from different positions in the bunker. In the case of a client not complying with the planning, there are three options:

1. Correction: the portion of supplies exceeding the planned supplies will be corrected in the next week. In other words, next week's supplies will be deducted from the extra portion of waste supplied in the current week.
2. Postponement: the entrance gate (just before the weighbridge) does not open for ± 30 minutes if the weekly amount of waste surpasses the contractual weekly supply (taking into account a margin of 5%-points on both sides of the 100%). This is a penalty to warn suppliers.

3. Nothing: municipal waste collection suppliers have negotiated that due to their high volatility of waste collection tons, they have no limits to bringing waste excesses.

In the occasion of new crucial information (e.g. a constant full bunker, clients repeatedly not sticking to their contracts, etc.) a new weekly bunker planning and delivery planning is developed in accordance with the account managers, who are responsible for customer acquisition and maintenance of customer contact.

2.2.2. Scheduling Factors

Whilst planning and monitoring weekly supplies per supplier there are a few scheduling factors taken into account. These scheduling factors are as follows:

- Maximal assumed bunker level throughout the whole year. The maximal assumed bunker level is a scheduling factor, since it constraints the capacity of the bunker. Two maximal bunker levels have been established for both bunker Lijn 1+2 and bunker Lijn 3. During the spring and summer months (April – September) the bunker is assumed to have achieved its maximum when it is filled with seven kilotons of waste. During autumn and winter months (October – March) the bunker is understood to have attained its maximum at nine kilotons. The reason for this difference in maximal bunker level is the difference in density during seasons. During the spring/summer season, less rain and more sun are causing the waste to be dryer. Dryer waste takes up more space and under the assumption that the mass does not change, the bunker cannot be filled with the same quantity of tons as in the winter. Namely, in the winter season, waste is in general wetter and therefore takes up less space.
- Priority level. The priority level is a number indicating the priority of every single supplier. Number five marks the highest priority level, whereas number one implies the lowest priority level. These prioritizations have been established by Sales' account managers based on the contents of the existing contracts with suppliers. This priority level rule is applied during establishing a problem within the delivery schedule; client supplies need to be restrained. First, the lowest ranked suppliers are informed that they need to cut in supplies, which continues until enough supplies have been restrained.
- Starting point of the bunker level at January first. The starting point of the bunker is the reference point on which the whole planning depends. The performance of the delivery planning and bunker planning are both dependent on the estimated bunker level at the start of the year. An estimation distant from reality may imply a revision straight away. Under normal conditions, the estimation is calculated by A&O.
- Proportionate division of waste. The proportionate division of waste means that the spread of waste supplies is (approximately) evenly segregated over the year (Table 2.1). However, that is not the case on a supplier level; especially municipal waste collection suppliers have weekly fluctuating supplies with sometimes differences of 200%.
- Contractual agreements. An important contractual agreement is the disposal of waste streams into specific bunkers. Household waste streams should mainly be discarded in the bunker preceding Lijn 1+2, whilst industrial waste streams should mainly be deposited in the bunker preceding Lijn 3. Twence is restricted to follow the 80/20 rule, which states that 80% of the supplies in the bunker of Lijn 1+2 must be household waste. Not obeying these agreements results in fines for Twence.
- Availability of TOP. The capacity of TOP is a factor to keep in mind whilst scheduling. A high space leftover at TOP could imply affording more risk, whilst a minimal leftover space demands for low risk and probably an acquisition of waste that is below the expected throughput.

- Throughput. Throughput is a scheduling factor. The throughput of the AEC determines the pace at which the bunker is emptied and thus the pace at which the bunker level declines. In general, a low caloric value guarantees a higher throughput. The burning installation has a constant energy input setpoint to which it obeys. By means of varying the throughput, the setpoint is maintained.

Month 2022	Planned (Tons)	Percentage	Month 2023	Planned (Tons)	Percentage
January 2022	53147	9%	January 2023	49145	9%
February 2022	41811	7%	February 2023	45286	8%
March 2022	55167	10%	March 2023	45748	8%
April 2022	47616	8%	April 2023	44355	8%
May 2022	47873	8%	May 2023	56408	10%
June 2022	52085	9%	June 2023	46529	8%
July 2022	46805	8%	July 2023	46284	8%
August 2022	53466	9%	August 2023	50609	9%
September 2022	48219	8%	September 2023	39378	7%
October 2022	38922	7%	October 2023	37204	7%
November 2022	41622	7%	November 2023	42574	8%
December 2022	48496	8%	December 2023	50534	9%
Total	575229	100%		554054	100%

Table 2.1 - Division of waste over the years 2022 and 2023

2.3. Arrival of Supplies

The arrival of supplies is assessed on a year, month, week and day basis. Twence has several supply streams to keep the AEC up and running (e.g. auxiliary materials, electricity, etc.), however for this analysis, solely the waste streams are being evaluated.

An analysis of the arrival of supplies on a yearly basis is conducted for the years 2022 – 2024. The full data set can be seen in Table 2.2. For the year 2022, 95% of the planned supplies were eventually realized, whilst for the year 2023 99% of the planned tons of supplies were delivered to Twence. The year 2024 has only partially passed yet and therefore this year can only be assessed on the supplies until the moment of this analysis (end of June). So far, 95% of the projected supplies have been delivered.

Year	Planning (tons)	Reality (tons)	Percentage R/P
2022	575229	549240	95%
2023	554054	548278	99%
2024 (30-06-24)	308176	292566	95%
Average			**96%**

Table 2.2 - Yearly supplies

The monthly match analysis between scheduled and real supplies concerns the period January 2023 – June 2024. Here, a bigger discrepancy between planned and realized supplies is visible, looking at Table 2.3. For example, March 2023 only managed to realize 79% of the expected supplies, whilst the months February 2023, June 2023 and January 2024 exceeded the expected supplies by 6%. Particularly, the differences from one month to the other stand out like the rise in percentage from May 2023 to June 2023, going from 94% to 106%. Also, the period September – December 2023 stands out, as it concerns a consecutive period of four months with only oversupplies (R/P > 100%).

Month	Planning (tons)	Reality (tons)	Percentage R/P
January 2023	49145	49308	100%
February 2023	45286	48087	106%
March 2023	45748	36085	79%
April 2023	44355	39500	89%
May 2023	56408	53122	94%
June 2023	46529	49427	106%
July 2023	46284	47423	102%
August 2023	50609	50084	99%
September 2023	39378	40184	102%
October 2023	37204	37431	101%
November 2023	42574	44038	103%
December 2023	50534	53589	106%
January 2024	58874	55792	95%
February 2024	44577	44464	100%
March 2024	39485	40427	102%
April 2024	55299	51977	94%
May 2024	58728	50781	86%
June 2024	51213	49124	96%
Average			**98%**

Table 2.3 - Monthly Supplies 2023 and 2024

For the first six months of 2024, an analysis on a weekly basis is conducted regarding planned and realized supplies. Table 2.4 shows a fluctuating pattern of supplies with a clear decline in absolute waste supplies during weeks 8 – 12. Especially the decline in supplies from week 10 onto week 11 catches the eye where the R/P percentage drops from 133% to 93%. Nevertheless, on average realized supplies turn out to be 95% of planned supplies.

Week in 2024	Planning (tons)	Reality (tons)	Percentage R/P
Week 1	14419	14340	99%
Week 2	13799	12679	92%
Week 3	11139	11100	100%
Week 4	11824	10331	87%
Week 5	12822	11766	92%
Week 6	11355	10852	96%
Week 7	11076	10751	97%
Week 8	9931	10226	103%
Week 9	8858	9836	111%
Week 10	7410	9866	133%
Week 11	7971	7385	93%
Week 12	9394	10340	110%
Week 13	12938	11211	87%
Week 14	11873	10708	90%
Week 15	12402	13193	106%
Week 16	12718	10822	85%
Week 17	13378	12290	92%
Week 18	12320	10709	87%
Week 19	12744	10754	84%
Week 20	12680	12751	101%
Week 21	13527	10345	76%
Week 22	12385	11188	90%
Week 23	12294	12797	104%
Week 24	12548	11739	94%
Week 25	14139	13459	95%
Week 26	12232	11130	91%
Average			**95%**

Table 2.4 - Weekly supplies 2024

The day-by-day analysis is executed by observing the end percentages of supply at the end of every day. Again, these observations are based on the period January - June 2024. Looking at the daily supplies per week, a few weeks have a more prominent pattern of supplies (Table 2.5):

- Week 3.
- Week 10.
- Week 11.

Ideally, the week buildup for a five-day working week is going from 20% at 19:00 on Monday to 40% at 19:00 on Tuesday to eventually 100% at the end of Friday. The ideally described division of waste over a week would contribute to a more constant bunker level. Week 3 in 2024 shows such an almost perfect pattern of waste division over a week. Actual supplies go from 21% on Monday, to 43% on Tuesday, to 63% on Wednesday, to 83% on Thursday and last to 100% on Friday. The biggest deviation on week terms from the norm is 3%-points (namely Tuesday, Wednesday and Thursday), whilst the biggest daily deviation is also 3%-points, namely on Friday only 17% was delivered where 20% was expected. The least ideal week build-up in 2024 is week 10's buildup of supplies. Not only does this week have a very high end deviation of 33%-points, it also has daily supplies that are not close to the expected supplies. Respectively from Monday to Friday, week 10 delivered 27%, 27%, 27%, 27% and 26% which results in an unreliable bunker level. In week 10 the suppliers together structurally delivered at least 5%-points more per day. Lastly, week 11 is evaluated since it shows a "regular" pattern of supplies throughout the week. The daily supplies of Monday – Wednesday are structurally above the reference values, implying an oversupply. Respectively, Monday to Wednesday have 24%, 22% and 21% deliveries. Nevertheless, on Thursday and Friday supplies were below the reference values with respective 14% and 12% eventually coming down to a 93% supply rate. Although week 11 is a regular week for Twence, it is not an ideal week, as the first part of the week suggests a possible oversupply which Twence might anticipate. The second part of the week displays a massive downfall in supplies resulting in the possible actions taken not paying off and Twence having to anticipate again.

Week Number	Planning (tons)	Reality (tons)	Reality/Planning	Accumulative R/P
Week 3	**11140**	**11101**		
Monday	2228	2348	21%	21%
Tuesday	2228	2437	22%	43%
Wendesday	2228	2225	20%	63%
Thursday	2228	2187	20%	83%
Friday	2228	1904	17%	100%
Week 10	**7410**	**9885**		
Monday	1482	1980	27%	27%
Tuesday	1482	2003	27%	54%
Wendesday	1482	1986	27%	81%
Thursday	1482	2007	27%	108%
Friday	1482	1909	26%	133%
Week 11	**7970**	**7384**		
Monday	1594	1912	24%	24%
Tuesday	1594	1775	22%	46%
Wendesday	1594	1676	21%	67%
Thursday	1594	1123	14%	81%
Friday	1594	898	11%	93%

Table 2.5 - Daily supplies for weeks 3,10 and 11

Table 2.6 displays the average contribution percentage to the weekly supplies per day of the week for the months January – June 2024. Since Saturday's and Sunday's contribution is negligible, a reference value of 20% is taken into account. It is observed that structurally on

Tuesdays and Wednesdays, suppliers provide more waste than was planned and on Thursdays and Fridays less waste is supplied than planned. Such analysis shows that the build-up of supplies throughout the week is not evenly spread.

Day	Number of Trucks	Percentage	Reference
Monday	4226	20%	20%
Tuesday	4483	22%	20%
Wednesday	4294	21%	20%
Thursday	3920	19%	20%
Friday	3707	18%	20%
Saturday	174	1%	0%
Sunday	4	0%	0%
Total	**20808**	**100%**	**100%**

Table 2.6 - Supplies per working day from January until June 2024

Lastly, the division of supplies per hour of the day is being discussed. Figure 2.4 demonstrates the number of trucks that have passed the weighbridge in 2024 up until June for the AEC per hour. It must be said that although the graph represents the average of half a year's observations, the pattern of the graph and primarily the ratio of the peaks per hour is similar to the daily arrival of trucks. Noticeable in the graph are the peaks during hours 07:00 – 08:00, 10:00 – 11:00 and 14:00 – 15:00. The first peak is caused by truckers that were not capable of delivering within the previous day's opening times and that want to discard their waste as early as possible such that they have a full day to collect waste. The other two peaks are caused by municipal waste collection trucks that drive allocated routes through cities. Most of these trucks start at the same time and have approximately the same amount of garbage cans to empty. The first batch is often deposited at about 10:30, whilst the second is discarded at about 13:30. Also, it must be noted that from 16:00 on, supplies immensely decrease.

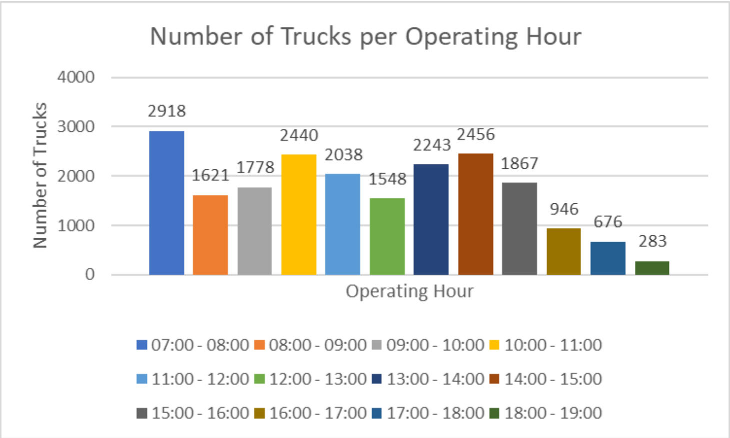

Figure 2.4 - Hourly division of supplies

In conclusion, assessing the arrival of supplies at different time intervals, it can be stated that improving the division of waste supplies throughout the week is the most effective. The problem of a mismatch between scheduled supplies and realized (actual) supplies is the most relevant at a weekly level.

2.4. KPIs Selection

Key Performance Indicators (KPIs) are quantifiable measurements used to evaluate a company's overall long-term performance (Twin, 2024). Regarding Twence's operations and their main problem of the weekly mismatch between expected and realized supplies, a few KPIs have been formulated to assess the performance of the planning department. The first five KPIs are measures used to analyze the regularity of the arrival of supplies. The last KPI describes the average terrain time for a supplier. The KPIs are as follows:

Supply Standard Deviation (SSD). The SSD measures the volatility of daily supply within a week. It is measured in tons and weekly. Regarding the equation, x_i is the number of tons supplied by suppliers per day and μ is the average number of tons supplied. The SSD is measured as follows:

$$SSD = \sqrt{\frac{1}{5} * \sum_{i=1}^{5}(x_i - \mu)^2} \qquad (2.1)$$

Maximum Deviation (MD). The MD observes the biggest irregularity per week that the realized supply varies from the planned supply. This number is represented as an absolute number and is measured in tons. Here, the supply scheduled for a day is assumed to be 20% of its weekly volume. Below, the formula is visible where the dots (…) represent the same calculations, but executed for days 2, 3 and 4. Equation 2.2 shows how the MD is measured:

$$MD = Max(|Day1Realized - Day1Planned|, \dots, |Day5Realized - Day5Planned|) \qquad (2.2)$$

Maximum Time Period (MTP). The MTP describes the longest consecutive period for every week where realized supplies are above or below 20%. The ideal line of supplies would go from 20% on Monday at closing time (19:00) to 40% on Tuesday at 19:00, etc. until 100% on Friday at 19:00 An example: accumulative supplies throughout a week are on Monday 21%, Tuesday 43%, Wednesday 62%, Thursday 82% and Friday 100%. Both at Monday and Tuesday more is delivered than scheduled, namely 21% and 22%. On Wednesday, Thursday and Friday respectively 19%, 20% and 18% of supplies are delivered. The longest streak of days where more or less than 20% of supplies are delivered is 2 days (MTP), namely Monday and Tuesday.

Ratio of Outliers (RoO). RoO is a KPI that determines the ratio between significant positive and negative peaks, where a significant peak is set to be a 5%-point difference. For a normal working week consisting of 5 working days, for example, the expected supplies per day are 20% of the whole week. However, if the supplies of a particular day are above 25% or below 15% of the weekly expected supplies, it is regarded as a positive peak and a negative peak, relatively.

End of Week Supplies Standard Deviation (ESSD). the ESSD assesses the total number of supplies at the end of the week. The standard deviation of the supplies at the end of the week is measured as ESSD and expressed in tons. n depends on the number of weeks that are being assessed, x_i is the total number of tons supplied in week i and μ is the average number of tons over the assessed number of weeks. Equation 2.3 measures the ESSD:

$$ESSD = \sqrt{\frac{1}{n-1} * \sum_{i=1}^{n}(x_i - \mu)^2} \qquad (2.3)$$

Terrain Time (TT). Although TT does not have a direct link to supply and bunker management it is of crucial importance to incorporate it as one of the KPIs, because it is expected to change. The average terrain time is measured as the sum of all the suppliers' terrain times (TT) divided by the total number of suppliers helped (n):

$$TT = \frac{\sum_{i=1}^{n} TT_i}{n} \qquad (2.4)$$

The chosen KPIs have been analyzed for the period January – April 2024. The KPIs are calculated in two ways:

- Including festivity days.
- Excluding festivity days.

In the first case, the KPI outcomes are bigger than for the second case. In the event of a festivity day occurring on a weekday (e.g. Easter Monday), Twence is closed on the festivity day and is opened on Saturday to compensate for the missed supplies on Monday. However, supplies are still scheduled and administered for Monday and not for Saturday, causing that on Monday for example 2200 tons of waste are expected and none are delivered and on Saturday zero tons of waste are expected whilst 800 tons of waste are delivered. Such an event disrupts the correctness of the KPIs. The KPI measured by excluding festivity days counts the festivity day as a regular working day and therefore is a better approximation. Thus, the "excluding festivity days" variant is used later to compare and contrast.

The realization of the best match between realized supplies and scheduled supplies demands an SSD that approaches the value of zero. A value of zero namely suggests that actual supplies exactly correspond to scheduled supplies. Including festivity days, the mean SSD is 602 tons with an observed minimum of 181 tons in week 3 and an observed maximum of 1346 tons in week 1. Excluding festivity days makes the maximum observed standard deviation drop to 795 tons and the mean drop to 267 tons.

The MD is described as the worst mismatch in supplies during one week. Again, the lower the value of this measure, the better the tuning of supplies. Including festivity days yields an average MD of 927 tons and a respective minimum and maximum of 324 tons and 2884 tons. Excluding festivity days results in an average MD of 675 tons and a maximum MD of 1182 tons.

MTP is a KPI describing the daily volatility of waste supplies. A high value for MTP means that supplies for a week are structurally too low or too high. A lower value, most of the time, indicates a better match of supplies. The found mean MTP is three days.

Concerning RoO, the preferred ratio is 0:0 as this means there have been no positive or negative peaks. Otherwise, it is best to have an equal ratio of 2:2, meaning that there have been a total of four peaks, from which two are positive and two negative. In this case, the peaks cancel each other out, taking supplies back in the direction of the reference line. The most occurring RoO-value, the mode, is 2:0, whilst the preferred ratio of 0:0 was found in five cases. The worst noticed ratio is 5:0.

A low ESSD implies a low standard deviation of weekly end volumes in supplies, whereas a high ESSD implies a high standard deviation of weekly end volumes. As Twence aims for a more predictable supply pattern, a low ESSD is the goal. At this moment, Twence scores an ESSD which is equal to 310 tons.

The terrain time is an output variable that is preferred to be as low as possible. Currently, the terrain time of an average supplier is 38:38 minutes.

3. Literature Study – Related Works

Section 3.1 provides insight into causes and remedies for uncertainty in supplies. Section 3.2 elicits methods to match supply to demand with special attention to the method of demand forecasting. Section 3.3 describes the process of supply planning and its major challenges. Section 3.4 shows the benefits, setbacks, integration, future perspective and sizes of time slots. Section 3.5 discusses some case studies about the use of discrete event simulation.

3.1. Uncertainty in Supply

The to-be-answered question in this subsection is how other companies deal with uncertainties in the supply. “Supply uncertainty elicits a diversification bias, wherein inventory managers tend to source from multiple suppliers, even when sole sourcing is optimal” (Bendoly, Boyer, Craig, & Paul, 2022). Common causes of uncertainty in supply are natural disasters, pandemics, wars, geo-political tensions, disinformation, climate change and cyberattacks (Friday, Ryan, Melnyk, & Proulx, 2023). According to Coskun et al. (2023), the major effects of uncertainty in supply are dynamic tensions in planning, volatility, internal uncertainty like stockouts and increased complexity.

As reported by Angkiriwang et al. (2014) the best way for companies to deal with supply chain uncertainty is the introduction of supply chain flexibility. Supply chain flexibility is defined as the ability of a system or a chain to respond to unexpected and unpredictable changes due to uncertain environments to meet a variety of customer needs or requirements, whilst still maintaining customer satisfaction without adding significant cost (Angkiriwang , Pujawan, & Santosa, 2014). Nevertheless, supply chain flexibility comes with the remark that every company should determine for itself to what degree the flexibility must be, since supply chain flexibility comes with a cost. Flexibility can either be proactive or reactive. According to Sen et al. (2022), proactive flexibility is defined as the organizational ability to anticipate emerging changes in the supply chain, whereas reactive flexibility is the ability to shift in behavior in response to a changing supply chain.

Reactive strategies consist of supplier backups and safety lead times. A strategy is supplier backups, which include maintaining several suppliers. Supplier backups guarantee availability, but often also increase costs. Last, safety lead time is the additional time buffer added to the standard lead time for ordering products to account for uncertainties or unexpected delays in the supply chain (Speedcommerce, 2024). Adding extra time assures that the prognosis of supplies is not too bright (Angkiriwang , Pujawan, & Santosa, 2014).

Proactive measures to take mostly concern a redesign of a particular process. Proactive measures are safety stocks, postponement, risk pooling, outsourcing, flexible supplier contracts and a throughput increase. Safety stock is the extra amount of stock that is ordered to protect the company from enduring risks like fluctuations in supply and demand (Netstock, 2024). Employing the application of safety stock, the company can reduce the chances of shortages in inventory. A postponement entails a whole redesign and/or revision of the current supply chain process like building an extra road entering the terrain, thereby decreasing the probability of an occurring traffic jam. Risk pooling means reducing facilities or centralizing stocks to fewer facilities. Risk pooling raises the question if having an additional storage space as an alternative storage location is a justified choice. Outsourcing makes use of external capacities. An example concerning Twence would for example be consignment stock at the supplier, implying that when Twence has enough waste, the supplier must temporarily store the waste at their terrain until Twence needs waste again. Negotiating flexible supply contracts could lead to minimum order quantities and a maximum number of deliveries per week. In this way, Twence has more control over the supply process. A throughput increase given the same supply, means that per time unit more end products can be fabricated, but that in total the same amount of end product is produced (Angkiriwang , Pujawan, & Santosa, 2014).

Niranjan et al. (2014) claim that there exist two measures to solve uncertainty. The first measure concerns both the supplier and the buyer of supplies to communicate their demand forecasts including the supply uncertainties. Qualifying the forecasts in an optimistic and pessimistic way and next to that assuming different scenarios should contribute to a more supportive relationship; the supplier can better justify the ordered quantities. As a second measure comes the introduction of an intermediary between the different suppliers and the buyer of the supplies. The goal is to reduce uncertainties and build trust such that the buyer of supplies has high visibility and the suppliers can subsequently be rewarded in proportion to their contributions.

3.2. Techniques Matching Supply to Demand

In today's competitive markets, being able to match supplies to demand is of great importance for achieving success. If too much of the end product is produced, the product is often discounted to a lower price, whilst an underproduction often leads to a loss of sales. In the case of Twence, demand represents the total amount of energy and steam production which is dependent on the realized throughput.

According to Richardson (2023) there are three main motives for the existence of the challenge of accurately matching supply to demand, namely unpredictable demand, the presence of lead times and the existence of inventory costs. Unpredictable demand is caused by rapidly changing market conditions, whilst long supplier lead times occur when dealing with international clients. Inventory costs are a challenge, since these costs are unnecessary, but do guarantee a safety buffer of materials. Richardson (2023) proposes three ways to better match supplies to demand. Firstly, by forecasting demand, secondly by planning production such that there is enough inventory to suffice demand and last by thoroughly managing inventory costs (Richardson, 2023).

"Demand forecasting is an imperative component within the business strategy domain, enabling organizations to peer into the future and anticipate the ebb and flow of market demand." (Salesforce, 2024). Wolter Kluwer (2021) describes the main goal of demand forecasting as follows: by means of leveraging historical data and analyzing future developments a future demand is estimated, which offers guidance for informed decisions about production planning. Nalini (2023) summarizes the significance of demand forecasting in the five main factors that it contributes to: efficient production planning, realistic inventory management, consistent supplier management, high customer satisfaction and cost reductions. By aligning production to demand, companies optimize production capacities. Moreover, having predicted demand prevents a surplus of inventory and therefore yields improved inventory management. In addition, an accurate projection of demand suffices for negotiating better-adjusted contracts with suppliers. Furthermore, the alignment of supplies and demand results in fewer delays and exact proportions, positively impacting the relationship between customer and company. Last, demand forecasting in general reduces costs throughout the whole chain (Nalini, 2023).

Nalini (2023) defines the following components as internal factors driving demand: pricing strategy, product features, brand reputation and marketing strategy. A relatively higher pricing often results in a demand reduction, whilst a relatively lower pricing with possible promotions generally leads to a demand increase. Product features like a direct connection from the company to its customers or a sustainable way of producing the product contribute to a positive image from clients towards the company and thereby increase demand. Next to that, a good reputation helps attract demand. Elements like reliability and loyalty are regarded to help build a high reputation (Nalini, 2023).

As external factors driving demand, Nalini (2023) illustrates economic conditions, market competition, consumer preferences, governmental factors and technological advancements. In practice, a combination of these factors drives demand. First of all, economic expansions and downturns determine the overall demand (and supplies) for a product. Take for example the economic downturn during the years 2020-2022 caused by the Covid-19 pandemic. In the Netherlands, household waste totaled 8,5 billion kilograms in 2019, whilst in the year 2020 household waste added up to 9,1 billion kilograms: an increase of almost 7% (Centraal Bureau voor de Statistiek, 2021). Secondly, market competition is often represented in the form of the number of competitors. Intense competition between competitors affects the demand per company. Thirdly, customer preferences are based on culture and behavior and impact the demand. Fourthly, governmental regulations and their compliances affect product/service demand. Fifthly, technological innovations can both increase and decrease demand; breakthroughs are often rewarded with an increase in demand, whilst a product/service becoming obsolete results in a decrease in demand (Nalini, 2023).

As stated by Meshram (2024) current challenges in demand forecasting are an always-altering market landscape, data silos, difficult-to-predict external factors, and flexibility. Regarding the constantly shifting market landscape, the following are included: a changing economy, changing people's wishes and a changing technology. Data silos occur when departments operate in isolation, causing a fractured perspective of demand. External factors with a low level of predictability are among others natural disasters like pandemics and earthquakes distorting the supply chain. Flexibility concerns executing a prognosis of demand and being able to play around with it (Meshram, 2024). Methods to counter these challenges encompass utilizing multiple demand forecasting techniques, both qualitative and quantitative (SupplyChainToolbox, 2023), to spread risk, include external factors with different scenarios in the forecasting, enhance collaboration throughout the whole organization, implement feedback loops that continuously analyze the forecast accuracy and look for subjects to improve on and lastly monitor leading KPIs for the organization (Nalini, 2023).

Anticipating what the future might bring us, Nalini (2023) lists three recommendations. Starting with investing in a good analytics tool. The right technology fosters efficiency and decision-making. Second comes engaging with suppliers, intending to increase visibility and responsiveness. The third recommendation includes continuous learning, meaning that every mistake must be turned into a positive thing by learning from it and gaining new insights.

3.3. Supply Planning Factors

"Supply planning is the process of determining the optimal quantity and timing of production, distribution and procurement activities in a supply chain. Supply planning aims to balance the supply and demand of products and services while minimizing costs, maximizing profits, and ensuring customer satisfaction" (Verrecchia, 2024).

As claimed by Phipps (2023), the process of building a supply planning consists of five steps. Firstly, a demand forecast is created (See section 3.2). The follow-up on the demand forecast is an inventory review. Here, an evaluation is conducted on the current inventory level and the potential need for inventory on grounds of the demand forecast. Subsequently, knowing the projected demand and inventory level, negotiations with the suppliers can start. After having negotiated favorable contractual terms with suppliers, a plan is designed that seeks to distribute the inventory throughout the whole operation. Step five concludes the five-step supply planning procedure and treats the monitoring of the planning, thereby paying special attention to the accuracy of suppliers' deliveries (Phipps, 2023).

Following the supply planning process there are a few challenges to consider whilst creating and executing the supply planning. First, the supplier choice. There is a world of difference between signing a contract including the number of supplies and receiving this contractually agreed upon number of supplies. Therefore, choosing reliable suppliers is a serious challenge. Factors to consider whilst choosing suppliers are the quality of the product the supplier delivers, received price for the deposit of the product, expected delivery times, payment terms (weekly basis, monthly basis, etc.), lines of communication (ease of getting into contact with the supplier) and potential ethical aspects. Second, in the event of a disruption; supply fails to fulfill the demand. At this stage, it is best to stay calm and follow a three-step sequence, starting by identifying the important products. The second step maps the risk of the availability issue. There are two possible situations:

- Supply exceeds demand, meaning an oversupply.
- Supply falls behind demand, meaning an undersupply.

The third step offers ways to mitigate the effects of the supply disruption to the maximum. For both cases, an oversupply and an undersupply, there are several mitigating options. Phipps (2023) states that for an undersupply of waste, one option is to take the supply disruption as a fact and communicate the supply issue to the customers and ask for their understanding and a change in their expectations. If the issue of supplies is a transportation issue, a solution might be to temporarily hire an external transportation company that drives the waste from the supplier to Twence. Nevertheless, this option is only triggered if the benefits of the continuing operations exceed the disadvantage of additional costs for transportation. A last opportunity is to attract new suppliers offering a stable supply (Phipps, 2023). According to Paul (2024) for an oversupply of waste there is the option of paying suppliers to temporarily put their supplies on hold. Another suggestion might be a market intervention, which means an intervention on a governmental level. However, this measure cannot be executed by the company itself and only happens in the case of a structural oversupply. Lastly, other options are to try and find more reliable suppliers or to try and negotiate better contracts with current suppliers concerning supply agreements (Paul, 2024).

3.4. Time Slots

“Time slot management is about mandating specific time frames of deliveries and pickups in the supply chain” (Branch, 2023). In line with Branch (2023), the goal of time slots is to guarantee a supply chain that is as smooth as possible, maximize the efficiency per working unit and offer transparency. As concluded by Cunnane (2022) the major benefits for the company implementing the time slots are the ability to save time, which saves money, improved utilization of assets (e.g. bunker, crane, etc.) and a better reaction to trucks not arriving according to schedule (Cunnane, 2022). Branch (2023) mentions consistency as an advantage of time slots for the implementing company. Next, Treschau (2020) mentions an improved inventory management with a reduction of storage capacity and an elevated customer satisfaction as possible positive impacts of the introduction of time slots (Treschau, 2020). Also, the supplier side’s story of the introduction of time slots must be illuminated. Cunnane (2022) concludes that suppliers benefit from time slots in the sense that they will encounter reduced waiting times and less congestion in front of the weighbridge and the waste platform. A reduction in waiting times and congestion leads to money savings as the supplier can drive more cargo on the same day (Cunnane, 2022).

Krislok (2024) claims that the drawbacks of time slots are their inflexible character, their accuracy challenges potentially leading to stress and their potential for overwork. Adjusting the schedule after having defined time slots comes with a high difficulty level, which describes the inflexibility of time slots. Accuracy issues happen when the time required for a certain activity is either over- or underestimated. There is a low level of understanding on behalf of the supplier concerning accuracy issues since the supplier also must deal with it. Too many accuracy challenges might lead to higher stress levels. Lastly, the existence of time slots might lead to overwork when a supplier just delivers outside the allocated time slot but within the allowed margins at opening and closing times, assuming an equal division of cargo over the day (Krislok, 2024).

Branch (2023) presents a six-step plan to integrate time slots into an organization. The first step consists of precisely identifying where in the supply chain the time slots must be applied and which suppliers should obey the time slots. The second step includes choosing between the different time slot management tools. The tool should correspond to the defined needs. Step three is the communication of the change towards the suppliers. Crucial here is to point out the advantages for the suppliers and emphasize that the change will be implemented gradually and that punctuality towards the time slots will be rewarded in the form of a bonus. Next, step four comprises training staff such that they will be able to work with the system. Moreover, step five monitors the performances of the introduced system. Monitoring KPIs should help find improvements in the system that subsequently must be implemented. Furthermore, in the last step suppliers regularly receive updates about the proceedings of the new system and the realized advantages. After a while, rewards will be shared with those that adhered to the schedule and showed to be a reliable supplier (Branch, 2023).

As for time slots, there are three options:

- Fixed time slots where suppliers are planned in per agreed size of time slot.
- Fixed flexible time slots where suppliers book their time slot given an agreed size of time slot.
- Flexible time slots where suppliers book their slot in a self-chosen size of time slot (within a predefined bandwidth).

Fixed time slots offer a predictable scheduling ability, no overbooking and enhanced planning. A disadvantage is the limited flexibility that fixed time slots offer according to Crossley (2023). Fixed flexible time slots offer some more flexibility to the suppliers in comparison to the fixed time slots but hamper an equal division of supplies throughout the week and therefore the enhanced planning. Last, flexible time slots offer an improved customer experience with a maximal customer experience, but also yield the most complex scheduling with the least control (Crossley, 2023). Flexible time slots represent the current situation, except that suppliers indicate when they are coming such that Twence has an increased anticipation level. The choice for the type of time slots is a choice based on industry-specific considerations such as competition.

For suppliers to comply with the time slots there must be a mechanism that either rewards suppliers that arrive in time or a mechanism that penalizes suppliers that do not arrive in time. Sharot (2017) argues that when it comes to motivating an action, rewarding is better than punishing. On the other hand, when having to deter an action from happening, it is best to penalize someone (Sharot, 2017). Nonetheless, Hannan et al. (2005) write in their paper that employees can be stimulated to better do their best when contracts possess negative consequences to failures in performance instead of positive consequences to excelling performances (Hannan, Hoffman, & Moser, 2005). This is due to the characteristic of loss aversion that most people carry with them.

A case study executed by Corolli et al. (2014) entitled “The time slot allocation problem under certain capacity” investigates whether assigning time slots to air traffic reduces congestion and thereby costs. As of now, time slot allocations are independent for every airport, whilst the need for collectively allocating slots to the departure location and arrival location is widely known (Corolli, Lulli, & Ntaimo, 2014). Corolli et al. (2014) propose a simultaneous allocation of time slots at all airports, considering a big network of airports and therefore ensuring a coherent result in the sense of an airline schedule. Results show that the collective integration of time slots could reduce operational delays by more than 50%.

3.5. Discrete Event Simulation

Simulation is one of the many analytic methods within the field of operational research. A simulation intends to display a model of a real-life situation that describes a process of moving units such as persons or products (Bangsow, 2012). A discrete event simulation (DES) exists out of two main building blocks, namely: the simulation objects and the events. The objects are the physical objects moving around and the events represent modifying the state of the objects (Ndih & Cherkaoui, 2015). Due to increasing computer speed and memory, DES has been applied to problems of increasing size and complexity (Allen, et al., 2015). Simulation helps answer questions starting with “what if?” by modeling a situation and adjusting it given several scenarios.

Tako, A.A. and Robinson, S. (2012) write in their paper about the application of DES that DES is most often used to model supply chains. Furthermore, it is concluded that DES can very well be used for decision-making on both strategic and operational issues (Tako & Robinson, 2012).

Vaidyanathan et al. (1998) write in their paper about “Application of discrete event simulation in production scheduling” that DES has been tested whether it functions as a production scheduling tool in coffee manufacturing. Difficulties occurring during the making of planning schedules were among others a large number of end products, irregular demand and a limited shelf life. Now, it was tested if the combination of a scheduling program and simulation model would yield better-fitting schedules. The scheduling program created schedules for the stages of the manufacturing process of coffee (roasting, grinding, etc.). The simulation model takes all the schedules into account and simulates the production of coffee with as outcome an adjusted schedule, in which all details such as performance factors are visible (Vaidyanathan, Miller, & Park, 1998). This paper proves that the application of DES for scheduling purposes can be very helpful.

Spieckermann et al. (2012) have executed a case study on a worldwide operating company experiencing the problem of not knowing where to build two new production locations. As a tool to solve the problem Spieckermann et al. (2012) used DES. The case study concerned a company having 700 locations, either warehouses or production sites, a company with customers originating out of a total of 56 different countries and a company with over 220 products with more than 1200 optional allocations of products. A DES model was developed to assess the consequences of the integration of two new production sites into the supply chain. KPIs to evaluate the alternatives were cost level, service level and utilization level. The company concluded that although DES is a rather costly option, it yielded valuable insights for the choice of the new production locations and insights that were implemented into tactical planning decision-making. Spieckermann et al. (2012) concluded that DES could not only be used to model a logistic supply chain, but also a chemical supply chain (Spieckermann & Stobbe, 2012).

Given the previous, it can be said that DES is a valuable technique to use when dealing with supply chain issues.

4. Discrete Event Simulation Design

This chapter describes the choice for motivation and the to-be-researched relationships between variables in Section 4.1. In Section 4.2 the simulation and its components are described. Section 4.3 presents a flow chart of the current situation of supply handling including assumptions, simplifications and limitations. Section 4.4 explains how data is collected and how data is being processed into usable information for the simulation. In Section 4.5 a short explanation is given of how the process model is being translated into a valid simulation model. Section 4.6 discusses the validation and verification of the created model. Section 4.7 reviews the introduction of a new model and tackles the comparisons between the two existing models.

4.1. Simulation Motivation

By means of a simulation model, a solution to the problem is found. In particular, discrete event simulation (DES) is used as this type of simulation is ideal for outlining processes that occur at specific moments in time, like in this case the arrival of suppliers (Leonelli, 2021). The simulation model is developed in Tecnomatix Siemens Plant Simulation. Simulation is chosen as the means to solve the problem, because Twence deals with daily supply variations and a complex network of relations. Simulation can represent variability, interconnectedness and complexity of a system. In addition, simulation offers various advantages like safety, cost efficiency and the ability of prediction. Without changing the working environment and involving costs, several scenarios can be tested. Also, a simulation model can be used to predict future events. The result is that simulation can predict the performance of the supply chain, without changing the supply chain and without the involvement of substantial costs (TNO, 2024). A simulation model of the **current situation** is developed, which from now on is called **Model A** and a simulation model of an **improved situation where time slots and quantity restrictions are applied** is designed, which from now on is called **Model B**. The fundamental objective of proposed Model B is to offer a better division of waste supplies throughout the week such that Twence's bunker can be managed in a better way with more control.

4.1.1. Interplay of Variables

Figure 4.1 visualizes the interplay of the existing variables. The dependent variable is the number of supplies, which is directly related to the other dependent variable "Bunker Level". The number of supplies is dependent on the independent variable "Alignment of Sales with External Suppliers". A good alignment between Twence's sales department and its external suppliers namely results in a better-tuned number of supplies supplied and therefore a better anticipated bunker level. The mediating variable is a variable that explains the relationship between the dependent and independent variables. In this case, the mediating variable is the degree of cooperation; the relationship between the dependent and independent variables can be described and measured as the degree of cooperation. The moderating variable is the application of time slots and quantity restrictions. A moderating variable affects the strength of the relationship between the dependent and independent variables. By implementing time slots and quantity restrictions the strength of the relationship is tested. The moderating variable investigates whether time slots and quantity restrictions influence the relationship between the independent and dependent variables.

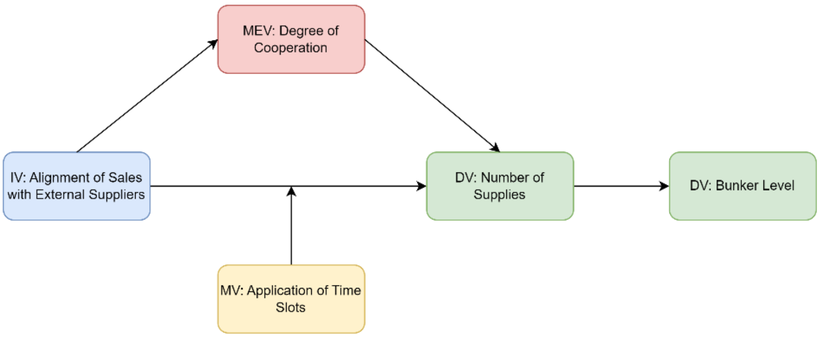

Figure 4.1 - Interplay of variables

4.2. System Definition

A DES model can be described in the following components: system, state, events, simulation clock, initialization, timing, report generator and statistical counters. Figure 4.2 displays the working of the DES model.

System = The system is a queueing system where trucks come and go to discard their waste.
State = The state of a model represents several variables that together describe the system at any given time. In this case, the state is described as the number of trucks in the system and the number of dump holes available.
Unconditional event = An unconditional event is an independent situation that may alter the system's state. The unconditional state is the arrival of trucks at the entrance gate of Twence.
Conditional event = A conditional event happens when a specific condition is true. The movement of a truck from the queue to the dump hole if the previous truck has left the dump hole is the conditional event in this situation.
Simulation clock = The clock is a time variable that keeps track of the time in the system. In this case, the total to-be simulated time equals five days.
Initialization = The initialization describes how the model selects the first event after the simulation has started. The selection of the first event is based on the arrival of the first truck at the gate. The first truck is the truck with the arrival time closest to the opening time (07:00).
Timing = The routine that selects the next event to happen, looks at the arrival time of the next truck and lets the truck enter the terrain.
Report generator = After every happened event, its data are registered in a table. Statistical counters are calculated and updated after every event by taking the average of the stored values in a table.
Statistical counters = Important statistical counters are the average waiting time, the throughput, the bunker growth and the total number of trucks helped during a period of time.

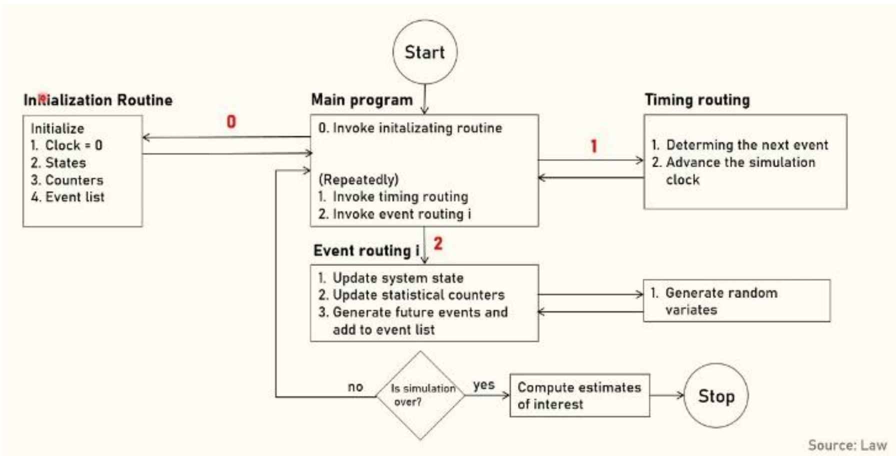

Figure 4.2 - Flow Diagram DES Execution

4.3. Model Formulation into Flow Chart

4.3.1. Model of Current Situation ~ Model A

Figure 4.3 visualizes a process model of the current situation of supply handling. This model describes that suppliers arrive randomly at an unknown day of the week at an unknown time. Then, the supplier passes the weighbridge where its number of tons are determined, its arrival time and its destination (either TOP or the bunker). Historical data conclude that in 3.5% of the cases that a truck arrives, it is being directed to TOP instead of its regular destination "Bunkers". The model tells that 96.5% of the suppliers are directed to the bunkers and 3.5% is directed to TOP. If there is a queue at either destination, the truck waits until it is first in line and discards its waste. Afterwards, the truck leaves the system. The total time in the system is calculated as: $Total\ Time = Waiting\ Time + Processing\ Time + Transport\ Time, \qquad (4.1)$

where the latter is a constant and is estimated at 6:12 minutes (Table 4.1).

Type of Truck	Relative Frequency	Travel Time	Frequency * Travel Time
Refusal Truck	48%	00:04:00	00:01:55
Walking Floor	17%	00:04:00	00:00:41
Double Container	20%	00:15:00	00:03:00
Single Container	15%	00:04:00	00:00:36
Average			00:06:12

Table 4.1 - Travel Time Calculation

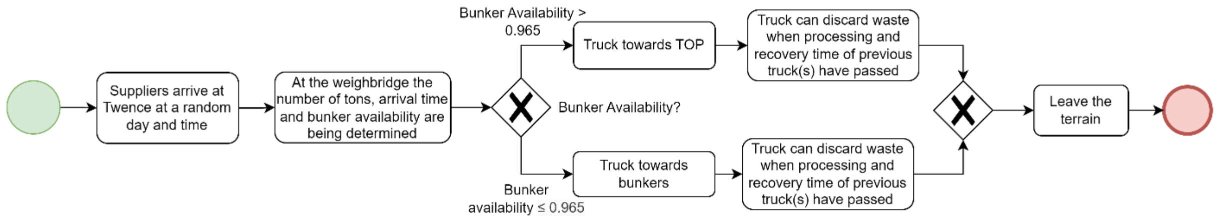

Figure 4.3 - Conceptual Model Current Situation

Some assumptions, simplifications and limitations have been defined to fill in missing information and simplify the model:

- Assumption: The capacity of the queue line is set to be unlimited.
- Assumption: On average, four dump holes are opened at the same time. There is no data available regarding the probability of the number of opened dump holes. Therefore, the system operates with the availability of four opened holes.
- Assumption: In consultation with operators the availability of the four opened dump holes and TOP is said to be 95%, meaning that in 5% of the cases, the specific dump hole or TOP is inaccessible.
- Assumption: The average total time in the system is calculated as the summation of the average waiting time, the average processing time and the constant value of 6:12 for the travel time on Twence's terrain (Table 4.1).
- Simplification: At the moment of arrival, the number of tons of every truck is being established, whilst in reality the discarded tons of waste can only be measured at departure.
- Simplification: A double truck only enters the bunker area once, instead of in reality twice. However, the processing time does account for a double truck.
- Simplification: The model runs for 5 days from 07:00 – 19:00, because Twence only accepts arrivals of supplies on working days. The throughput which is normally created over 7 days (including Saturday and Sunday) is now created in 5 days. However, this simplification does not hinder the outcome.
- Limitation: Only the suppliers that were planned to deliver a minimum of 2% of the total number of tons (at the start of 2024) delivered to Twence are considered in the

simulation. This implies that in total 17 suppliers are considered, who together are responsible for 86% of Twence's yearly total supplies. The reason for this decision is that these 17 suppliers have a significant impact and are therefore worth investigating. However, to receive reliable output, all supplier's yearly tonnages are multiplied by factor $\frac{100}{86} \approx 1.16$.

- Limitation: An error time is incorporated of $\frac{60}{2} = 30\ seconds$. Due to restrictions of the simulation model, a supplier can only be forwarded in the system at every whole minute. If a supplier for example has an arrival time of 13:51:07, it will be forwarded into the waiting area at 13:52:00. The waiting time of a supplier normally would be defined as follows:

$$Waiting\ Time = Arrival\ Time\ at\ Dumping\ Hole - Arrival\ TimeAtGate. \qquad (4.2)$$

However, to account for the limitation, the waiting time is reduced by 30 seconds:

$$Waiting\ Time = Arrival\ Time\ at\ Dumping\ Hole - Arrival\ Time - 00{:}00{:}30. \qquad (4.3)$$

According to equation 4.2, an average supplier would spend half a minute more waiting than they would in reality and therefore the second formula is a proper approximation.

4.4. Data Analysis

Data and processes describe the input needed for the simulation model to work according to the described model. Retrieved data per supplier are among others: Netto Tons of Waste delivered, Average Supplied Tons per Weighing, Preferred hour(s) of delivery (established by account managers) and Average Terrain Time. A data analysis was needed to gather insight into the distributions.

When specifying random input processes for the simulation, a Theoretical Probability Function (TPF) is fit to the existing data, and common data rules like the empirical rule (also known as the 68-95-99.7 rule) are used. An advantage of applying a TPF over for example using direct data is that it facilitates data generation outside the range of historical data. First of all, summary statistics are calculated and observed before the historical data are transformed into graphs to see if the data conforms to an existing known distribution. An analysis of the standard deviation and kurtosis can already exclude some distributions. Then, a histogram of the existing data is made. Additionally, a Cumulative Distribution Function (CDF) is created with the expected distribution type and its parameters. The CDF forms the basis for the expected frequency of events within every bin (interval) of the existing histogram. The expected frequency graph is added to the histogram to determine the goodness-of-fit. A (nearly) coinciding graph implies a good fit, whilst big deviations between the graphs imply no fit and having to try another distribution and its fit. Subsequently, a test can be conducted with the calculated real error and the allowed error. If the calculated error is smaller than the allowed error, this indicates no rejection of the H_0 hypothesis and therefore no rejection of the assumed distribution. In this research, the assumption has been made that no rejection of the H_0 hypothesis is equal to assuming the H_0 hypothesis. A situation in which a TPF is developed is the interarrival process of trucks. A sample is taken from the year 2024. Its summary statistics are visible in Table 4.2. Table 4.2 shows all data concerning the interarrival process of trucks.

Summary Statistics Interarrival Process B	
Mean	00:04:31
Standard Error	00:00:04
Median	00:01:58
Mode	00:00:35
Standard Deviation	00:04:04
Kurtosis	10:03:21
Skewness	22:39:46
Minimum	00:00:00
Maximum	01:01:26
Sample size	3140

Table 4.2 - Interarrival process

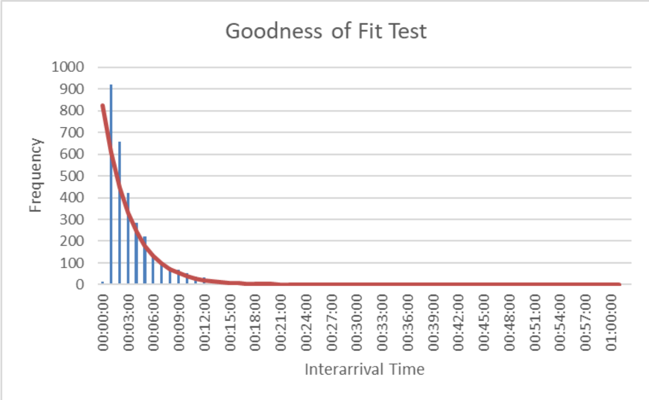

Figure 4.4 - Goodness-of-fit test

The high value for the positive skewness suggests a right-tailed distribution with no symmetry, indicating that a distribution like the normal distribution does not fit the existing data. Furthermore, the median and mode are both situated below the mean, inferring the mean not being in the middle of the distribution (and the peak being left from the mean). Evaluating the summary statistics, the exponential distribution is suggested as the most probable distribution. Figure 4.4 combines the data points (blue) with the chosen exponential distribution (red). Analyzing the graph, it is visible that in general the two graphs overlap. Therefore, the exponential distribution is assumed in the simulation model (*negexp ~ μ = 00:04:31)*.

The following distributions have been assumed in the simulation model after a thorough data analysis:

- Interarrival time of suppliers: Negative exponential distribution with $\mu = 4{:}31$.
- Number of tons delivered: Two normal distributions with $\mu_1 = 9.2$ and $\sigma_1 = 3.0$ and $probability_1 = 0.58$ and $\mu_2 = 22.6$ and $\sigma_2 = 3.5$ and $probability_2 = 0.42$.
- Bunker Availability: Uniform distribution (0,1).
- Throughput: Probability distribution function ranging from 4667 to 14000 tons.
- Processing time: normal distribution with $\mu = 7{:}33$ *and* $\sigma = 7{:}30$.
- Recovery time: normal distribution with $\mu = 3{:}07$ *and* $\sigma = 2{:}12$.

An explanation for all the selected distributions and the associated parameters can be found in Appendix A.

4.5. Model Translation

Siemens Tecnomatix Plant Simulation has been used as the tool to translate the process model from section 4.3. into a valid simulation model. With the help of Plant Simulation's programming language SimTalk 2.0, the process model including its assumptions, simplifications and limitations is translated into a simulation model.

4.6. Verification and Validation

Verification is the process of ensuring that the model behaves as intended (University of Houston, 2024). Verification is realized by making sure that the simulation model conforms to the process model, which has been established in consultation with Twence. In addition, verification of the model is realized by having error-free coding, having the model tested by a peer who is familiar with the simulation software and having performed both consistency and range checks.

Validation guarantees no significant difference exists between the designed model and the reality (University of Houston, 2024). Validation can be checked by determining whether the output of simulation Model A matches the observed historical data in Twence's analytics tool QlikSense. Regarding the model validation of Model A, three variables have been defined to monitor and compare to the observed historical data:

- Average Total Terrain Time.
- Average Throughput.
- Average Number of Weekly Suppliers Helped.

A 5%-margin for errors is taken into consideration, meaning that when the observed variables from the simulation deviate less than 5% from the historical data, the model is set to be validated.

The goodness-of-fit is determined by comparing the simulation's output to the existing data in QlikSense. However, simulation output often is not an exact match with reality for calibration reasons. Historical data study a value of 38:38 minutes for the average total terrain time, a value of 10775 tons for the average throughput and a value of 798 for the average number of weekly suppliers helped. The simulation generates an average total terrain time of 39:29, an average throughput of 10780 tons and an average number of weekly suppliers helped of 798.

Variable	Historical Data	Simulation	Deviaton
Total Terrain Time	00:38:38	00:39:29	2,2%
Throughput	10775	10780	0,0%
Suppliers Helped	761	798	4,9%

Table 4.3 - Model Validation

Table 4.3 reveals that the three defined variables are within the error bound of 5% and that therefore the designed model of the current situation is a proper approximation of reality. The model modeling time slots uses the same input values and is therefore also validated.

4.7. Experimentation and Analysis

This phase of the simulation study consists of introducing adjusted models, performing simulation runs, doing a sensitivity analysis concerning some involved variables and comparing the performances of the adjusted situation with the current situation that everyone knows.

4.7.1 Adjusted Model ~ Model B

Model B is Model A with the applications of time slots and quantity restrictions. Figure 4.5 shows a process model describing how the simulation model based on time slots and quantity restrictions is going to work. The double circle splits the process into two parts for readability purposes. Every year, volumes are being agreed on with suppliers for the upcoming year. By dividing these volumes evenly over the year, every week roughly has the same number of scheduled supplies. Subsequently, implementing time slots for trucks of suppliers guarantees more control over the inflow of supplies. Every truck is allocated a time slot of size two hours at the start of the week. Within the size of the allocated time slot, the truck is allowed to arrive at Twence. Twence's opening times remain from 7:00 until 19:00, implying that every day Twence is opened for twelve hours. Given the time slot size of two hours, every day has six time slots starting with time slot 7:00 until 9:00 and ending with time slot 17:00 until 19:00. Every time slot has a maximum number of trucks that it welcomes, namely 28. Multiplying the number of time slots per day by the maximum allowed number of trucks per time slot gives a maximum of 168 trucks allowed to visit Twence daily. Looking at historical data, this defined maximal number of trucks allowed per day should be more than enough. The daily number of trucks arriving per day is set to be between 150 and 168 to allow for some day-to-day variations. Suppliers are set to follow quantity restrictions. Yearly supplier volumes are divided by the total number of weeks in a year (52) and subsequently multiplied by 105% to account for a 5% margin (Table 4.4). If a truck arrives and exceeds its weekly allowed volume, it is rejected and sent back to its home depot.

Supplier	Tons per year	Tons per week	5%Margin
Abfallwirtschaftsbetriebe Münster	44639	858	901
Andusia	10750	207	217
CirculusBV	48100	925	971
ECO Solutions	9975	192	201
ENOS	27025	520	546
Geminor GmbH	9990	192	202
InternTAS	29900	575	604
Kockmann	16000	308	323
M van Happen	33300	640	672
Prezero	10000	192	202
Regio Twente Groep	75400	1450	1523
Remondis NL	30000	577	606
Renewi	76951	1480	1554
Rouwmaat Groep	11825	227	239
Stenau	27000	519	545
Ter Horst Milieu	25550	491	516
Van Werven	17700	340	357

Table 4.4 – Weekly Quantity Restrictions

The foundation for the allocation of time slots is according to equation 4.4:

$$Priority\ outcome = Relative\ share\ size * Twence\ \ supplier\ priority\ number * 100, \qquad (4.4)$$

where the relative share size is the number of contracted tons per supplier divided by the total year volume for the AEC and the priority number is a value given to suppliers from 1 to 5 by Twence (1 represents the lowest priority and 5 the highest priority). The suppliers with the highest outcomes regarding the formula mentioned in 4.4 are allocated the most popular time slots and the suppliers with the lowest outcomes are assigned to the least popular time slots. Every truck receives its own time slot of length two hours. The reason for the choice of two hours is based on a competitor of Twence already working with time slots. That competitor has established time slots of length two hours and has received positive feedback on the implementation and size of the time slots. Table 4.5 displays the algorithm and the outcomes. The assumptions, simplifications and limitations valid for Model A are also all valid for Model B.

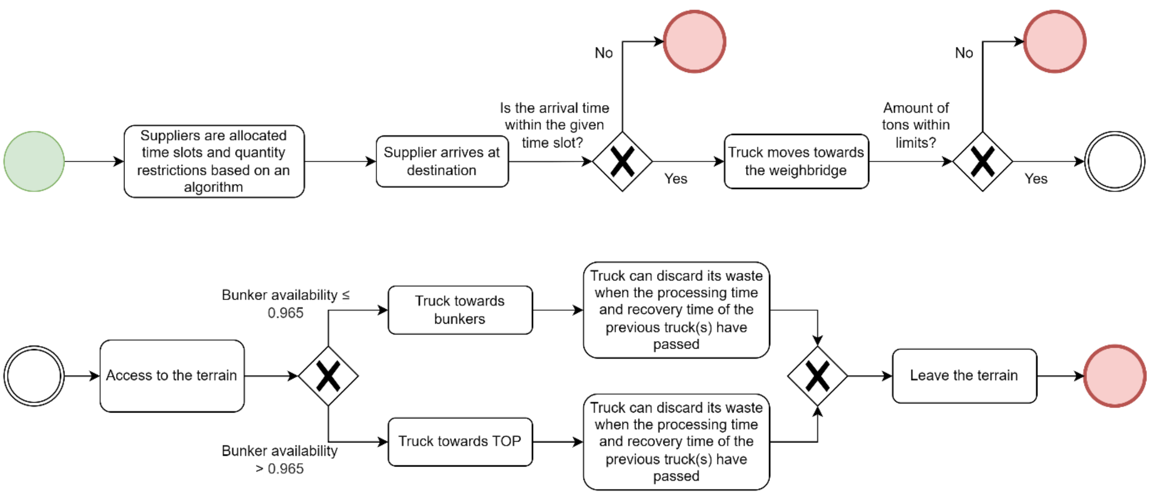

Figure 4.5 - Conceptual Model Time Slots and Quantity Restrictions

Referring to Table 4.5 again, the suppliers with the highest outcomes and $Accumulative\ share \leq 33\%$ are awarded urgency level 1, suppliers with intermediate outcomes and $33\% < Accumulative\ share \leq 67\%$ are awarded urgency level 2 and suppliers with the lowest outcomes and $Accumulative\ share > 67\%$ are awarded urgency level 3. The accumulative share rule ensures that the time slots are mostly filled with suppliers of the right urgency level.

Supplier	Share	Priority	Algorithm	Outcome	Accumulative Share	Urgency
Regio Twente Groep	15%	5	0,15 * 5 * 100	75	15%	1
Circulus BV	10%	5	0,10 * 5 * 100	48	24%	1
Abfallwirtschaftsbetriebe Münster	9%	5	0,09 * 5 * 100	44	33%	1
Renewi	15%	2	0,15 * 2 * 100	31	49%	2
Intern TAS	6%	5	0,06 * 5 * 100	30	55%	2
ENOS	5%	4	0,05 * 4 * 100	21	60%	2
M van Happen	7%	2	0,07 * 2 * 100	13	67%	2
Remondis NL	6%	2	0,06 * 2 * 100	12	72%	3
Stenau	5%	2	0,05 * 2 * 100	11	78%	3
Van Werven	4%	3	0,04 * 3 * 100	11	81%	3
Ter Horst Milieu	5%	2	0,05 * 2 * 100	10	86%	3
Kockmann GmbH	3%	3	0,03 * 3 * 100	10	90%	3
Rouwmaat Groep	2%	2	0,02 * 2 * 100	5	92%	3
Prezero	2%	2	0,02 * 2 * 100	4	94%	3
Andusia	2%	1	0,02 * 1 * 100	2	96%	3
Geminor GmbH	2%	1	0,02 * 1 * 100	2	98%	3
ECO Solutions	2%	1	0,02 * 1 * 100	2	100%	3

Table 4.5 - Priority Rule

Table 4.6 shows the popularity of the specified time slots, where e.g. during the period 13:00 – 15:00 most suppliers pass the weighbridge. The suppliers with the highest urgency (Urgency = 1) receive the most popular time slots, which are the time slots with popularity numbers 1 and 2 (Table 4.6). Subsequently, suppliers with urgency level 2 obtain the time slots with popularity 3 and 4 and last suppliers with urgency level 3 obtain the time slots with popularity 5 and 6.

Time Slot	Weightings per Time Slot	Share	Populartiy	Urgency
07:00 - 09:00	4539	22%	2	1
09:00 - 11:00	4218	20%	3	2
11:00 - 13:00	3586	17%	4	2
13:00 - 15:00	4699	23%	1	1
15:00 - 17:00	2813	13%	5	3
17:00 - 19:00	959	5%	6	3

Table 4.6 - Time Slot Popularity

When a truck from a particular supplier requests a waste delivery, its urgency level is evaluated, and an assessment is made on the availability of time slots. To evenly spread suppliers over the day and thus obtain a more controllable bunker and lower waiting times, a maximum of 28 suppliers are planned per time slot. A truck of a supplier always gets the most popular time slot within the bounds of their urgency level, if it is not full yet. Otherwise, the availability of the time slot $Popularity + 1$ is checked.

An example of time slot allocation: A truck working for supplier M. van Happen registers for the next week that it would like to deliver waste. Twence receives a notification that a truck from M. van Happen wants to discard waste. Subsequently, Twence first looks at Table 4.5 to determine the urgency level of M. van Happen, which turns out to be 2. Then, Twence checks which time slots belong to the urgency level. Table 4.6 shows that time slots 09:00 – 11:00 and 11:00 – 13:00 refer to urgency level 2. Since 09:00 – 11:00 is the more popular time slot, Twence first looks if there is a spot left on Monday at 09:00 – 11:00. In the case that this time slot has 27 or less trucks registered, the truck is appointed time slot Monday 09:00 – 11:00. Elseif, Twence observes if time 11:00 – 13:00 still has space left (again <27). If this time period is full as well, Twence moves on to Tuesday to time slot 09:00 – 11:00 and sees whether the truck can be scheduled for this time slot. This sequence continues for the remaining working days until a free time slot is found.

When a truck arrives at Twence, it is being weighed, where the weigh-in time represents the time of arrival. If this time is within the allocated time slot, the supplier moves to the next step. Reversely, if the supplier arrives outside of the time slot, it is removed from the system and must discard the waste at another moment. Every supplier has a weekly maximum number of tons that they can bring. Exceeding the total maximum amount, results in the truck being rejected and taken out of the system. It is also at this moment in time that the total supplies per week per supplier are updated. If a truck holds a number of tons that is within the weekly supply limits, the truck joins the queue waiting to discharge the waste. To be able to fairly compare the results of the simulation models, this model also uses the number 0.965 as a criterion for TOP or the bunkers. After depositing the waste, the truck leaves the system at departure. However, it is expected that when time slots are implemented, supply streams are more predictable, probably resulting in TOP not being used with a frequency of 0.035 anymore, but a lower frequency.

4.7.2. Experimental Setup

Elements that need to be defined before experimenting with the simulation and analyzing its output are the simulation's warm-up time, the run length and the number of replications. A simulation's warm-up period is defined as the required start-up time before a model reaches a steady state (Robinson, 2014); it is applied when the model starts empty, but the modeled system (reality) does not start empty. An empty model is a model with all defined variables being zero and a run time of zero. The run length of the simulation is the time that passes in the simulation between its start time and end time (Robinson, 2014). The number of replications involves running a simulation scenario several times with different seed values with corresponding different random number streams. A correctly chosen number of replications guarantees accuracy and precision (Robinson, 2014).

In this case, the simulation is made as a terminating simulation, which ends after one working week of supplies. The simulation intends to observe how the arrival of supplies throughout the week takes place and what the effect of time slots is on the average waiting time of a supplier. There is no need to extend the run time of the simulation as every week consists of the same operations. Several replications of the simulation model's output yield a reliable outcome.

The simulation run length of the model is equal to the number of days in the week that supplies are allowed to be brought to Twence, which is five days. Within these five days, the arrival of supplies is admitted on every day between 7:00 and 19:00. However, the run time of the model itself only takes a few minutes.

The number of replications typically depends on the variability and the level of precision (allowed error) between the different kinds of output. A high level of variability asks for a higher number of replications, whereas a low level of variability requires a lower number of replications. Logically, a high level of precision requires more replications than a lower level of precision. In this simulation, a confidence interval of 95% is chosen, where $\alpha = 0.05$.

According to Asadi (2023), an estimation for the number of replications needs to consider the student distribution with one degree of freedom, the standard deviation of the taken sample, the motivated relative error and the sample mean. The estimation for the number of replications is defined as follows:

$$n^* = \left(\frac{t_{n-1,\frac{1-\alpha}{2}}\sqrt{S_n^2}}{d|X_n|}\right)^2 \quad (4.5)$$

A sample of size $n = 100$ and $d = 0.05$, yields $t_{n-1,\frac{1-\alpha}{2}} = 1.984$, $\sqrt{S_n^2} = 17507$, $|X_n| = 463.19$, where $t_{n-1,\frac{1-\alpha}{2}} = outcome\ of\ the\ student\ distribution$, $S_n^2 = sample\ variance$ and $X_n = sample\ mean$.
Filling in these input values, results in $n^* = 128$. The exact number of replications required is determined utilizing the sequential procedure. The sequential procedure determines for every n the outcome until:

$$\frac{t_{n-1,(1-\alpha)/2}\sqrt{S_n^2/i}}{|X_n|} < d, \quad (4.6)$$

where $\alpha = 0.05$ and $i = number\ of\ observations$.

Thoroughly executing the sequential procedure results into $n^* = 122$. The number of replications for the experiments is fixed at the value $n^* = 122$.

In short, for the execution of the simulation, there is no warm-up period required, the run length is equal to five days and the number of replications is determined at 122.

4.7.3. Output Comparison of Model A with Model B

This analysis runs Model A and simultaneously also runs Model B and thereby discovers whether the application of time slots and quantity restrictions pays off. In this experiment the output of the two models is compared in three variables, namely:

- Spread of supplies throughout the week (measured as the standard deviation between a week of supplies).
- Supplier waiting time.
- Supplier terrain time.

Model	Variable	Mean	Standard Deviation	Minimum	Maximum
Model A	Spread of supplies	228	-	180	286
Model B	Spread of supplies	87	-	59	125
Model A	Waiting Time	00:21:14	00:10:29	00:06:30	01:19:40
Model B	Waiting Time	00:13:05	00:02:42	00:07:58	00:21:42
Model A	Terrain Time	00:39:29	00:10:33	00:24:39	01:38:19
Model B	Terrain Time	00:31:19	00:02:49	00:26:08	00:40:19

Table 4.7 – Output Model A & B

Table 4.7 displays the results for the spread of supplies, waiting time and terrain time for both models. First of all, the spread of supplies is expressed as the standard deviation of a week of daily supplies and is present under the mean in the table (which is the reason why the standard deviation is empty). The more evenly distributed the arrival of supplies throughout the week, the lower the standard deviation. The standard deviation is measured over the five days of supply arrivals. Model B yields a standard deviation of 87 tons, whereas Model A returns a standard deviation of 228 tons: a decrease of 62%. The standard deviation of Model A deviates from historical data since the model cannot account for unprojected activities. In addition, it is visible that the mean waiting time for Model B is eight minutes less than the waiting time for Model A. Furthermore, the standard deviation is almost four times as small, which causes the waiting time interval of the time slots to be relatively small. The terrain time for Model B is also approximately eight minutes smaller, since the processing time and terrain time for both models is equal.

In short, the introduction of time slots yields a waiting time reduction of approximately 40%, a total terrain time reduction of approximately 20% and a standard deviation of the waiting time and terrain time which is roughly 4 times as small. The standard deviation of supply distribution throughout the week is reduced by approximately 62% by the implementation of time slots.

4.7.4. Sensitivity Analysis

Four sensitivity analyses are conducted regarding Models A & B. The first analysis concerns a sensitivity analysis of the size of the time slot and observes the possible consequences to output variables. Analysis two relates to a study concerning the width of the interval of the number of trucks arriving daily, whereas analysis three assumes a fixed throughput and assesses for both models the relative bunker growth. Lastly, factors that could be subject to change in the short term due to revised technologies and innovation are modified.

Analysis 1: Varying Time Slot Size

This analysis concerns Model B and varies the size of the time slots. Highlighted in the table is the time slot of size two hours, which is the size used in model B. Observations are done for time slots of size half an hour, one hour, two hours and four hours. The purpose of this sensitivity analysis is to see what an increase or decrease in time slot size would do to the mean and standard deviation of the waiting time

Size of Time Slot	Mean	Standard Deviation
1/2 hours	00:10:20	00:02:24
1 hour	00:11:56	00:02:31
2 hours	**00:13:05**	**00:02:42**
4 hours	00:14:01	00:02:56

Table 4.8 – Analysis 1 Output

Table 4.8 shows that the smaller the size of the time slot, the smaller the waiting time becomes. A time slot of size two hours has been chosen as the foundation for the remainder of the analyses since its size is not too narrow and therefore does not completely ignore suppliers' flexibility and one of Twence's competitors called AEB also operates with time slots of this size and for them and their suppliers it works out.

Analysis 2: Varying Interval of Number of Daily Arrivals

This analysis is executed for Model B and investigates what happens to the spread of supplies throughout the week if there is a better or worse indication of the number of arriving suppliers in the week. Table 4.9 shows the output of the executed analysis. For determining the standard deviation, equation 4.7 has been applied:

$$\sigma = \sqrt{\frac{1}{5} * \sum_{i=1}^{5} (x_i - \mu)^2}, \qquad (4.7)$$

where x_i represents the number of supplies on day i and μ represents the average number of supplies.

Experiment #	Input	Standard Deviation
Experiment 1	Negexp ~ (160, 158, 162)	39
Experiment 2	Negexp ~ (160, 155, 165)	71
Experiment 3	**Negexp ~ (160, 150, 168)**	**87**
Experiment 4	Negexp ~ (160, 145, 168)	97
Experiment 5	Negexp ~ (160, 130, 168)	177

Table 4.9 - Analysis 2 Output

Again, the highlighted input is the input used in Model B. The input must be interpreted as the negative exponential distribution with $\mu = 160$ arriving suppliers, $min = 150$ arriving suppliers and $max = 168$ arriving suppliers. In experiment one the interval has width five, meaning that the number of daily arriving trucks can only have five outcomes, namely 158, 159, 160, 161 or 162 trucks. Due to this reduction in options, the standard deviation of daily supplies is reduced from 87 tons to 39 tons. Reversely, it can be seen that when increasing the interval and thereby the number of options, the standard deviation of daily supplies increases.

In short, a strict time slot division including a fixed daily number of arriving suppliers (within a tight interval) causes a lower standard deviation and therefore a better division of supplies throughout the week.

Analysis 3: Bunker Growth

In both simulation models, throughput is uncertain and fluctuates from week to week, making the bunker growth a difficult variable to assess. In this analysis, the throughput is set at 10800, which is the average weekly throughput through the years 2023 – 2024. The weekly Bunker Growth: $Weekly\ Bunker\ Growth = Total\ Number\ of\ Supplies - 10800$ *(4.8)*

The purpose of this experiment is to determine via 4.8 whether the models substantially differ in terms of the mean weekly bunker growth and the standard deviation of bunker growth. Bunker growth is a valuable measure to decide the utilization of TOP and is expressed in tons.

Type of Model	Mean	Standard Deviation
Current Situation	388	443
Time Slots	343	238

Table 4.10 - Analysis 3 Output

Table 4.10 displays the results of the experiment. It shows a clear discrepancy between the standard deviation of the current situation and of the time slots; the current situation has a standard deviation that is almost twice as high. A higher standard deviation leads to an increased probability of the need for TOP, since there is a bigger chance of obtaining high bunker levels in consecutive weeks. Therefore, the probability of TOP utilization decreases with the application of time slots. This experiment also displays that the bunker level varies less when time slots and quantity restrictions are applied, since the bunker growth influences the bunker level. A less varying bunker level implies more bunker certainty.

Analysis 4: Other Options

Factors, whose values are likely to be adjusted in the short-term due to for example technology advancements or making different decisions have been investigated during analysis four. Both factors influence the waiting time for suppliers. These factors concern:

- The failure rate of the dump holes (FR).
- The recovery time (RT).

The failure rate corresponds to for example a dump hole temporarily not being accessible due to it being fully packed from the bunker side (Figure 4.6 shows that the most left dump hole is inaccessible due to it being fully packed). The recovery time is defined as the time needed between the departure of a truck from a dump hole and the arrival of a new truck at the same dump hole. During the recovery time, the crane operator empties the dump hole from the bunker side, such that a new truck can discard its waste. The input for the factors varies around the actual value, which is equal to the input value used in the simulation model (the number in bold). Table 4.11 shows the results of the experiments. Through the OFAT method, each factor is separately assessed on its contribution to the change in output value. In this way, the interaction effect is erased. The output is measured in minutes.

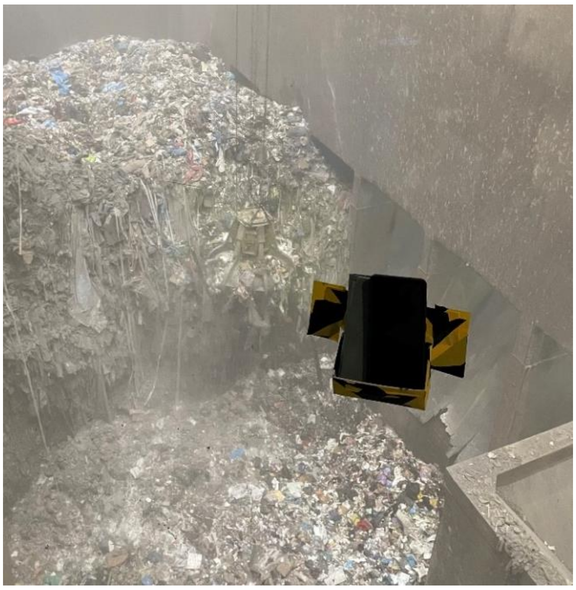

Figure 4.6 - Bunker from the inside

Factor	Input	Mean	Standard Deviation
Failure Rate	0%	00:10:04	00:01:49
	3%	00:11:54	00:02:16
	5%	**00:13:05**	**00:02:42**
	10%	00:17:44	00:03:14
	20%	00:33:47	00:05:14
Recovery Time	00:02:00	00:08:06	00:01:24
	00:02:30	00:09:47	00:01:41
	00:03:07	**00:13:05**	**00:02:42**
	00:04:00	00:20:14	00:03:46
	00:04:30	00:25:56	00:04:36

Table 4.11 – Analysis 4 Output

The output displays that a maximal decrease in failure rate brings the average waiting time to a value of approximately ten minutes. Reversely, an increase in failure rate increases the waiting time. Also, it is noticed that the relationship between failure rate and waiting time seems to be linear, looking at the spread of percentages and waiting times. Regarding the recovery time, it is visible that a relatively small change in recovery time causes a big change in waiting time.

5. Solution Results regarding KPIs

This chapter provides information regarding the results of the analyses in Section 4.7 and targets to formulate a solution given the results. Section 5.1 shows the defined KPIs for the simulation models followed up by a comparison. Secondly, Section 5.2 concludes the section with a description of the solution. Lastly, Section 5.3 assesses whether the conclusion in Section 5.2 matches with earlier conducted researchers on a similar topic.

5.1. Performance Supply Chain KPIs

The purpose of the application of time slots is to create a better division of waste over the week and to have a smaller interval of the number of supplies delivered at the end of the week. The purpose of the quantity restrictions is to have a fixed maximum number of supplies that cannot be exceeded. To make up for the loss of flexibility in arrival time encountered by suppliers, the waiting time is reduced with the application of time slots such that suppliers waste less time queuing. Defined KPIs to express planning predictability and observe the difference between the two situations are:

- Supply Standard Deviation (SSD).
- Maximum Deviation (MD).
- Maximum Time Period (MTP).
- Ratio of Peaks (RoO).
- End of Week Supplies Standard Deviation (ESSD).
- Terrain Time (TT).

In section 2.4 the KPIs for the current situation have already been defined and calculated. The upper row of Table 5.1 has been taken from the output found in Section 2.4. The middle row is completed with output from simulation model B. The lower row indicates the objective value in an ideal world.

Situation	SSD (tons)	MD (tons)	MTP (days)	RoO	ESSD (tons)	TT (minutes)	WT (minutes)
Current	267	675	3	2 : 0	310	00:38:38	00:21:14
Time Slots	87	139	1	0 : 0	113	00:31:19	00:13:05
Objective	0	0	0	0 : 0	0	00:18:00	00:00:00

Table 5.1 - KPI comparison

One noticeable characteristic of the table is that the “Time Slots” row contains all the lower values and the upper row contains all the higher values. As stated in Section 2.4, it is for all defined KPIs best to have an as low as possible value, since such would mean that the supplies follow a more constant pattern and are therefore better predictable. Furthermore, the size of the difference also catches the attention; for some of the KPIs, the time slots’ output is a factor three smaller or even a factor higher than three smaller.

The SSD describes the build-up of supplies throughout the week. A standard deviation of 267 for the current situation indicates that 267 tons is the average amount for a day in the week to be off the target value. Evaluating the same KPI with the application of time slots yields a value that is three times as small: 87. Time slots cause the daily precision of supplies to increase.

The MD illustrates the maximal deviation that realized supplies on a day of the week deviate from scheduled supplies. For the current situation that number is equal to 675 tons, which is approximately 30% of an average day’s supplies (~ 2200 tons). The time slots model only has an average maximum deviation of 139 tons, which is a value almost five times as small.

MTP outlines a streak of days where the arrival of supplies is structurally above or below the reference value of 20%. An average value of three days is obtained for the current situation, whereas an average value of only one day is obtained for the time slot situation. So, in the time slots case, a supplier does not structurally deliver too much or too low, meaning that the final number of supplies must be close to the expected number of supplies.

RoO is defined as the ratio to which positive supply peaks and negative supply peaks relate. A positive peak happens when instead of the aim of 20% of supplies on a day, 25% or more is delivered. Similarly, a negative peak is created when 15% or less is supplied. The mode value for the current situation is 2:0, whilst the mode value for time slots is 0:0 and no other value than 0:0 has been observed for time slots.

The ESSD assesses the end volumes of weekly supplies. Subsequently, the standard deviation of all the end volumes in the sample is determined. The current situation averages a standard deviation of 310 and the time slots model yields a standard deviation of 113. This indicates that on average consecutive weeks only vary by 1% (given that average supplies are 10800 tons) for time slots. The decrease in standard deviation indicates that the probability of an outlier and especially the probability of two outliers occurring after each other is very small. This induces that the probability of using TOP decreases as well, since TOP is often used when there is a longer period of oversupplies.

Lastly, the total time of the suppliers at Twence's terrain is set to be the departure time minus the arrival time, which is equal to the summation of the waiting time, the processing time and the travel time on the terrain (equation 4.1). Since the implementation of time slots has had no effect on the processing time and the terrain time, the difference in terrain time is fully devoted to the waiting time. Using the time slots, the terrain time drops from 38:38 to 31:19. Therefore, waiting time should be reduced by approximately seven minutes as well. According to the simulation output of the current situation, the waiting time is 21:14 minutes. The time slot model yields a waiting time of 13:05 minutes. In short, time slots cause the waiting time to reduce by roughly 40% and thereby cause the terrain time to decrease by the same amount of time and with a percentage of roughly 20% (Figure 5.1). Finally, it must be noted that the waiting time from the simulation model is taken, because Twence does not have data concerning the waiting time.

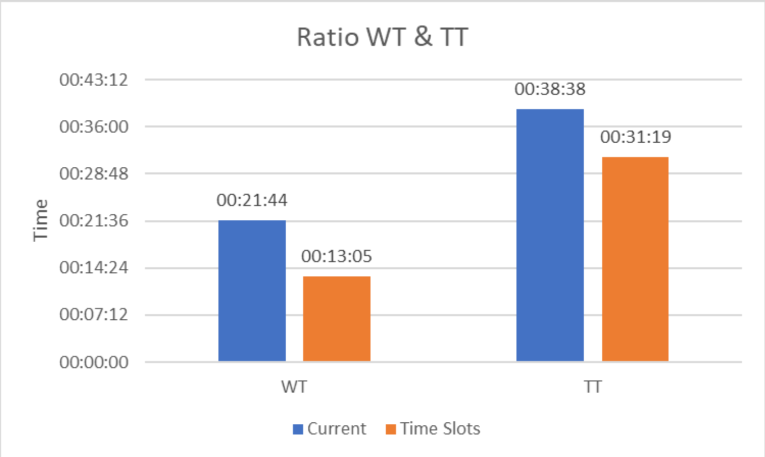

Figure 5.1 - WT and TT

5.2. Conclusion

This thesis aims to find an answer to the research question: "How can Twence increase planning predictability of waste supply to have a better-operating bunker management?" Subsequently, this answer should provide a foundation for tackling the problem of having an uncontrollable bunker management.

By means of following the research design described in Section 1.3.1, the research has been executed in a structured manner. The sub-questions, together, form a basis for the answering of the main research question. An analysis of the current situation of supply handling found out that the mismatch in supplies especially occurs on a weekly basis and that the arrival of supplies is mostly unknown. Moreover, the literature review identified ways to decrease uncertainty in demand, techniques how to improve demand forecasting, supply planning factors, theories about the application of time slots and investigated cases in which DES techniques are often applied. Next, a model of the to-be-designed "improved model" including time slots and quantity restrictions was designed, which established the making of the simulation model. In the end, two simulation models were developed: one model representing the current situation and one model representing the situation in which time slots and quantity restrictions are being applied. Inserting the same input data and distributions in both simulation models, resulted in a fair comparison of the two model's outcomes. Also, a sensitivity analysis was performed regarding the newly developed situation.

A comparison of the two models yielded a reduction in day-to-day supply standard deviation (SSD) from 267 to 87. Furthermore, the number of outliers in the number of tons supplied is strictly reduced and the maximal average deviation of supplies in a week is reduced by a factor of five. Moreover, the differences in end volumes on a weekly basis are represented by the standard deviation. Time slots score a standard deviation of 113, whereas the current situation registers a standard deviation of 310. Evaluating the growth of the bunker, the standard deviation for time slots is almost twice as small as it is for the current situation. A smaller standard deviation induces the probability of making a detour to TOP to decrease. Also, the smaller bunker growth standard deviation yields more certainty in the bunker. Lastly, an evaluation of the difference in waiting time. Time slots cause a reduction in waiting time of more than eight minutes from an average of 21:14 minutes to an average of 13:05 minutes.

Taking all of the results into consideration, it can be stated that with the help of time slots and quantity restrictions, weekly predictability of supplies is increased and therefore yearly predictability is increased as well. Time slots cause a more even spread of supplies throughout the day and the week, bring certainty about the delivery time of supplies and in addition create a more constant end-week volume of supplies. Quantity restrictions lead to suppliers not being able to discard more than their weekly contracted portion, thereby guaranteeing a maximum end volume of supplies. The effects created by the time slots and quantity restrictions lead to more certainty at the front of Twence's supply chain and suffice to create more certainty later in the supply chain. By capturing uncertainty at the front of the supply chain, the bunker level is more influenceable and therefore the bunker management is more controllable.

5.3. Discussion

This research assignment intended to find a solution for the low supplies planning predictability. As a tool, time slots with quantity restrictions for incoming supplies were implemented into Twence's operations. The conclusion is that time slots not only increase supply predictability, but also offer an improved build-up of supplies throughout the week. An improved supply predictability means that Twence can (partly) solve its main problem of uncertainty in its bunker management. A higher certainty level of supplies leads to more certainty in the bunker.

A prerequisite for a research contribution is that it is a meaningful addition to a specific area of study, which boosts current knowledge (Hassan, 2024). This thesis contributes to research as it intends to demonstrate that for (industrial) companies dealing with supply uncertainties, time slots with quantity restrictions might be a good option to reduce supply uncertainty. The feasibility of time slots must be assessed on the grounds of the following aspects:

- Size of the company: Is the company big enough to demand from its customers to deliver according to time slots?
- Alternative suppliers: Are there alternative suppliers in the market and what is their price?
- Size of suppliers: Is the supplier big enough to be able to deal with time slots?
- Type of industry: What is the norm in the industry and is there a monopoly?

Previous works suggest that suppliers benefit from time slots in the sense of reduced waiting times and reduced congestion (Cunnane, 2022). These reduced waiting times for suppliers can be invested in driving another round of waste collection, thereby increasing working efficiency. Referring to this research, also a reduced waiting time for suppliers was found. Per Crossley (2023), a negative aspect of time slots is the limited flexibility offered to suppliers. However, Crossley (2023) also mentions that the company allocating time slots encounters advantages like predictable scheduling, no overbooking and enhanced planning. Looking at the research conducted, the defined KPIs suggest a more predictable scheduling of supplies.

Comparing the outcome of this research to outcomes of similar related studies produces comparable results. However, the theory also suggests that suppliers experience limited flexibility. Unfortunately, during this research, no information is retrieved about supplier satisfaction (excluding one supplier) concerning the possible introduction of time slots. Therefore, an improvement for this research would be to ask suppliers using a survey what they think of the introduction of time slots. Crucial is to emphasize what is in it for the suppliers: describe the advantages and ask the suppliers to make a fair assessment. Additionally, follow-up research can be conducted after the stimulus of money. Whereas in the newly developed model including time slots (Model B) there is no room for arrival outside of the given time slot, it would be refreshing to investigate allowance outside of the assigned time slot. If a truck arrives outside of the allocated time slot, it is still able to discard its waste, but this time for an increased tariff of e.g. 110% of the regular price (including a time penalty of 10%). The idea is that the supplier responsible for the late arriving truck pays for the inconsistency in Twence's operations that it creates (and for the potential detour to TOP). In this case, the supplier gets the option to deliver within the allocated time slot and pay the regular price, or to deliver outside of the allocated time slot and receive a penalty totaling the price up to 110%.

6. Recommendation and Implementation

Chapter 6 intends to join theory with practice in the form of an advice and implementation plan. The results and solutions in Chapter 5 are translated to practical solutions, used by the working personnel. Firstly, Section 6.1 describes a general recommendation plus a motivation for that recommendation. Secondly, Section 6.2 specifies the parties that are subject to the changes that the proposed model brings. Thirdly, Section 6.3 outlines a plan for how to modify the theory to practice for the parties involved.

6.1. General Advice

It has been proven that the application of time slots in combination with quantity restrictions has a significant positive impact on output variables like the daily number of supplies and the waiting time for suppliers. Time slots and quantity restrictions benefit the company implementing it by gaining a better indication of the total number of weekly supplies, gaining more insight into the build-up of supplies during the week, having less congestion on the terrain itself and in general experiencing more certainty in the supply chain. For the company realizing the change there are no direct disadvantages to the change. On the other hand, the supplier does encounter a disadvantage in the sense of reduced flexibility of delivery. The reduced flexibility of delivery induces fewer peak times and therefore brings the positives of a lower waiting time and a higher reliability of delivery. The suppliers experience a trade-off between flexibility and waiting time: a lower level of flexibility creates a lower waiting time, whereas a higher level of flexibility yields a higher waiting time.

Because of its immense impact on the executing company, which is in this case Twence, time slots and quantity restrictions cannot be ignored and therefore are recommended to be implemented into Twence’s day-to-day business. Two hours is chosen as the time slot size, since it provides a big reduction in waiting time and at the same time provides an acceptable level of flexibility, given the fact that most suppliers are located within a radius of 60 kilometers from Twence. However, it must be noted that it is of high importance to continuously monitor the defined KPIs, supplier satisfaction and time slot feasibility. Indications for the trial of another time slot size are reduced supplier satisfaction and/or a limited number of trucks arriving within their assigned time slot. Also, it is essential to run trial runs beforehand and slowly introduce the “new delivery rules” such that the suppliers can get accustomed to them. Trial runs should be executed with only a part of the whole supplier population. A slow introduction to the new measures can be done by at first only applying time slots for one day in the week and expanding from there. Another option is to start with time slots of size six hours and gradually decrease them with time.

6.2. Parties Involved

The idea of implementing time slots and quantity restrictions into the current system requires some departments within Twence and Twence’s suppliers to (temporarily) adjust their day-to-day activities. The influenced groups are:

- Account Managers. Their work consists of acquiring customers (suppliers), agreeing on yearly volumes and maintaining contacts with the suppliers. The change in supply delivery from unknown to time slots demands Account Managers to announce the change to the suppliers in their portfolio and convince them that it is best for all parties. Subsequently, they are asked to maintain regular contact moments to monitor supplier opinions about the change in delivery style.
- IT department. Day-to-day working activities regarding the supply chain are arranging the SAP environment and maintaining QlikSense. The switch to time slots causes IT personnel to adjust and change the SAP environment. SAP should be able to register suppliers, appoint time slots and monitor weekly supplies per supplier. IT should find a way to incorporate a booking system for the suppliers in either SAP or a new tool. SAP can work with time slots and the booking system of time slots.

- Operators at the dump floor. Operators check the type and quality of waste of the incoming trucks and appoint a dump hole to a truck. Time slots generate a more even spread of waste supplies throughout the day and week, resulting in lower waiting times and therefore a lowered working pressure. Operators have more time to check the waste's quality, which causes more insight into what exactly every supplier brings. The result is that suppliers have better fitting contracts and that operators experience less hustle and bustle on the work floor.
- Sales. Sales' planning department is responsible for dividing the waste supplies over the year and monitoring waste supplies throughout the week. With the introduction of time slots, the time needed for the planning of supplies is reduced. More time can be invested in communication with suppliers. In the case of for example another explosion in the burning installation, Sales' planning department needs to deviate from the created time slot scheme and manually allocate weekly volumes to its suppliers.
- Suppliers. Suppliers arrive with their filled trucks at Twence hoping to discard their waste. Given the switch to time slots, suppliers are affected in terms of flexibility. Suppliers are required to improve their planning ability, as trucks are only welcome within a bound of two hours, instead of the earlier sixty hours (full week).
- U&L. Personnel of U&L arrange all the movements of material over the terrain. This includes guiding the supply process of trucks. Time slots, theoretically, create less movements towards TOP and fewer queues. The result is that U&L employees can concentrate more on their initial working activities and less on non-essential issues.
- Weighbridge personnel. Current main operations for the weighbridge employees include the administration of incoming suppliers and the weighing of trucks. The introduction of time slots produces certainty in the weekly number of arriving trucks at the start of the week. Knowing that, yields a better fitting division of tasks over the week. In addition, weighbridge personnel are exposed to a new element, which is the rejection of trucks. In such a case, the employees should request the truck to turn around and book a new time slot.
- More. Possibly more departments are involved in the transition to time slots. However, those have a rather small impact or are not directly involved in the supply chain and therefore have not been incorporated.

6.3. Implementation Plan

The solution found in this research can be translated into an implementation plan representing eleven steps. The implementation plan can be found in Table 6.1.

Step	*Description*	*Elaboration*
1	**Internal Communication**	Communicate the decision of switching the delivery of supplies based on time slots and quantity restrictions, internally.
2	**Inform the affected departments of the projected changes**	The impacted departments are informed and the expected changes in work tasks are communicated.
3	**Training programs and workshops**	The people whose tasks are significantly changing receive training or workshops on how to best execute the additional/substitute activities.
4	**Supplier Selection**	Determine which suppliers to incorporate for time slots (e.g. exclude municipal suppliers).
5	**Development of a new SAP environment**	A new SAP module is developed, which accounts for time slots, quantity restrictions and the booking of time slots.
6	**Trial run with internal trucks**	Experiment with the new SAP module by allocating time slots to internal "Intern TAS" trucks. The goal is to remove errors and optimize the working of the newly designed system.

7	**External communication with suppliers**	Timely inform the suppliers about the change in the delivery of supplies. Emphasize the motivation of a more controllable bunker and the advantages for the supplier of a more reliable delivery and a lowered waiting time.
8	**Introduction of time slots**	Carefully assess the best way of calmly introducing the new measures (time slots and quantity restrictions).
9	**Monitoring**	Foster an optimal collaboration by monitoring supplier satisfaction and opinions. Additionally, keep track of the KPIs. Weekly come into contact and ask about the encountered challenges.
10	**Make improvements/changes**	Based on the supplier input and the KPIs, improvements can be made which benefit all parties.
11	**Scaling up**	Step-by-step approach the recommended solution of time slots of size two hours for the selected group of suppliers.

Table 6.1 - Implementation Plan

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Appendix A – Distribution Choices

Data used for analyzing the fitting of distributions is merely coming from QlikSense. Depending on the number of data points, the period of observations has been established. Furthermore, the following selection criteria have been selected: 1) only waste intended for the AEC (including TOP) is considered and 2) only suppliers that are scheduled to deliver at least (rounded) 2% of the total yearly supplies are considered as relevant data points.

The Interarrival Process of Suppliers

The Interarrival Process of Suppliers is represented as an exponential distribution. The simulation model includes the Interarrival time as a negative exponential distribution with $\mu = 4{:}31\ minutes$.

Summary Statistics	Column1
Mean	00:04:31
Median	00:01:58
Mode	00:00:35
Standard Deviation	00:04:04
Kurtosis	10:03:21
Skewness	22:39:46
Minimum	00:00:00
Maximum	01:01:26
Sample Size	3140

Table A.1 - Interarrival Process

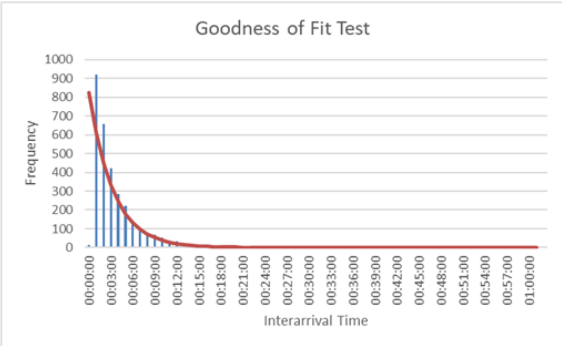

Figure A.1 - Goodness-of-fit test

Distribution of the Number of Tons

The Number of Tons supplied is represented as two normal distributions with means $\mu_1 = 9.2$ and $\mu_2 = 22.6$ and standard deviations $\sigma_1 = 2.9$ and $\sigma_2 = 3.5$. The black line indicates the dividing line between the left and right distribution. The area under the left normal distribution is relatively 58%, whilst the area under the right normal distribution is 42%. The distributions are processed into the simulation software by implementing a variable x which varies between 0 and 1. A value $x \leq 0.58$ takes the left normal distribution as input, whilst a value $x > 0.58$ takes the right normal distribution.

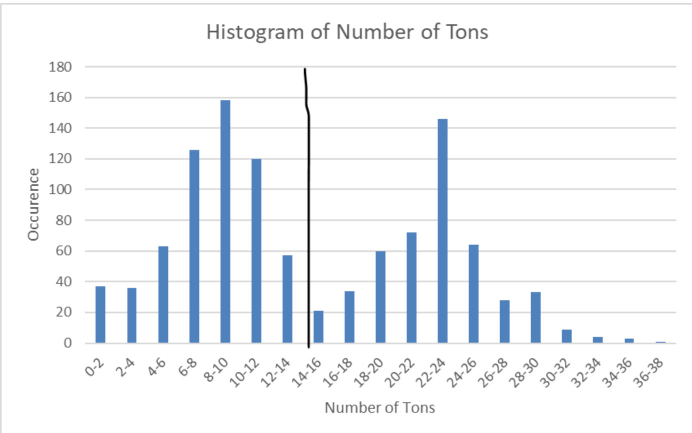

Figure A.2 - Number of tons distribution

Throughput

The total throughput per week is represented as a probability distribution function. The summary statistics of the throughput are visible in Table A.2 The throughput does not have a clear-cut distribution and therefore the following has been implemented: With probability x interval y is being chosen (Table A.3). Subsequently, the uniform distribution determines which number in the interval is taken as throughput.

Summary Statistics	Column1
Mean	10775
Median	11452
Standard Deviation	1986
Kurtosis	1,35
Skewness	-1,36
Minimum	4667
Maximum	13701
Sample Size	77

Table A.2 - Throughput

x	y
0 < x ≤ 0.05	U [4667, 6500]
0.05 < x ≤ 0.09	U [6500, 7000]
0.09 < x ≤ 0.10	U [7000, 7500]
0.10 < x ≤ 0.13	U [7500, 8000]
0.13 < x ≤ 0.16	U [8000, 8500]
0.16 < x ≤ 0.17	U [8500, 9000]
0.17 < x ≤ 0.18	U [9000, 9500]
0.18 < x ≤ 0.23	U [9500, 10000]
0.23 < x ≤ 0.30	U [10000, 10500]
0.30 < x ≤ 0.36	U [10500, 11000]
0.36 < x ≤ 0.52	U [11000, 11500]
0.52 < x ≤ 0.77	U [11500, 12000]
0.77 < x ≤ 0.87	U [12000, 12500]
0.87 < x ≤ 0.96	U [12500, 13000]
0.96 < x ≤ 0.99	U [13000, 13500]
0.99 < x ≤ 1.00	U [13500, 14000]

Table A.3 - Distribution choice

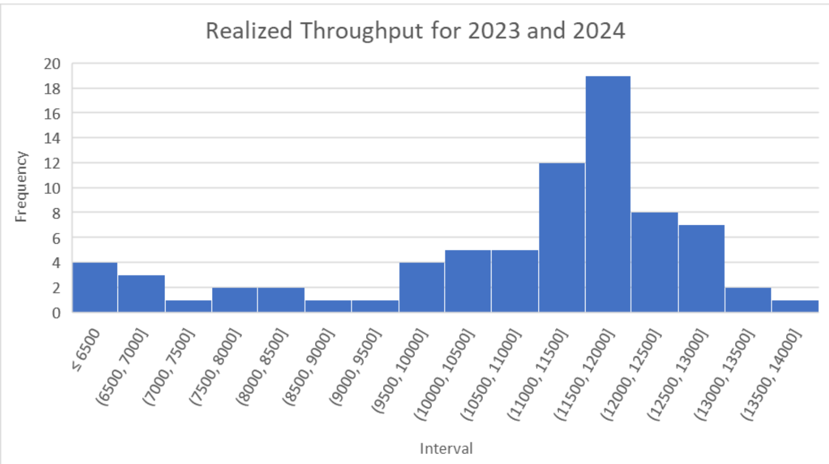

Figure A.3 - Throughput Distribution

Processing and Recovery Time

There is no data available concerning the processing time of trucks at the working stations in the data gathering tool QlikSense. With the help of interviews, Table A.4 was constructed, displaying the processing time needed per type of truck. It was agreed upon to assume the normal distribution for the processing time, with: weighted $\mu = 9{:}02\ minutes$ (derived from the table), $\sigma = 6{:}35\ minutes$ (derived from the table), $minimum = 5{:}00\ minutes$ and a $maximum = 35{:}00\ minutes$. Table A.4 also shows the recovery time needed for the crane operator to remove the waste from the end of the dump hole before another truck can enter the unloading space. Again, the normal distribution is assumed with parameters $\mu = 3{:}41\ minutes,\ \sigma = 2{:}08\ minutes,\ minimum = 0{:}00\ minutes\ and\ maximum = 8{:}00\ minutes$.

Type of Truck	Relative Frequency	Processing Time	Recovery Time
Refusal Truck	48%	00:06:00	00:02:30
Walking Floor	17%	00:20:00	00:07:00
Double Container	20%	00:10:00	00:05:00
Single Container	15%	00:05:00	00:02:00

Table A.4 - Processing and Recovery Time

Bunker Availability

From history, it can be taken that in 3.5% of the cases, a truck is redirected to move towards TOP. The bunker availability function can be described as the uniform distribution between 0 and 1. Randomly, a number x is drawn between the values 0 and 1. If $x > 0.965$, the truck is redirected to TOP, whilst if $x \leq 0.965$, the truck drives towards the bunkers in AEC.

Appendix B – Model Descriptions

This appendix aims to describe the working and flow of the different designed simulation models.

Current Model

This model is a representation of how suppliers currently arrive at Twence on a weekly basis (Figure B.1). A supplier enters Twence's terrain at the gate near the weighbridge, which is represented as "Arrival" in the simulation model. Suppliers arrive with an interarrival time of 4:31, according to the negative exponential distribution. At the moment of arrival, a supplier's arrival time and weight of the cargo are registered. Next to that, also the decision for the dump location is made at the gate. With a probability of 96.5% a truck is allocated to the bunkers and with a probability of 3.5% a truck is allocated to TOP. These percentages are taken from historical data. After allocation, the truck is moved to either TOPWR or BunkerWR (depending on the dump location). TOPWR represents the waiting line standing in front of TOP, whereas BunkerWR represents the waiting queue in front of the bunkers. The waiting lines are organized according to the FIFO principle, indicating that the first arriving truck is also allowed to enter the bunkers or TOP. The moment that a supplier is finished discarding the waste at the bunkers or TOP it leaves its spot and makes way for the gate (represented as "Departure"). The crane operator clears the back of the dump hole and the truck first in line goes to the dump hole (either Bunkers1, Bunkers2, Bunkers3 or Bunkers4) without a truck in front of it. The point in time that a truck arrives at the dump hole marks the end of the waiting time and is described as the "ArrivalAtDump" time. The waiting time is measured as the current time minus the arrival time. The supplier discards the truck from its waste and leaves the working station. Now, the processing time is determined, which is "ArrivalAtDump" subtracted from the current time. The supplier leaves the system at which the end time is set and the total time in the system is measured.

Once all the suppliers for a week have discarded their waste, the average waiting time, processing time and total time are measured, as well as the number of tons delivered per entity.

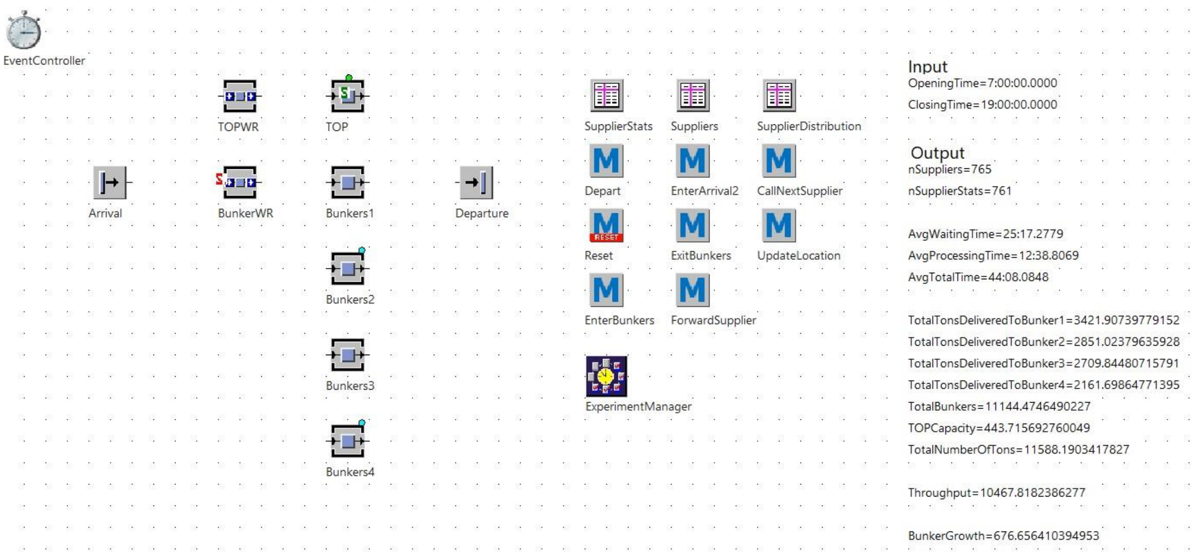

Figure B.1 - Simulation Model Current Situation

Time Slot Model

This model is a representation of the improved situation, representing time slots and quantity restrictions (Figure B.2). Every day, several trucks in the interval between 150 and 168 arrive via the negative exponential distribution. Before the start of the week, trucks of suppliers need to indicate whether they are willing to discard waste in the upcoming week. At the start of the week, it is clear which suppliers arrive that week and how many trucks in total are scheduled. The arrival of trucks over the day is evenly divided in six time periods of two hours (per time slot a maximum of 168/6 = 28 suppliers can arrive). The first period is from 7:00 – 9:00 and the last period is from 17:00 – 19:00 (adapted to Twence's opening times). Based on a supplier's yearly volume and priority number, the supplier receives a more popular time slot or a less popular time slot. The application of time slots guarantees a better spread of supplies throughout the day and the week.

Once a truck enters Twence within the allocated time slot, its number of tons is determined. Every supplier has a defined maximum weekly number of tons that it may bring. Before the gate opens and entrance is allowed, a check is done whether the current truck's delivery is within the weekly limits or not. A truck within bounds is granted entrance, whereas a truck exceeding its weekly limits is requested to move away and book another time slot.

From this moment on, the same process happens as for the current model, in order to measure the sole impact of the time slots and quantity restrictions. At this point, the decision is made whether the truck is supposed to drive towards TOP or the bunkers. In 3.5% of the cases, a truck is directed towards TOP. Subsequently, the truck moves to the waiting line (BunkerWR or TOPWR). Waiting is according to the FIFO principle, which is short for first in, first out. The moment a supplier is done discarding their waste at a working station (TOP, Bunkers1, Bunkers2, Bunkers3, Bunkers4) it leaves the station and moves to "Departure". Before the first supplier in line is allocated to the working station, the crane operator clears the dump hole. This time is referred to as the recovery time, which is normally distributed. The point of allocation marks the "ArrivalAtDump" time and the calculation of the waiting time of the supplier; waiting time is measured as current time minus arrival time. The supplier discards the waste and leaves the working station. Now, the processing time is determined, which is the "ArrivalAtDump" subtracted from the current time. The supplier leaves the system at which the end time is set and the total time in the system is measured.

Once all the suppliers for a week have discarded their waste, the variables are measured and represented in the model under "Output".

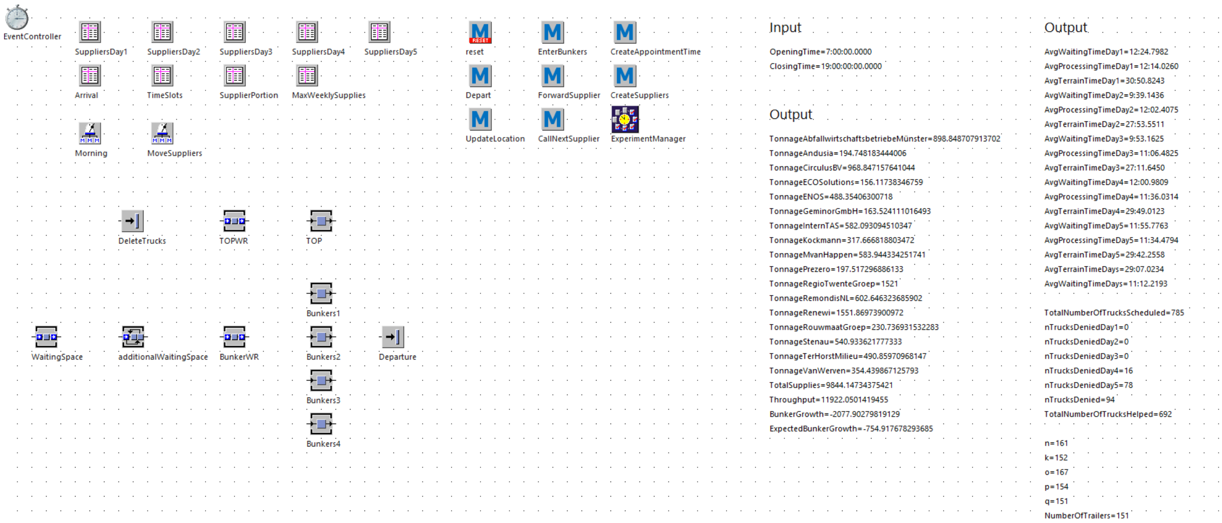

Figure B.2 - Simulation Model Time Slots

Appendix C – Map of Twence

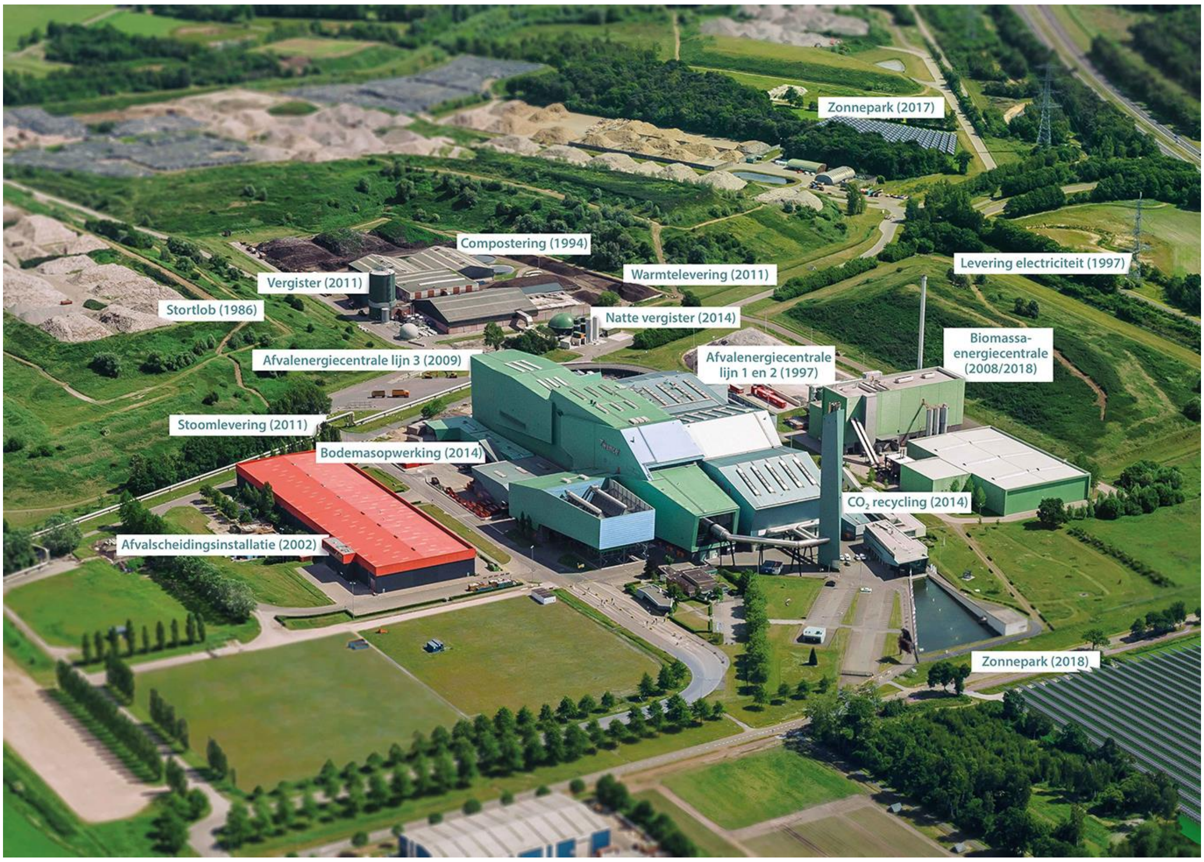

Figure C.1 - Overview of Twence Terrain, Hengelo