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Ahold Delhaize

Leveling Inbound Flow

Item allocation under fixed capacity inbound flow at the Ahold Delhaize Inbound Logistics department

Master Thesis Industrial Engineering and Management

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MANAGEMENT SUMMARY

This research is conducted at the Ahold Delhaize Inbound Logistics (ADIL) department. ADIL is an internal wholesaler within Ahold Delhaize, an international food-retail group. The department imports goods from international suppliers on behalf of its banners and stores these goods in its warehouses in the Netherlands, before transporting the goods to Ahold Delhaize's different organisations in the Netherlands, Belgium and the Czech Republic. The department is responsible for in- and outbound transport and setting up a network of suppliers and tradelanes.

Currently, the inbound flow at ADIL's Distribution Centres (DCs) demonstrates high variability. During the peaks in the inbound flow, the DCs experience capacity problems that lead them to not being able to process all goods at the appropriate time. The problem surfaces multiple times per year and, therefore, one of ADIL's main goals is to ensure that the DCs will not experience these under-capacitated periods. This goal is the motivation for this research. Levelling the inbound flow over the year would take care of the problematic peaks in inbound flow. With levelling as discussed in this research, we mean spreading the current inbound flow (number of transport units) evenly throughout the year on a weekly basis for each country of origin. This would entail that each week the inbound flow would be the same.

Currently, items are ordered on a weekly basis, based on the inventory level and forecasted demand. When the inventory level of an item is expected to fall below the safety stock, the item is ordered. Orders are made such that mostly only full truck loads (FTLs) are transported. This current ordering approach leads to the high variability in inbound flow.

Therefore, the research question is formulated as follows: "How should the number of transport units and item allocation to them be determined such that the inbound flow is levelled and costs are minimised?". In order to properly evaluate the effects, the fixed number of transports units on a weekly basis is determined. After which an item allocation method, based on the literature review, is developed and applied to assign the items to the available TUs, such that the effects on the operations, costs, and inventory can be determined. Based on these effects, a recommendation can be formulated for ADIL.

During the literature review, it is found that there is not a single item allocation model or method that is an exact fit to the problem. Relevant parts from the lot sizing problem, the bin packing problem, the 0-1 knapsack problem and its variants, and finally, the container loading problem are taken to create an approach that meets all requirements. These parts are the consideration of multiple periods, the fact that all demand must be met, and the item allocation is constrained by the pallet and weight capacity, showing the need for multiple constraints. The literature review demonstrates that almost all item allocation models are solved via a heuristic approach. The heuristic approaches that show the closest link to the problem iteratively add the items with the highest profitability as long as the constraints do not get violated. The approach needs to be adjusted slightly, to fit the problem, but idea behind the heuristic remains intact.

The designed approach is general and can be applied to all of ADIL's DCs throughout the Netherlands. The experiments will only be conducted with the Simon Loos DC in Tiel. This is ADIL's largest and most important DC. It has the problematic high variability as described, and the location stores pallets that are transported via all transport modes.

To solve the problem, a two-phase approach is followed. First, the number of weekly transport units (TUs) is generated using the historic data from 2021. For each scenario, the ceiling is taken from total number of TUs during 2021 divided by 52 weeks. This number is the initial number of TUs to which items are assigned in the second phase, and can later be adjusted through the TU heuristic. This heuristic either increases or decreases the number of TUs by one, depending on the case at hand. Second, after the number of weekly TUs have been decided, the item allocation approach must be formulated. The item allocation method first generates an initial solution through a constructive heuristic. In this

constructive heuristic, items are assigned subject to various constraints (such as the number of weeks items are allowed to be transported in advance, the pallet and weight capacity of the available TUs, and the fact that all demand must be fulfilled before its demand week), while aiming for the lowest possible penalty for early transportation. Next, the initial solution is improved through a meta-heuristic, namely a Reduced Variable Neighbourhood Search (RVNS). If after the RVNS has been applied, there are items that do not fit or the utilisation is too low, the TU heuristic is applied.

The proposed approach is tested for fifteen scenarios. These scenarios consist of the items that must be ordered, and the required information (such as the number of demanded pallets, the demand week, transport unit type, etc) of 15 countries, and are of different sizes and configurations. As the RVNS involves randomness, 5 replications are performed for each scenario to obtain a better estimate of the mean performance. First, three parameter tuning experiments are performed to understand the algorithm's behaviour under different parameter settings, such that the settings can be used to perform the further experiments with better results. A fourth experiment is performed with these settings in order to evaluate the performance of the algorithm and the new situation. With this information, a recommendation is formulated for ADIL. Finally, the robustness of the algorithm is evaluated through a sensitivity analysis. This helps to determine what the impact can be of a decision on or change in the input to the algorithm, such that the researcher can act accordingly.

After performing the experiments, it is concluded that the different characteristics of the scenarios make some better suited for levelling through the approach as described in this research and with the parameter settings as found in experiments 1 to 3. Larger scenarios often have higher peaks in demand, making it harder to level the demand throughout the year with the current parameter settings. Also, some scenarios have no demand for an extended period of time making them less suited.

Overall, it is shown that in some respects the new situation in which the inbound flow of items is levelled outperforms the current situation. This situation displays the lowest standard deviation of the inbound flow and DC capacity utilisation. This demonstrates that levelling the inbound flow could indeed solve the current problems the DC is experiencing with the high variability in inbound flow. However, the results also demonstrate that the standard deviation of the inventory level is higher for the new situation, but this is expected as the outbound flow remains variable while the inbound flow levels out. In addition, the inventory costs increase with 2.12%, however, when the transportation costs are lowered by 1% this can already account for the increase in the inventory costs. It is expected however that, due to the fact that ADIL will be able to make fixed purchasing commitments with its logistic providers as for each week an equal number of TUs are utilised, ADIL is likely able to negotiate a lower price with the logistic providers. The conclusion that can be drawn from the experiments relates to the utilisation levels of the TUs. For many scenarios, and especially for truck transport, the utilisation levels are too low. These low utilisation levels are caused by the limitation on the number of weeks items are allowed to be transported in advance and the fact that all items must be transported to meet demand. In order to fulfil these constraints, the number of fixed TUs will be increased to deal with periods of increased demand, leaving them with much lower utilisation levels for the periods with lower demand.

In conclusion, the approach as described in this research can have a positive impact on the operations, as it is able to decrease the large fluctuations in inbound flow at the DC, as the standard deviation of the inbound flow lowers with roughly 41% when comparing the results of the algorithm with the current situation. Despite that the approach also has some downfalls. Most importantly, the utilisation levels of the TUs in many cases would be too low, leading to resources being wasted and the transportation costs being higher than strictly required. This challenge prevents a recommendation to directly implement the approach as discussed in this research. As the approach does demonstrate promising results in terms of resolving the capacity problems at the DC in Tiel, it is recommended to conduct further research to improve the approach in order to increase the performance.

The first suggestion for further research to improve the utilisation levels of TUs, while still resolving the capacity problems, is to not fully fix the number of transport units throughout the year, but apply a ‘bandwidth’ approach. This would allow the number of TUs to fluctuate a little within this bandwidth, during periods of increased demand. The second suggestion is to not consider the countries of origins (scenarios) separately, but rather consider one total fixed number of weekly transport units, that can be divided over the countries according to their demand. In addition, it is suggested to allow consolidation for suppliers that are in close proximity, to increase utilisation levels. A test shows promising results, should this be applied to scenario 8. Another suggestion for further research is to evaluate the effects of moving from road transport towards intermodal train transport for other European countries, such as Spain, France, and Germany. Intermodal train transport from scenario 7 shows high utilisation rates, so a change in the transport mode could also show an improvement in the utilisation rates for other European countries, next to potential financial and sustainability gains.

PREFACE

Hereby I proudly present my thesis marking the end of my Master in Industrial Engineering and Management. Finalising my Master also means my time as a student has come to an end. I would like to express my gratitude to a number of people who have helped me whilst writing my Master thesis, as well as during my time as a student in Enschede.

First of all, I would like to thank Eduardo Lalla-Ruiz and Alessio Trivella, who have been my supervisors for the past months. Despite their busy schedules, they always found the time to provide their feedback for which I am very grateful. Their feedback always challenged me and has allowed me to continuously improve my thesis and lift my work to a higher level.

Second of all, I would also like to thank Pieter Meints from Ahold Delhaize Inbound Logistics for the opportunity. His continuous belief and words of encouragement were a huge motivation during the past months. I would also like to thank the other colleagues that helped me during the process of writing my thesis, through providing me with the necessary information or offering some welcome distractions when that was needed. I look forward to continue working with Pieter and the rest of the department, as I start my new role as an Inbound Logistics Specialist after my graduation.

As my time as a student comes to an end, I look back on a wonderful five and a half years, during which I have had so many fun experiences and made wonderful friends that I will cherish forever. I would like to thank everyone that has made my time in Enschede so special.

A special thanks goes out to my family, who always support me and believe in me unconditionally, no matter how many times I challenge them with my doubts. Finally, to my boyfriend Sven, thank you. Thank you for sticking up with me and always, always, continuing to help me, even though you were also busy with your own Master thesis. I could not have done it without you and I am so happy we get to finish this chapter together, as both graduate from our Master two days apart.

With great enthusiasm, I look forward to the future and taking the first step in my professional career at ADIL. In the wise words of Pippi Longstocking: 'I have never tried that before, so I think I should definitely be able to do that'.

I hope you enjoy reading my thesis.

Elles de Rooij,

May 2023

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LIST OF ABBREVIATIONS

AD = Ahold Delhaize
ADIL = Ahold Delhaize Inbound Logistics
BPP = Bin Packing Problem
C&P = Cutting and Packing
CLP = Container Loading Problem
DC = Distribution Centre
EDI = Electronic Data Interchange
FDD = Forecasted Delivery Date
FTL = Full Truck Load
KP = Knapsack Problem
KPI = Key Performance Indicator
LTL = Less than Truck Load
MDKP = Multi-Dimensional Knapsack Problem
MDMKP = Multi-Dimensional Multiple Knapsack Problem
MKAP = Multiple Knapsack Assignment Problem
MKP = Multiple Knapsack Problem
MDMKP = Multi-Dimensional Multiple Knapsack Problem
RVNS = Reduced Variable Neighbourhood Search
TU = Transport Unit
VNS = Variable Neighbourhood Search
3PL = Third Party Logistics

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1. INTRODUCTION

This first chapter introduces the research. In Section 1.1, the company is introduced. Section 1.2 introduces the problem, including the problem context and the motivation for the research. Section 1.3 outlines the research goal and problem. In Section 1.4, the action plan is defined. Section 1.5 lists the research questions. Section 1.6 elaborates on the stakeholder analysis. In Section 1.7, the outline of the thesis is presented.

1.1 COMPANY INTRODUCTION

1.1.1 Ahold Delhaize

Ahold Delhaize was formed by the merger of Ahold and Delhaize group in 2016. Delhaize Group originates from Delhaize, a wholesale grocery business founded in Charleroi in 1867 by the Delhaize brothers. Ahold originated from the Dutch supermarket chain Albert Heijn. Albert Heijn was founded in 1887 in Oostzaan, when Albert Heijn opened a small grocery store. Both Ahold and Delhaize opened hundreds of new branches over the years and later both became one of the largest supermarket chains in the Netherlands and Belgium respectively. In 2016, Ahold and Delhaize group combined forces to become a world-leading food retail group. Ahold Delhaize wants to aid its customers in shopping anywhere, anytime and in any manner, both online and in store (Ahold Delhaize, 2021a).

Currently, Ahold Delhaize is active in the United States, Europe and Indonesia, in a total of 10 countries. The group is a family of 19 local brands that together have over 7,000 local stores around the world (Ahold Delhaize, 2021d). Ahold Delhaize's headquarters are located in Zaandam, the Netherlands (Ahold Delhaize, 2021b). In the Netherlands, the supermarket chain Albert Heijn, online retailer bol.com, drugstore Etos and wine and liquor retailer Gall & Gall operate under Ahold Delhaize (Ahold Delhaize, 2021d).

1.1.2 Ahold Delhaize Inbound Logistics

The Ahold Delhaize Inbound Logistics (ADIL) department, formally Ahold Delhaize European Sourcing B.V., is an internal wholesaler within Ahold Delhaize and was established in 2006.

The Inbound Logistics department imports goods from its international suppliers on behalf of its banners and stores these goods in its warehouses in the Netherlands. From these warehouses, the goods are then transported to Ahold Delhaize's different organisations in the Netherlands, Belgium, and the Czech Republic. The department is responsible for in- and outbound transport and setting up a network of suppliers and tradelanes. Through this network, the department ensures the lowest possible lead times, inventory/working capital, prices and ecological footprint. Moreover, the department is responsible for the handling of custom authorities.

Some key figures of 2021 are shown, to illustrate the size of the operations of the ADIL department. In 2021, the department dealt with over several hundreds of suppliers and a couple thousand SKUs. They imported multiple hundreds of thousands of pallets from 37 countries worldwide, as shown in Figure 1, of which 75 percent from Europe. Figure 2 shows a more 'zoomed-in' view of the cities from which items are shipped in Europe. They work together with 19 Third-Party Logistics providers and have 4 warehouses in the Netherlands to and from which they transport the imported goods.

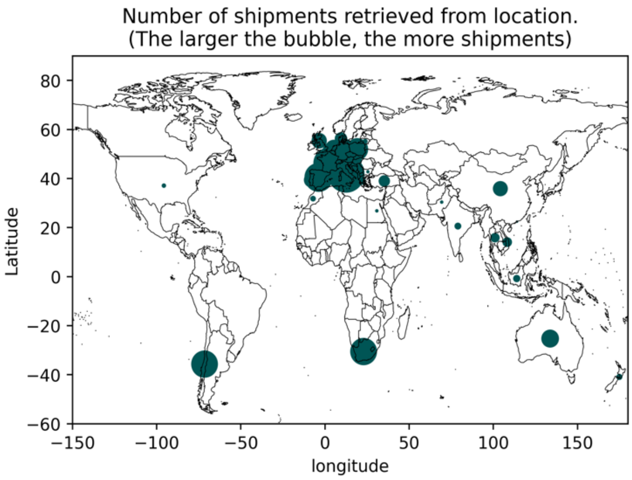

Figure 1: Overview number of shipments worldwide

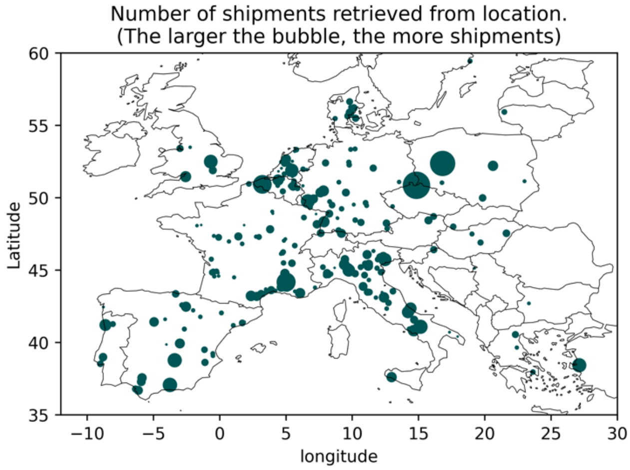

Figure 2: Overview number of shipments Europe

1.2 PROBLEM DESCRIPTION

1.2.1 Problem context

This section serves as a brief introduction into processes and operations that are related to the problem. A more in-depth problem context is provided in Chapter 2: Context Analysis.

The ADIL department imported items from 37 countries in 2021. The transport of items is done by sea, road, or train. Roughly 82 percent of transport is done by road and train transport, as most items originate from Europe. From this 82 percent, truck transport account for almost 71 percent, and is thus the main mode of transport.

Consolidation takes place for transport via sea and train. We speak of consolidation when items that would originally be transported separately, as they are placed as separate orders from different suppliers for example, are transported together in one transport unit (TU). In order to allow for this consolidated transport, the separate orders from different suppliers often need to be moved to a consolidation hub first, where they can be moved from their separate TUs to one TU. Consolidation ensures that TUs have higher utilisation rates, and as such transportation costs are decreased. The consolidation process and the different transport modes are discussed more elaborately in Section 2.2.

From its distribution centres (DCs), ADIL uses a one-day lead time for Albert Heijn, Gall & Gall, Etos, and the online DCs of these banners. Orders for wines stored in ADIL's warehouse in Almere that are placed in the morning can be delivered the same evening. Orders from Delhaize in Belgium have a lead time of 2 days. For deliveries to the Czech Republic, orders need to be placed 5 working days in advance of delivery. Moreover, deliveries are done on fixed days, namely Wednesdays and Fridays.

Important to note is that the capacity limitation that the ADIL department experiences is not related to the storage capacity, but mostly to the workforce/inbound capacity. Each DC has a certain inbound capacity, and at times of increased inbound flow this inbound capacity has to be exceeded in order to ensure that all goods are unloaded. In deciding on the appropriate number of inbound flow, this inbound capacity therefore is the limiting factor that must be taken into consideration.

1.2.2 Research motivation

The motivation for this research is multifaceted. Currently the inbound flow at the ADIL DCs is not evenly distributed, as there are often high peaks in inbound flow. These peaks in inbound flow cause several problems, and therefore the ADIL department wants to learn how to prevent the peaks in inbound flow of goods.

As of now, at times these peaks are so high that the warehouse operatives are not able to process all goods at the appropriate time. The problem surfaces multiple times per year, and therefore one of ADIL's main goals is to ensure that the DCs will not experience these under capacitated periods. Levelling the inbound flow over the year would take care of the problematic peaks in inbound flow. With levelling as discussed in this research, we mean spreading the current inbound flow (number of transport units) evenly throughout the year on a weekly basis. This would entail that each week the inbound flow would be the same. An example for four weeks illustrates this case: instead of having 78 transport units in week 1, 32 transport units in week 2, 28 transport units in week 3, and 50 transport units in week 4, 48 transport units would be transported each week. Naturally, for the case at hand, 52 weeks would be considered instead of 4 weeks, but the same method holds.

Moreover, levelling the inbound flow of goods suggests making fixed purchasing commitments with ADIL's logistic providers. The negotiations on these fixed number of transport units (TUs) potentially allows for making agreements on eco-friendly trucks. This would allow the ADIL department to contribute towards Ahold Delhaize's goal to reduce carbon emissions from its brand's own operations by 50% in 2030 (Ahold Delhaize, 2021c).

In addition, in today's climate, we are dealing with a global rise in transportation and logistics costs. Not only did the costs of shipping a container increase sevenfold in the 18 months after March 2020 (Placek, 2022). Also, the prices for ground transport via truck have increased drastically due to climbing oil prices (Page, 2022). Therefore, companies are inclined to look for ways to decrease these transportation costs. Hence, the Ahold Delhaize Inbound Logistics department wants to investigate whether it would be beneficial for the company to negotiate weekly purchase commitments with their logistic partners. Currently, transportation is done such that inventory is minimised while demand is met. Implementing these fixed purchasing commitments would entail that inventory will rise, but it could also allow for significant cost savings on transportation. The ADIL department wants to learn how many cost savings on transport are required to make up for the rise in inventory costs.

Finally, next to the increasing costs, another problem that has emerged since the COVID-19 pandemic is decreased reliability of transport. As transport opportunities are more scarce, logistic providers are not able to consistently offer transportation slots at the last minute. Moreover, the high fluctuation in transport orders with the logistics provider makes it harder for the provider to anticipate the demand and ensure that they have sufficient capacity. Naturally, not having the required transportation slots available at the appropriate time can become problematic. Therefore, having a fixed number of transportation slots reserved will have a positive impact on the organisation.

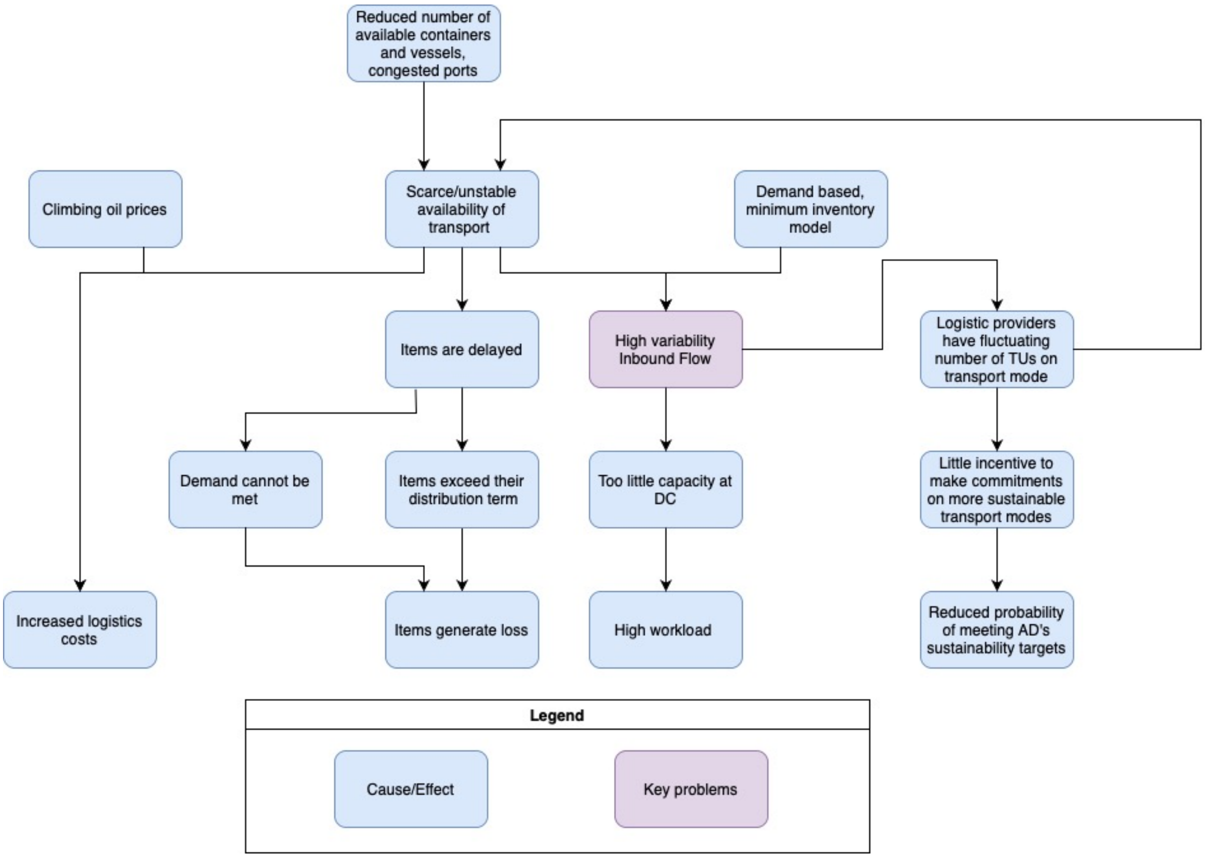

Figure 3: Problem diagram of current inbound logistics process at the ADIL department

Figure 3 shows the problem diagram, in which an overview of the problems and their relationships are depicted. The problems and their relationships are described from cause to effect and will be described starting at the top of the diagram. Mostly as a result of the COVID-19 pandemic, less containers and vessels are available to transport goods. Moreover, port congestion caused by reduced productivity levels as a result of lockdowns and/or increased demand, has resulted in significant delays (LaRocco, 2022). Both factors contribute to a lower availability of transport. As availability has become scarcer and oil prices have increased significantly, logistics costs have increased. Moreover, lower availability of transport can cause items to be delayed. These delays in turn can result in a disability to meet demand or items exceeding their distribution term, as the demand for the delayed items is significantly lower after the time they were originally expected. As a result, the delayed items generate a loss as they can either not be sold at the time they are needed or not at all.

The demand based, minimum inventory model is ADIL's current model based on which orders are planned and placed. This means that orders are placed such that demand is met, with minimal inventory. As such, in weeks with high demand a larger number of orders will arrive at the DC compared to weeks with lower demand. The demand fluctuations can be so strong that the resulting variability in inbound flow is also high. Moreover, the decreased reliability in transport can enhance the variability in inbound flow as a result of delays. Because of the high peaks in inbound flow the DC capacity is not high enough to process all of this flow in time. As the capacity is insufficient during the high peaks in inbound flow, DC employees experience a high workload. In addition, as there is a high variability in the inbound flow the logistic providers also experience this fluctuation, so for example they do not have a stable number of containers on a container ship or a fixed number of trucks they have to transport to the Netherlands. This also results in lower reliability of transport units, as the logistic providers are not always able to offer available slots at the last minute for sea or train transport as the limited number of spots have already been occupied by others. As the 3PL are uncertain on the number of TUs they are more hesitant to make the investments in more eco-friendly modes of transport, such as hydrogen-powered trucks.

This makes it harder for Ahold Delhaize to meet its sustainability targets of reducing its carbon emissions by 50% by 2030.

The high variability of inbound flow is selected as the core problem that is aimed to solve, given the fact that this problem is the cause of capacity problems at the distribution center, and the resulting high workloads for the DC operatives. Moreover, the ADIL department has expressed that solving this problem has a high priority and is an important goal that they want to solve for the future. In order to do so, the single cause that can be influenced directly will be addressed, namely the current demand based, minimum inventory ordering model.

1.3 RESEARCH GOAL AND QUESTION

The research goal follows, amongst other motivations as described in Section 1.2.2, from the problematic peaks in inbound capacity at the DC. The main aim of the research is to determine the number of transport units and allocation of items to them such that the inbound flow is levelled and the penalties and transportation costs are minimised. This should allow to provide the Ahold Delhaize Inbound Logistics department with insights into the feasibility and effects of levelling the inbound flow under this new fixed capacity item allocation method. As mentioned in Section 1.2.2, with levelling it is meant that the current inbound flow is spread out evenly throughout the year, such that each week the inbound flow is the same. As such, the current high peaks in inbound flow would be removed. Accordingly, the main research question can be formulated as follows:

How should the number of transport units and item allocation to them be determined such that the inbound flow is levelled and costs are minimised?

1.4 ACTION PLAN

To ensure that the research goal can be attained, first the appropriate fixed number of transport units on a weekly basis must be determined. Based on this number of transport units, it needs to be found how the items that must be ordered can be spread out over the number of available transport units.

We perform a literature review to find the appropriate method for the allocation of items to transport units. This item allocation method is then applied to the problem at hand. Finally, we evaluate the effects of the resulting inbound flow to provide the ADIL department with an advice.

1.5 RESEARCH QUESTIONS

To answer the main research question, multiple research questions are formulated.

1) How does the Ahold Delhaize Inbound Logistics department currently determine the incoming number of transport units and items?
    a. How does the ADIL department currently determine which items are ordered when?
    b. What is the current methodology with regards to the item allocation to transport units?
    c. What does the transportation process at the ADIL department currently look like?
    d. What were the number of inbound transport units and items for the reference year 2021?
    e. What Key Performance Indicators are used or can be formulated to evaluate the performance of the current process?
    f. What constraints are taken into consideration for the allocation of items to transport units?

The first research question is split into multiple sub-questions. The goal is to present an overview of the current approach on the determination of inbound transport units and items. First, the ordering process is explained. Next, the current method for the allocation of items to transport units is described. In addition, the Key Performance Indicators (KPIs) to measure the performance of the ordering process are described. Then it should be evaluated what constraints need to be taken into consideration for the allocation of items to ensure that no allocation rules are violated. Having a clear overview of the current situation and approaches allows for a better comparison to the studied scenario, and thus aids in giving the ADIL department some advice. Moreover, an overview of the necessary constraints to the model are needed to generate a realistic model for the allocation of items to transport units.

2) What does the literature propose for assigning items to a given number of transport units with fixed capacity?
    a. What methods are available for item allocation given fixed capacity?
    b. Which method is the best fit to solve the item allocation problem to fixed number of weekly transport units at the Ahold Delhaize Inbound Logistics Department?

The second research question will be answered through a literature review. The goal is to describe all relevant literature regarding the assignment of items to transport units. First, all methods that are described in literature that allocate items to a given capacity are evaluated. From these methods, the best fit to solve the item allocation problem at the ADIL department is selected.

3) How should the assignment of items to transport units be designed?
    a. What is the scope of the model?
    b. What assumptions are made?
    c. What is the final model formulation?
    d. What is the solving method?

The third question describes the model for the allocation of items to goods. This question is again divided into multiple sub-questions. The first sub-question is used to scope the model. Next, due to the complexity of the model several assumptions must be made, which are shown in sub-question 4b. In question 4c, the model formulation is provided. Finally, the solving method is formulated.

4) What are the effects of levelling the inbound flow throughout the year on Ahold Delhaize Inbound Logistics' operations, costs and inventory?
    a. What are the main changes in the performance of the KPIs of the solution compared to the current performance?

Sub-question 4 evaluates the effects of the new situation on ADIL's operations, costs and inventory. In order to do so, the performance of the algorithm is analysed and compared to the current situation. This evaluation is an important aspect of the research as it aims to clearly show the differences, potential benefits or pitfalls and thus aids the advice on the feasibility of the model in practice. Sub-question 4a considers the main differences between the performance of the solution under the optimal parameter settings and the current situation.

5) What are the conclusions and recommendations for the Ahold Delhaize Inbound Logistics department?

The final research question aims to advise the ADIL department on the feasibility of levelling the inbound flow throughout the year. This recommendation is multifaceted and considers all relevant aspects that contribute to a conclusion. The effects on inventory, transport costs, operations, etc., are discussed in this final chapter.

1.6 STAKEHOLDER ANALYSIS

Freeman and Reed (1983) define a stakeholder as “any identifiable group or individual who can affect the achievement of an organization’s objectives”.

There are multiple stakeholders involved in this research and it is important that these are taking into consideration during the research to ensure the highest value and applicability of the solution. The relevant stakeholders are listed below:

- Ahold Delhaize Inbound Logistics department: *the ADIL department is an important stakeholder in the project as they are the problem owners. They are responsible for the potential implementation of the results of the research and will offer their expertise during the research.*
- Ahold Delhaize: *the company as a whole is concerned with the results of the research as it might result in significant costs savings and after the implementation and negotiation with the logistic providers potentially even improvements on sustainability by transporting with more eco-friendly transport. Moreover, if the research findings are positive, they might be able to implement a new approach in other departments and regions of the organization as well.*
- Third-Party Logistics Providers: *the 3PL are stakeholders as they are responsible for the transport of items to AD’s warehouses. In case the project is implemented, they would need to make the fixed purchasing commitments with the ADIL department, having strong implications for their daily operations.*
- Suppliers: *ADIL’s suppliers are also considered to be stakeholders, as when the project would be implemented, they will experience big changes to their current demand. As the inbound flow of goods would be spread out evenly, their spikes in demand would likely also level out.*

1.7 OUTLINE OF THESIS

Figure 4 shows the outline of the thesis including the methodology. The research questions are displayed in blue. The required input to answer the research questions is displayed in green. The answers to Research Questions 1 and 2 that contribute towards the conceptual solution framework are shown in orange. The conclusions of the chapters, i.e. the answers to Research Questions 3, 4 and 5, are displayed in red, and are also used as input for answering the next research question. The questions and conclusions are placed in horizontal boxes labelled with the chapter numbers, to show in which chapter each research question is answered.

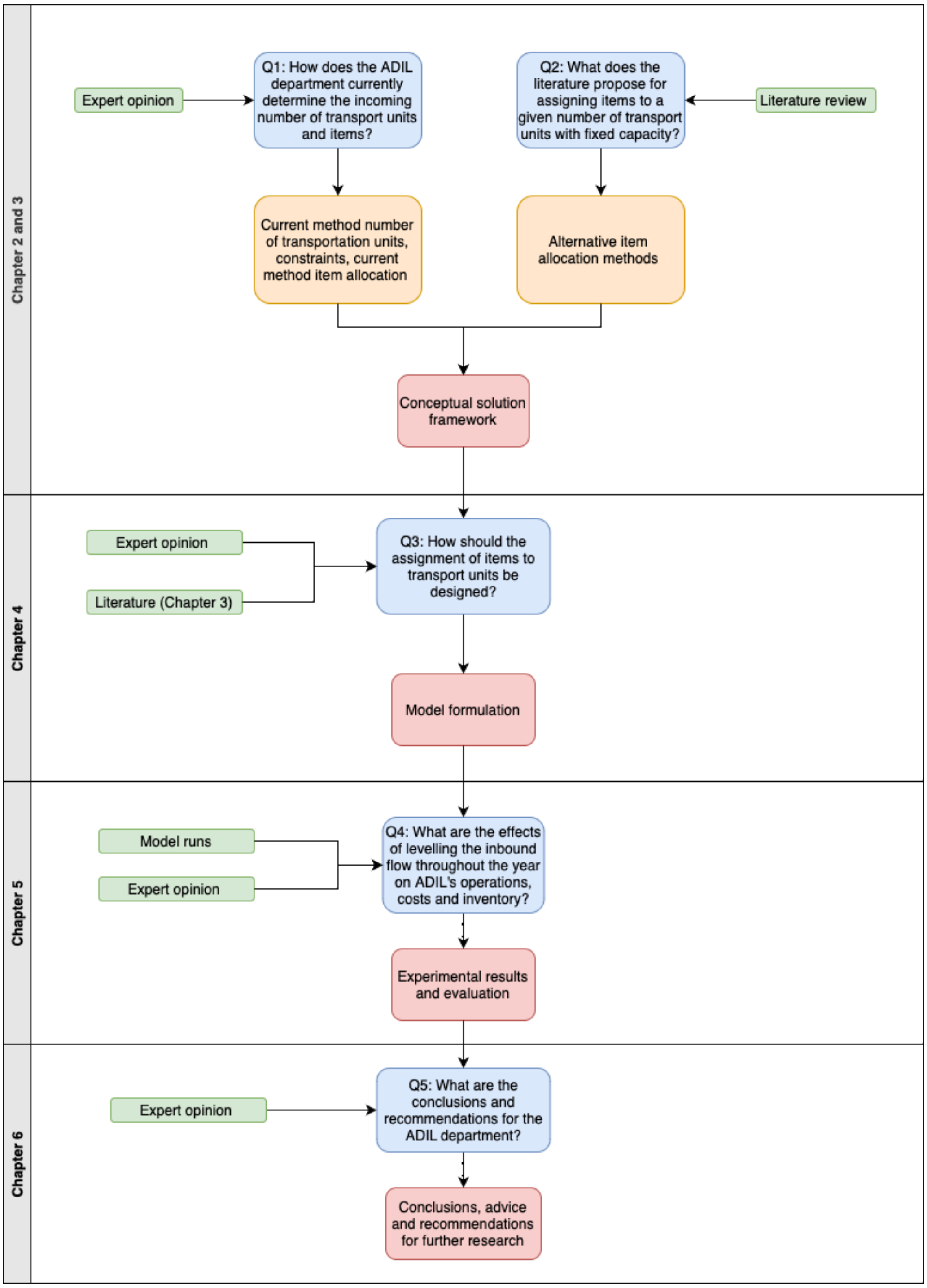

Figure 4: Outline of thesis with research question and chapter overview, methodology, and required answers to the research questions

2. CONTEXT ANALYSIS

This chapter describes the context analysis, and it aims to answer Research Question 1: “How does the Ahold Delhaize Inbound Logistics department currently determine the incoming number of transport units and items?”. Section 2.1 answers sub-questions 1a (“How does the ADIL department currently determine which items are ordered when?”) and 1b (“What is the current methodology with regards to the item allocation to transport units?”) and elaborates on the current situation with regards to the ordering process and the item allocation to transport units. Section 2.2 discusses the current transportation process, and thus answers sub-question 1c: “What does the transportation process at the ADIL department currently look like?”. Section 2.3 shows the supply chain network that summarises the current process description. In Section 2.4 an overview of the number of transport units and orders is given for the year 2021, answering sub-question 1d: “What were the number of inbound transport units and items for the reference year 2021?”.In Section 2.5, the Key Performance Indicators are described to answer sub-question 1e: “What Key Performance indicators are used or can be formulated to evaluate the performance of the current process?”. Section 2.6 answers sub-question 1f (“What constraints are taken into consideration for the allocation of items to transport units?”) and as such, describes the constraints.

2.1 CURRENT ITEM ALLOCATION AND ORDERING PROCESS

The total ordering process is described in Figure 5, shown on page 11. The following section describes this process in more detail and also discusses the item allocation to transport units.

Items are ordered on a weekly basis, based on the inventory levels and forecasted demand. The inventory levels at the distribution centres are communicated through the Electronic Data Interchange (EDI) connections between de DCs and ADIL. The forecasted demand is solely based on a forecast, as the orders made at the ADIL department by most of their banners have a 24-hour lead time. In case of promotions, their banners have to communicate these promotions far in advance, such that the ADIL department can anticipate for the additional expected demand. An example illustrates this case: if Albert Heijn is planning to have a big wine promotion in week 50, this promotion must be communicated to the ADIL department in week 30.

Based on the items’ lead times, orders are made in advance, such that the orders arrive at the desired time. An item must be ordered in case the expected inventory level is expected to drop below the safety stock over the lead time of the product, based on the forecasted demand. The lead times are known for each country, and in some instances for each supplier (in case of variable lead times per supplier). The regular lead times are dependent on the country of origin and the transport method and vary from 2 to 15 weeks. Promotional lead times vary from 4 to 16 weeks, as suppliers need more time to prepare for the higher demand. This also demonstrates the reasoning behind the need for early communication on promotions between the ADIL department and its banners.

Moreover, during some periods (such as December) multiple suppliers pause their operations. Naturally, these periods are communicated to the ADIL department. In these cases, the planners place the orders in advance to ensure that enough inventory is available for the period in which the suppliers are closed.

At all times, a safety stock must be maintained. The level of safety stock is dependent on the turnover rate of the item, as well as the item’s lead time. In general, items with a longer lead time have a higher safety stock to account for the longer period of uncertainty.

ADIL’s planners use the ERP-system Navision for the item allocation and planning of orders. Important to note is that the information available to the planner in Navision is a snapshot and does not consider or show the orders that must be placed after the current moment. This can cause the planner to miss possibilities to order more efficiently. All items that are transported with Hillebrand (sea freight and European consolidation) are planned via their platform, named AXIS. In this platform, both Hillebrand

and the suppliers have insight into the expected demand. Based on this demand and current inventory of ADIL Hillebrand generates order suggestions. These suggested orders then have to be approved by ADIL's planners.

Orders are made such that mostly only multiples of a full truck load (FTL) are transported. A truck is considered full if all pallet capacity is utilised. The ADIL department does not determine the number of items on a pallet, and therefore there might be instances in which based on the pallet's actual height, in reality the truck is not fully utilised.

In principle, a truck is filled with items from a single supplier. If based on the order suggestion, the volume for a single supplier does not result in a FTL, the order gets 'pushed'. When an order is 'pushed', the planner checks what the order suggestion volume would amount to in the days after. The order is 'pushed' until the total volume amounts to a FTL. In this case, the items that must be added to the original order suggestion such that a FTL is attained, are transported before they are strictly required, resulting in higher inventory. However, ADIL assumes this additional inventory has less negative financial impact than transporting LTLs. If several items from the same supplier are ordered, an item has to be selected of which to increase the volume. This decision depends on the planner in charge of the order. However, mostly the item with the highest turnover rate is chosen, as the additional inventory of such an item is considered to be the least problematic.

As mentioned previously in Section 1.2.1, in some instances consolidation takes place to ensure that lower volumes of items from suppliers do not result in less than truck load (LTL) shipments. There is only one instance in which LTLs are transported, namely in case the item's distribution term is so short that the item will definitely exceed this distribution term in case more volume is added to the truck. The distribution term is the time period within which an item must be distributed to the customer, and it is often related to the item's best before date. The reason for this is that when the items will be sold in the customers' stores, they need to have a long enough period before they pass their best before date.

If an order is made in the AXIS platform, the availability of an item is shown. If items are not available at the requested time, they cannot be ordered. For orders made in Navision, this information is not known and as such, orders are made and then later denied by the supplier. Therefore, an order can be placed many times over in case the desired item is unavailable for an extended period of time. When the order is made via the AXIS platform, naturally it could also be that the items the planner wishes to order are unavailable for a longer time period. However, in that case, the planner will be able to see when items are available again and place an order once that is the case, so it is not needed to place multiple orders. In both cases, ordering the items is delayed as long as their lead time is within the time they are demanded, i.e. as long as the items would arrive in time for the moment of expected demand. If based on their lead time, they are not expected to arrive in time for demand to be met, they are considered to generate lost sales and will almost always not be ordered any more (unless the item is so highly demanded that it will definitely be sold in a very short time frame).

During the ordering process it is determined at which time items must be transported and delivered to the appropriate DC. Each day the distribution centres receive a list of the orders that will be delivered on that day. For the delivery of the goods, the logistic provider has to sign up to a transportation slot in advance. Normally, deliveries are done between 06:00 and 18:00, so drivers are able to book their delivery slots within these times. In case the lead time of an order is very short and there is little risk involved, often the logistic provider is able to book its delivery slot further in advance, ensuring that the truck driver is able to deliver the items at their desired time. If transport takes longer and more uncertainty is involved, it is often harder to book these transport slots further in advance, leading to the truck drivers potentially having to deliver at a time they feel is less convenient. The ADIL department does not intervene in this process and only agrees on a delivery date with the logistic provider.

Once the pallets are unloaded from the trucks, they get checked by the warehouse operative. In case everything is in order, they are accepted, and the truck driver can leave. When this process is completed, the pallets are moved to their location in the DC.

As mentioned in Section 1.2.1, the capacity limitation that the ADIL department experiences at the DC is mostly related to the workforce/inbound capacity. The daily inbound capacity of each DC is known.

Practically all consolidation is done by the logistic provider Hillebrand. Hence, they oversee which items are added to which containers, based on the actual orders made. For the very small volume wine retailers in South Africa for example, which are almost all sourced for Gall & Gall, the ADIL department generates the orders such that they order in a larger batch from multiple suppliers occasionally. Then these orders are added to the regular containers that would be ordered, by adding a mixed pallet of these combined wines with low demand.

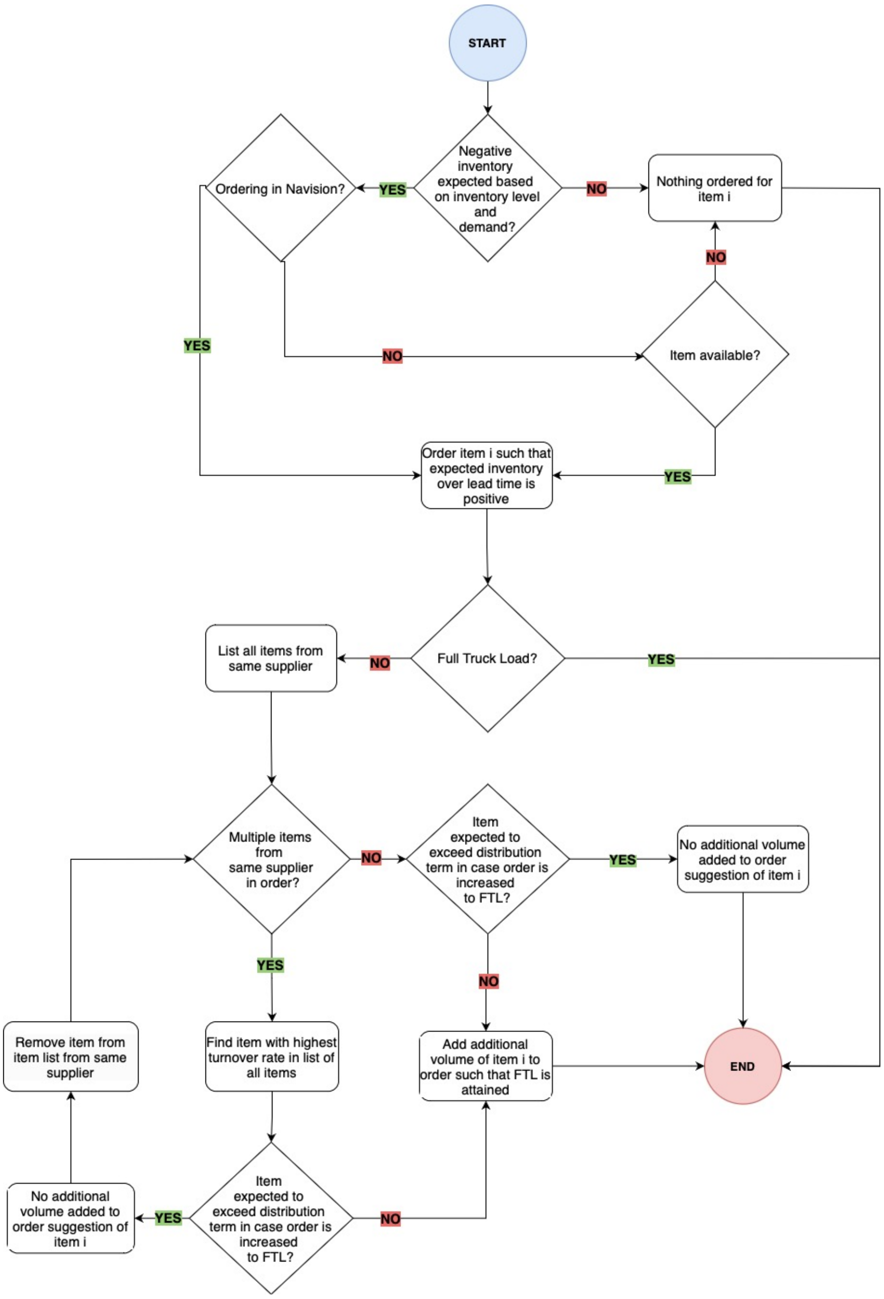

Figure 5: Overview of the ordering process at the ADIL department

2.2 TRANSPORT PROCESS

As the problem at hand relates to the allocation of items to a levelled number of transport units from different modes of transport, it is relevant to understand how the transportation process currently works. This helps to gain a better understanding of the different aspects that must be taken into account during the item allocation phase, as well as the implications and effects of certain decisions on the current process. For clarity, we refer to the intermodal transport of which most of the transport is done by train as intermodal train transport. For this transport mode the small part of the journey that is done by truck is necessary in order to facilitate the train transport, i.e. arrive at the train station or origin and from the train station of arrival to the DC. The same logic holds for intermodal sea transport, so the sea transport is used for the long haul and truck transport is a necessary mean to perform the remaining short haul transport.

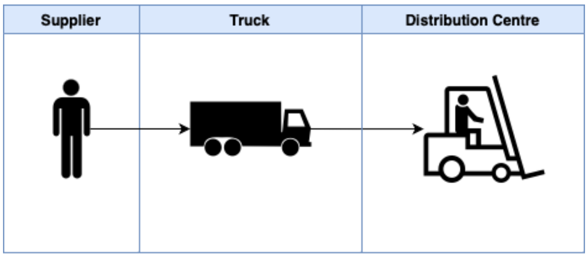

Figure 6: Direct truck transport process from supplier to DC

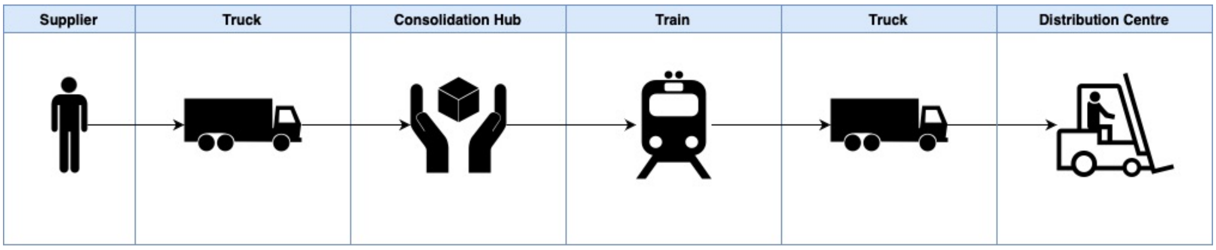

Figure 7: Consolidated intermodal train transport process from supplier to DC

Truck transport is done directly from the supplier to the distribution centre. The goods move directly from the supplier to the truck and to the distribution centre Figure 6. Intermodal train transport requires three legs of transport for each transport order, as shown in Figure 7, namely first by truck, then by train, and finally the items are again transported via truck to one of AD's warehouses.

For intermodal train and intermodal sea transport, consolidation can occur. First, we consider intermodal train transport. As the suppliers of goods can be located in remote areas and/or far from other suppliers, next to the fact that some suppliers deliver in lower volumes, consolidation is sometimes required to ensure that the transport units with poor utilisation do not travel all the distance from the supplier to the warehouse alone with this poor utilisation. Consolidation takes place at a consolidation hub and is done such that the transport unit is optimally utilised. Figure 7 provides a visual overview of the total process of intermodal transportation by train in case of consolidation.

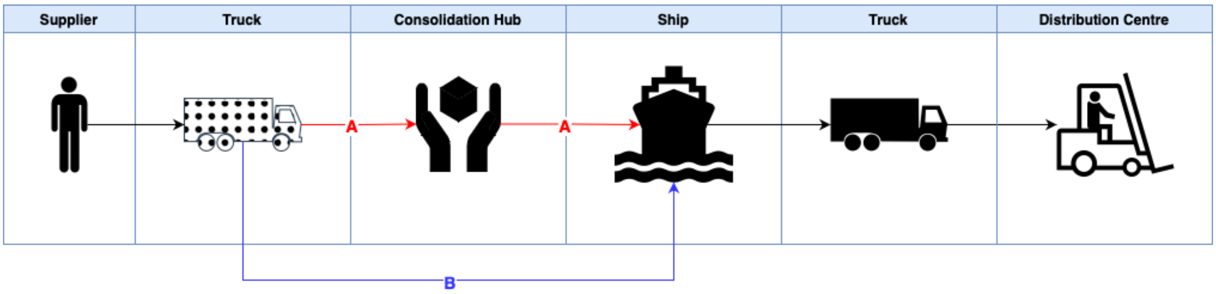

Figure 8: Intermodal sea transport

Intermodal sea transport contracts with logistics providers can be Free On Board (FOB) or Free Carrier (FCA), and can consist of consolidation, illustrated in the red path A in Figure 8. First the process is described without consolidation, in which case truck transport is directly followed by sea transport as shown by blue path B in Figure 8. In case of an FOB shipment, the ADIL department accounts for 2 transport legs, namely the sea shipment and the truck transport from the harbour to the AD warehouse. The supplier arranges that the goods are moved from its warehouse to the ports and on board of the cargo ship (i.e. they account for the dotted truck transport in Figure 8). When the transport is FCA, the ADIL department is responsible for all transport legs from the supplier to the warehouse in the Netherlands. This means that the items first have to be transported via truck from the supplier to the harbour of origin, from here the goods travel via sea to Rotterdam, where they are loaded on a truck to be transported to one of AD's warehouses.

Intermodal sea transport is subject to consolidation as well, for wine, food and non-food items. As there are a lot of small volume retailers, the AD banners do not deal with these retailers directly. As such, ADIL imports the items from multiple small and larger retailers overseas. Naturally, consolidation must take place before the items are transported, as small volumes lead to poor utilisation of the sea container. This consolidation is done by ADIL's logistic provider Hillebrand in consolidation hubs in South Africa, South America, and the Oceania. In case consolidation takes place, the items follow red path A as visualised in Figure 8.

2.3 SUPPLY CHAIN NETWORK

Figure 9 shows the current operational model for the Belgium and Netherlands (BENL) banners and Albert in the CSE (Central and Southern Europe) region. This overview summarises the process/supply chain as described in Sections 2.1 and 2.2. It is important to note that there is quite a large difference between the guiding principles for the BENL banners model and the Albert Model. For the BENL network, the suppliers are located far away from the hub and the banners are close to the hub. On a smaller scale, there are also suppliers located in the BENL region that are part of the BENL model. In the current Albert model, the suppliers are mostly located close to the hub and the banners far away from the hub. The items that pass through the hub on the European continent are transported via train, and for a small number transport is done via truck. Items from the large DC in the BENL region are transported directly to the banners in the CSE region.

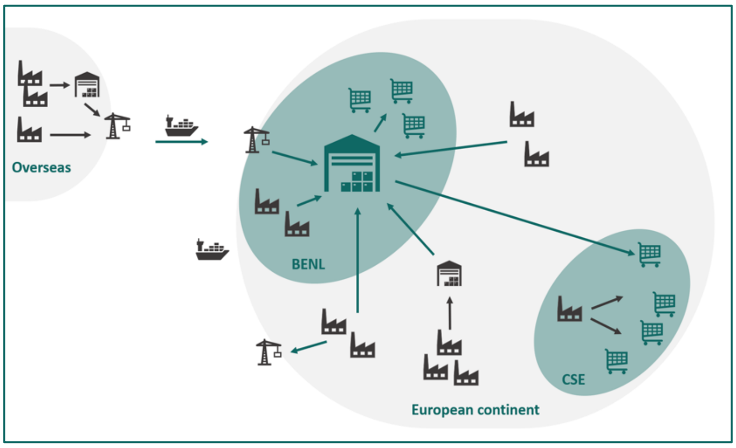

Figure 9: Current model BENL banners and CSE region

2.4 DATA OVERVIEW FROM 2021

2.4.1 Number of item orders

The total number of item orders can be deduced from the shipments overview file in Navision. The shipments overview is generated for the year 2021. In this shipment overview, all transport orders are listed. Since the total number of item/transport orders must include all orders from 2021, no adjustments need to be made to the data. The total number of transport orders to all of ADIL's DCs amounts to roughly 14,000. Comparing this number with the number of transport units, shows that in 2021 roughly 2,500 transport orders were consolidated for transport.

2.4.2 Number of transport units

The data on the number of transport units for the year 2021 was not directly available. Hence, gathering the required data consisted of several steps which are elaborated below.

The data on truck, intermodal train and intermodal sea transport done by Hillebrand is gathered separately from the data from the truck transport by other logistic providers. This is done, because some additional information is required to filter out multiples of the same transport unit as a result of consolidation, which is only done by Hillebrand. This information is not available in the traditional data files in the ERP system Navision, as this system is not used to plan the orders with Hillebrand.

Hillebrand is responsible for both all transport overseas as well as train transport. Moreover, they perform a small section of truck transport. As such, the information on the orders by Hillebrand was gathered through their daily updates. Hillebrand provides information on all active orders. Daily updates every 14 days were collected in one file, after which all rules on the orders before they were delivered to their final destination were deleted. The resulting data set consisted only of transport orders that had been completed. In the occasion that a completed order was posted in the daily updates for over 14 days and thus appeared multiple times in the grouped file, these duplicates were deleted. The resulting file provides a complete overview of all fulfilled orders by Hillebrand through their different transport modes.

On intermodal sea and intermodal train transport, consolidation often takes place. This means that multiple orders are transported in the same transport unit. To find the number of transport units on a yearly basis, these duplicates need to be removed from the dataset. This is done by removing all multiples of deliveries in the same container on the same Forecasted Delivery Date (FDD), such that only 1 rule remains.

For truck transport, the carrier overview of 2021 available in Navision is used. Here, first all transport orders transported by Hillebrand are removed, as the right number of transport units transported by Hillebrand for all modes of transport have already been found (as described above). Next, the number of required trucks for each transport order is determined. This number is calculated given that 1 truck can transport 26 Block pallets and 33 Europallets. In case both Euro and Block pallets are transported in the same transport order, the number of required trucks is calculated using 0.4 loadmeter per Euro pallet, 0.5 loadmeter per Blockpallet and maximum number of loadmeters of 13.5. Every combination of Euro and Block pallets is allowed, as long as they fit the maximum capacity of 13.5.

By combining both data sets, the number of transport units of 2021 is found. The total number of transport units for all types of transports worldwide to all of ADIL's DCs amounts to roughly 11,500 TUs. Figure 10 shows an overview of the division of the total number of transport units over the different types of transport. First a distinction is made between the different transport modes, namely intermodal train transport, intermodal sea transport and truck transport.

Moreover, as the country of origin is not stated directly in the data files, the country of origin is determined based on the load zip code. These countries are then grouped into their continent. With this information, for each transport mode, the division of the number of transport units over the different continents is determined, which is shown in Figure 10. As can be seen, truck transport and intermodal train transport only takes place in Europe.

Finally, for each transport mode and related continent, Figure 10 shows the percentage of consolidated and unconsolidated transport units. This information demonstrates for which types of transport the transport orders are consolidated the most. The type of transport with the most consolidation is intermodal sea freight from Africa. The reason for this is the high number of low volume wine retailers that are located in this region. Moreover, because all item orders pass through Hillebrand's consolidation hub before intermodal sea transport, these item orders will be consolidated into a full truck load before they are transported.

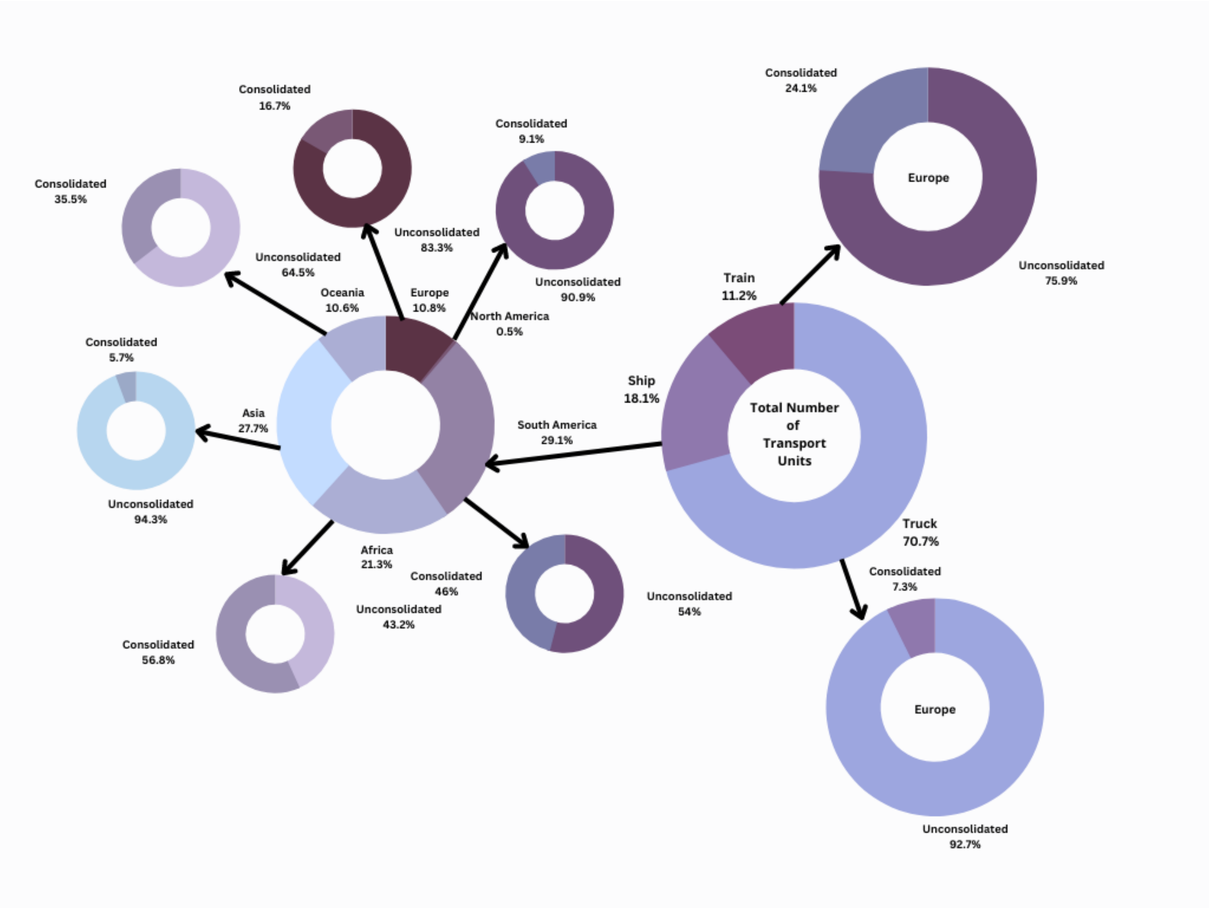

Figure 10: Overview of the division of the number of transport units over the different transport modes, continents of origin and consolidated/unconsolidated transport for the year 2021

2.4.3 Variation of inbound flow

While ADIL has multiple DCs throughout the Netherlands, only the Simon Loos DC in Tiel will be considered during this research. This is ADIL's largest and most important DC. It has the problematic high variability as described, and the location stores pallets that are transported via all transport modes.

In order to demonstrate that the ADIL department currently experiences the high variability of inbound flow that has been discussed in depth in earlier sections, data on the year 2021 was gathered to create a figure for the Simon Loos distribution centre in Tiel on the number of inbound pallets over time. To do so, the total carrier overview of 2021 was extracted from Navision. In this file, the number of pallets in each transport order from all carriers is available. Moreover, the file consists of information on the unloading date of all transport orders. Finally, the DC at which the transport orders are delivered are known. With this knowledge, a graph is generated for the ADIL's largest distribution centre in Tiel. As mentioned, the decision is made to only consider ADIL's largest DC and also to not consider the total inbound flow from all of ADIL's DCs together. This is done since the problems occur at these distribution centres separately, aggregating the distribution centres does not provide the proper insight into the fluctuations in inbound flow as a week with higher inbound flow in a particular week in DC 1 might be compensated by a week with lower inbound flow for that same week in DC 2.

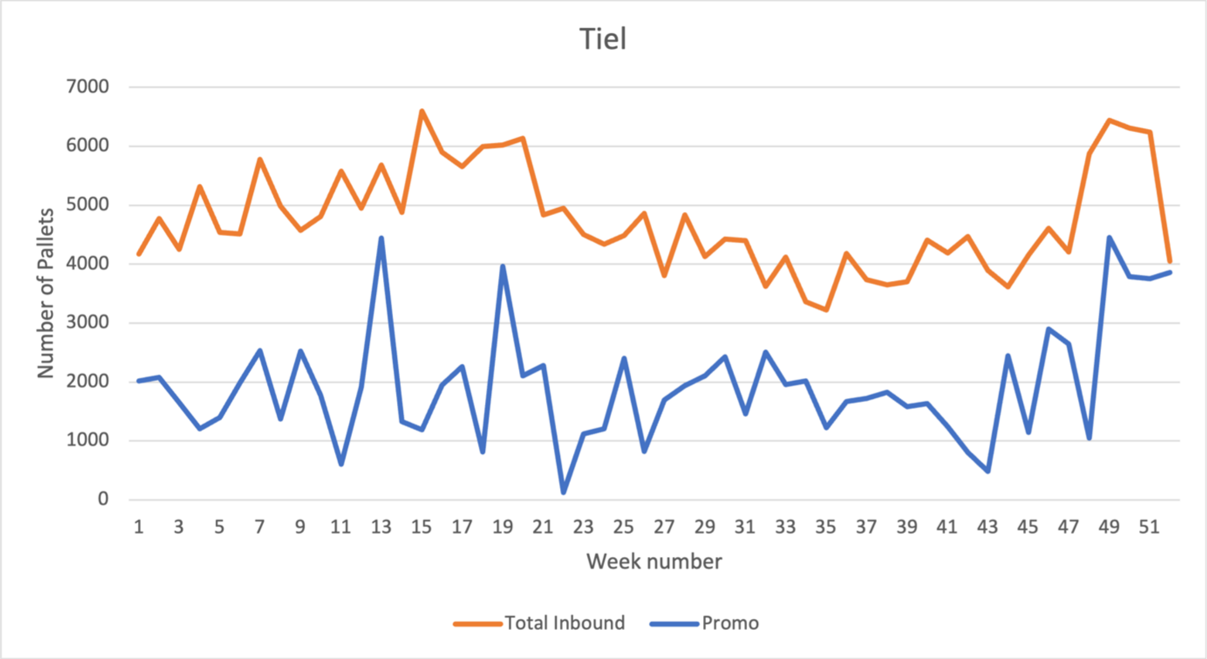

Figure 11: Number of inbound pallets and promotions on a weekly basis at the Simon Loos DC from 2021

Figure 11 shows the inbound flow in the number of pallets at Simon Loos on a weekly basis for 2021, as well as the promotion volumes in number of pallets for each week. The figure clearly demonstrates the high peaks in the inbound flow that were previously described. The highest peak in inbound flow amounts to 6,595 pallets, compared to 3,224 pallets in the weeks with the lowest inbound flow. Since the week with the highest inbound flow is over two times higher than the week with the lowest inbound flow, it becomes clear what extreme capacity fluctuations the Simon Loos DC experiences. The standard deviation of the number of inbound pallets on a weekly basis for the year 2021 amounts to 865.9344 pallets. This also shows that these high capacity fluctuations are more incidental rather than continuous, which can be explained by their nature. As demonstrated by Figure 11 a large part of the fluctuations in the inbound flow are caused by the promotions. For the promotions demonstrated in Figure 11 only the wine promotions and the Albert Heijn promotions that are stored in Tiel are taken into consideration. Important to note is that next to the promotions, holidays and seasonality also account for some of the peaks in inbound flow. Christmas and New Year's eve for example are large contributors to the peaks in inbound flow, as well as Easter and the Dutch holiday King's day.

Important to note is that the data, as presented in this section, has already been improved by manual intervention during the periods with high inbound flow. Currently, when the inbound flow becomes too high for the distribution centre to handle, one of ADIL's inbound specialists intervenes and expected deliveries are moved, or potentially the distribution centre remains open for longer hours. Some of these interventions might cause the peaks in the graphs to be lower, as the intervention tries to ensure that the distribution centre is better able to cope with the inbound flow, i.e. the specialist tries to lower the inbound flow (on a daily basis, and as such it is also potentially reflected in the weekly number of inbound pallets).

Figure 11 demonstrates the high variability in inbound flow, that is the cause of the capacity problems at the distribution centre. This variability is mostly caused by the fact that orders that are made to fulfill promotions and increased demand due to seasonality and holidays are not spread out over a longer period of time, but are made (to arrive) at once. The goal of the research is to evenly spread this inbound flow over the year, such that the capacity problems during the peaks at the DCs are resolved.

2.5 KEY PERFORMANCE INDICATORS

The ADIL department needs to measure the extent to which it is able to achieve its goals. One approach to measure the performance is through Key Performance Indicators (Domínguez et al., 2019). As defined by Parmenter (2007), "KPIs represent a set of measures focusing on those aspects of organisational performance that are the most critical for the current and future success of the organisation".

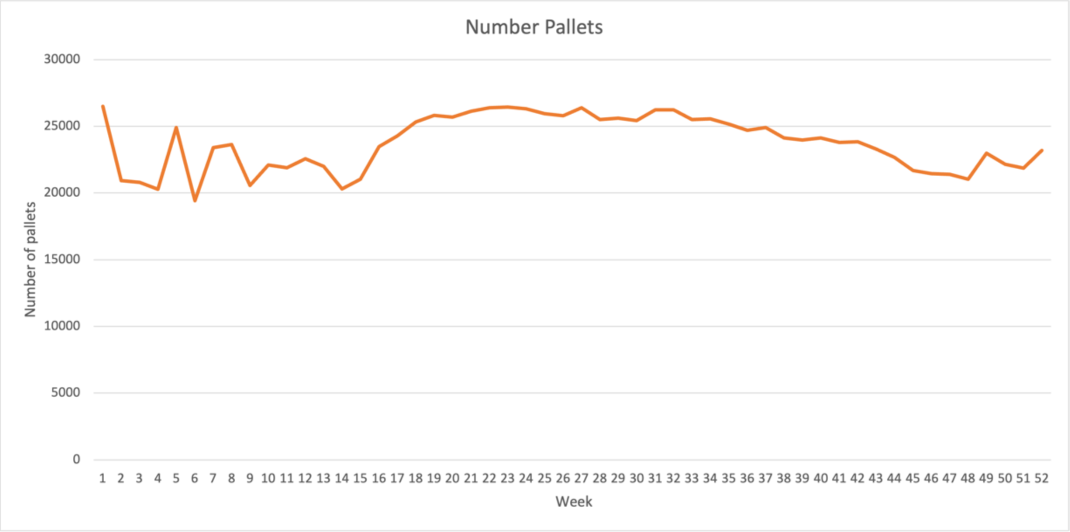

Figure 12: Inventory level at the Simon Loos DC in Tiel in terms of number of pallets on a weekly basis for the year 2021

Figure 12 shows an overview of the inventory level in terms of number of pallets for each week of the year 2021 for the Simon Loos distribution centre in Tiel, where most of ADIL's items are held. In Figure 12, the inventory level at the DC shows relatively stable behaviour throughout the year. This can be explained by the current ordering policy. As items are ordered as late as possible, they do not stay in the DC for an extended period of time. Therefore, the inventory level is mostly determined by the safety stock that the ADIL keeps in its DCs. From Figure 12, it can be found that the inventory was at a higher level for an extended period of time (from roughly week 18 to week 36). This increase in inventory can be explained by the fact that ADIL increased its safety stock due to the availability issues it was experiencing as a result of COVID-19. Ideally, the inventory level variation at the distribution centre is minimal. This to ensure that no additional capacity must be available that is not utilised most of the time. The inventory level variation will be measured through calculating the standard deviation. The formula to calculate the standard deviation is shown below, where s is the sample standard deviation, X represents each value, $\bar{x}$ is the sample mean, and n is the number of values in the sample.

$$s = \sqrt{\frac{\sum(X - \bar{x})^2}{n - 1}}$$

The standard deviation of the inventory level during 2021 amounted to 2,042.9448 pallets.

Moreover, the ADIL department has expressed that it would be valuable to monitor the performance of distribution centre, as this is where currently the most problems occur. A KPI that demonstrates this performance is the variability in utilisation of the inbound flow capacity. The utilisation levels can be calculated through dividing the daily or weekly inbound flow by the total inbound flow capacity on a daily or weekly basis respectively. The ADIL department wants this variability to be as low as possible, since a low variability not only means that the DC operatives don't experience high peaks in workloads, but also that the workforce can be arranged such that sufficient capacity is available for this constant inbound flow. Again, this variability will be measured through the standard deviation. Important to note is that the variability in the utilisation of the inbound flow and the inventory level variation are not directly related to each other, as the inventory level variation is influenced also influenced by the outbound flow. Hence, ordering and item allocation decisions can have a different impact on the inventory level variation compared to the inbound capacity utilisation variation. The standard deviation of the utilisation of inbound capacity during 2021 for the Simon Loos distribution centre amounted to roughly 8,25%.

2.6 CONSTRAINTS

In order to ensure that the model is feasible, several constraints need to be taken into consideration. These constraints were extracted from the knowledge of the ADIL department. As the decision making is currently mostly done by ADIL's planners, not all constraints are always fully met as would be the case through a decision-making model. However, to make the result of this research as feasible and realistic as possible, these constraints should always be met, and as such need to be added to the model.

- Demand must be met. This entails that delivery of items must be done on time, in advance of the expected demand.

- Items cannot be delivered too early before their expected demand date. If an item is delivered too early the distribution term might be violated, as the item spends too much time on the shelf waiting to be distributed. Therefore, items should be penalised more if they have a short distribution term or a low turnover rate (as a low turnover rate leads to items spending longer in the DC when they are transported early). Additionally, a hard constraint should be added such that items cannot be transported more in advance then the time they are allowed to spend in the DC.

- The transport units' capacity is a constraint. The transport units have both a pallet and a weight capacity, within which the assigned items need to fit.

- The transported items need to fit within the weekly capacity, otherwise they should be assigned to another transport unit in different week. If there is no possibility to assign all items to the available number of weekly transport units under all constraints, this number should be increased by one, as long as there are items that do not fit.

- The origin of items must be taken into consideration in case of truck transport. As we want to minimise the transport costs, we want to ensure that trucks do not have to pass multiple suppliers warehouses to pick up the goods. As such, the maximum number of suppliers in a truck should be set at 1.

2.7 CONCLUSION

This chapter investigates the current operations and performance of the Ahold Delhaize Inbound Logistics department in terms of the ordering and transportation process, key performance indicators, constraints, variation of inbound flow, and the number of transport units and items.

The current ordering process is visualised in Figure 5. Orders for a certain item are made when the item's inventory is expected to drop below the safety stock over lead time. On direct truck transport, only items from the same supplier are transported in one transport unit. The planner tries to order such that only FTLs are transported, so if the order of one item does not amount to a full truck load, the planner tries to add additional volume of the item or other items from the same supplier. On intermodal train and intermodal sea transport, consolidation can take place. The consolidation is done by logistics provider Hillebrand.

The transportation of items is done via truck, intermodal train transport, and intermodal sea transport. Truck transport is done directly from the supplier to the destined distribution centre. Intermodal train transport consists of three transport legs, namely first by truck, then by train and finally by truck again. Here again, for transport units with low utilisation consolidation can take place in the consolidation hub. The final mode of transport that the ADIL department uses is intermodal sea transport. Intermodal sea transport again uses three transport legs, in order of appearance truck, ship and truck. The ADIL department can either be responsible for all transport legs (FCA) or the last two transport legs (FOB). two or three legs of transportation.

In order to measure the performance of the current situation and compare it to the results of the research, Key Performance Indicators are formulated. The KPIs that will be used during the research are inventory level variability, and variability of the inbound flow capacity utilisation. The standard deviation of the capacity utilisation of the inbound flow amounted to 8.25% at the Simon Loos DC during 2021. The standard deviation of the inventory level amounts to 2,043.94 pallets, which is 19.47% when compared to the weekly inbound capacity. The standard deviation of the inbound capacity utilisation and the inventory level differ significantly, and this can be explained by the fact that the inventory level also depends on the outbound flow.

Moreover, the ADIL department currently plans its operations under several constraints, which also need to be taken into consideration. First of all, orders must be made such that in principle all demand is met. Moreover, the items should not arrive too far in advance of their demand point. Also, the origins of items must be taken into consideration to minimise transport and handling costs. Finally, the transport units have a certain capacity that cannot be exceeded. This capacity relates to both the volume and the weight.

For the reference year 2021, the data on the number of transport units and items was gathered. The total number of transport orders in 2021 amounted to 14,000. The total number of transported units equalled roughly 11,500 in 2021. Truck transport accounted for most of these transport units, namely 70.7%. Intermodal sea transport and intermodal train transport were responsible for 18.1% and 11.2% respectively, and all of these transport movements took place in Europe. Sea transport consisted of transport movements from South America, Asia, Africa, Europe, Oceania, and North America, in decreasing order of percentage of the total number of transport units. All modes of transport can consist of consolidated shipments. Most consolidation in 2021 took place for sea transport from Africa. The number of transport units can be used to determine the required number of transport units in case the inbound flow is levelled throughout the year.

3. LITERATURE REVIEW

Chapter 3 answers Research Question 2: "What does the literature propose for assigning items to a given number of transport units with fixed capacity?", and thus describes the relevant literature. In Section 3.1, transportation networks are introduced. Section 3.2 describes the planning levels. In Section 3.3, the potential methods that can be used for item allocation to transport units are described (sub-question 2a: "What methods are available for item allocation given fixed capacity?"). Section 3.4 concludes on the most appropriate method for the problem at hand, and as such answers sub-question 2b: "Which method is the best fit to solve the item allocation problem to fixed number of transport units at the Ahold Delhaize Inbound Logistics Department?".

3.1 TRANSPORTATION NETWORKS

Transportation networks consist of nodes and links. The connections between these nodes and links represent how flows/goods can move through the network (Woxenius, 2007). In this research, we also consider a transportation network, namely the transportation network from ADIL's suppliers to its distribution centres. While no changes will be made to the structure of the transportation network, it is relevant to know more about which type of transportation network exist, and which type(s) are in place at Ahold Delhaize Inbound Logistics.

Six types of transportation networks can be formulated, which are applied in different industries, such as air transport and maritime (Chouman & Crainic, 2021; Siozos-Rousoulis et al., 2021). The transportation network types, as described by Woxenius (2007), are discussed below. In the given examples, O represents the origin from which items must be moved to D, the destination.

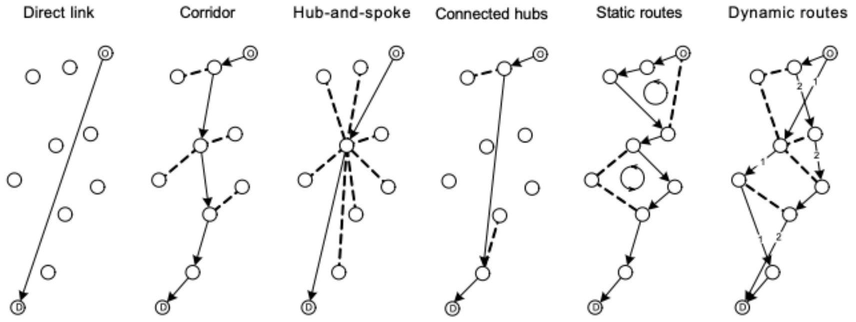

Figure 13: Transportation network types (Woxenius, 2007)

In Figure 13 the different types of transportation networks are shown. Their definitions are elaborated below.

- Direct link: according to Woxenius (2007), in direct link transport, items are moved directly from O to D without passing through other nodes. The direct link design is applied most in road transport, as it is the most efficient. It applies to both passenger services and freight services.
- Corridor: the corridor network formulation, as provided by Woxenius (2007), is defined as a design with one artery (corridor) with a high-density flow and short capillary services to nodes of this artery. In this design, nodes are hierarchically ordered. The corridor alternative finds many applications, not only in industry, but also in the supply of infrastructures, such as canals and rivers. Another typical application of the design is in intercity passenger trains with regular stops along the way. Finally, the corridor resembles the geographical layout of inland waterways, and as such is often applied to this case as well.
- Hub-and-spoke: the hub-and-spoke design consists of a hub, through which all movements must pass, even movements between an adjacent O and D (Woxenius, 2007). The hub-and-spoke

layout is mostly applied in areas with a dominating centre and depending surrounding cities/nodes. It finds applications in both freight transport and passenger transport. The location of the hub is based on the minimal transport cost for freight transport, but for passenger transport it is chosen from a selection of centrally localised terminals with a significant role as origin and destination. The hub-and-spoke design is mostly found in air transportation, but also finds some applications in rail freight.

- Connected hubs: in the connected hubs layout local flows are collected at hubs that are connected to other hubs in different regions. According to Woxenius (2007), this design can be described as regional consolidation. This design is mostly applied in international transportation, while it also applies to domestic general cargo by road in some instances. In case of international transportation, applications have been found in container shipping, rail freight, and truck transport.
- Static routes: as stated in Woxenius (2007), in the static routes alternative, several links are designated to be used on a regular basis. Multiple nodes are used as transfer points along the route, at which usually only part of the load is transferred. Transfer is not needed at every node. Most applications of this network design can be found in public transport, with some applications also available on cargo truck services. Other freight transport modes do not find many applications.
- Dynamic routes: in the dynamic routes design links are designated based on the demand, and a decision can be made between different routes from O to D (Woxenius, 2007). This network type's freight applications can be found in LTL operating where all items stay on the truck and no terminals are used.

The direct truck transport at ADIL follows the direct link, as items travel directly from the supplier to the Distribution Centre. The intermodal rail and intermodal sea transport can all be considered to be a hub-and-spoke network. Items move from the origin through a hub, where they are potentially consolidated. From this hub, they are moved onto their mode(s) of transport and transported to the final destination.

3.2 PLANNING LEVELS

As stated by Crainic and Laporte (1997), "transportation systems are rather complex organizations which involve a great deal of human and material resources and which display intricate relationships and trade-offs among the various decisions and management policies affecting their different components". These policies can be divided into three planning levels (Crainic & Laporte, 1997):

1. Strategic (long term) planning: this planning level considers long term planning decisions that require large capital investments over a long time period, such as the design of a physical network, location of facilities and resource acquisition. For these decisions, the highest level of management is typically involved.
2. Tactical (medium term) planning: at this planning level, decisions are made to improve the performance of the whole system through an efficient allocation of the existing resources over a medium-term horizon. Decisions made at the tactical planning level only consider aggregated data and no day-to-day information. Examples of decisions made at this planning level are design of the service network, traffic routing under the available services and terminals, repositioning of resources, etc.
3. Operational (short term) planning: operational planning is the most dynamic planning level, in which time plays an important role (short time horizon). Decisions at this level include scheduling of services and routing and dispatching of vehicles. These decisions are made by local management.

This description by Crainic and Laporte (1997) shows the clear flow of data between these different planning levels, from general policies (strategic planning level) that are used to make decisions (tactical planning level), which in turn effect the goals and rules on the operational level. The data flows from the lower planning levels to the higher levels in order to provide the information required for the decision-making process at these higher levels.

Decisions made on one of the planning levels strongly influence the decisions that can or must be made on the other planning levels, as a result of the high information flow between these different levels. Therefore, it is essential to be aware of the planning level in which one is making decisions and the resulting implications for the other planning levels. For this reason, it is important to determine in advance which planning level decisions will be made during this research, and how these decisions influence each other or other planning levels.

The research considers separately both the strategic planning level, as well as the tactical planning level. The strategic planning level decision is related to the determination of the fixed number of transport units. Determining this number has long-term implications, as the number will be fixed for the entire year (both in reality and in the model) and will strongly influence the tactical and operational decisions the ADIL department will be able to make. Deciding on too few transport units will result in capacity problems, which could result in items that cannot be moved with the set fixed capacity. Moreover, setting the number of transport units at a number that is too high will have financial implications, and in addition, as the utilisation of the number of transport units can vary, it could result in a solution that still does not result in a levelled inbound flow (of actual number of pallets rather than transport units). How items are allocated to the fixed number of transport units is a tactical planning level decision, as this decision can vary each week, such that the performance is improved through efficient allocation of the existing resources, as described by Crainic and Laporte (1997).

3.3 ITEM ALLOCATION TO TRANSPORT UNITS

3.3.1 Model formulations

Many different theories are available in the literature on ways in which items can be allocated to a transport unit, container, or other location, under a variety of objectives. Due to its many application possibilities, item allocation is considered in various industries in different forms. Naturally, as these varieties all consist of similar aspects, not all apply to the allocation of items to transport units.

This section aims to provide insight into so-called ‘Cutting and Packing (C&P) problems’, which are problems that are described with different terms in literature, but essentially have the same structure (Dyckhoff, 1990). According to Wäscher et al. (2007), the structure of C&P problems consists of two sets, (1) a set of large objects and (2) a set of small items, which are defined in one or multiple geometric dimensions. From the set of small items, some or all items can be grouped together, and each group should then be assigned to a single large object, such that all assigned small items fit in the large object and no small items overlap (Wäscher et al., 2007). According to Dyckhoff (1990), the bin packing problem, container loading problem, knapsack problem and multi-processor scheduling problem, amongst others, are C&P problems.

In this research, items must be assigned to transport units, under a levelled and fixed inbound flow. The cutting and packing problems are highly related to this case, because of their nature: each problem considers assigning smaller items to one, multiple or limited large objects (of a defined capacity). In Sections 3.3.1 to 3.3.4, some of these related problems will be described, as well as how they relate to the problem at ADIL.

Lot sizing problem

The lot sizing problem has been extensively researched and aims to determine the economic production or order lot sizes considering inventory and setup/order costs (Glock et al., 2014). Bitran and Yannase

(1982) show special cases for which the problem is considered to be NP-hard. According to Karimi et al. (2003), the complexity of a specific variant of the lot sizing problem depends on the planning horizon, number of levels and products, capacity or resource constraints, inventory shortage, demand, deterioration of items and setup structure.

The objective of the lot sizing problem is to meet demand while minimising the total costs (Lee et al., 2005). In literature, various heuristics and dynamic programming algorithms can be found to solve the model to optimality or near optimality (Glock et al., 2014; Latha et al., 2021; Lee et al., 2005; M. Zhang, 2015).

The lot sizing problem is relevant to consider as it is able to consider a multi-period case. Moreover, the model assumes that demand is met, which is what should be considered for the case at the ADIL department as well. Since, to allow for this, all items must arrive on time. The uncapacitated lot sizing problem has been researched extensively, however the research on the capacitated lot sizing problem is relatively limited. For the problem at hand, the capacity must be taken into consideration. Finally, the lot sizing problem focusses on determining when and how much of a product to produce, such that the setup, production and holding costs are minimised (Karimi et al., 2003), or in the case of the problem at hand, when and how much of a product to transport under the same/similar constraints. As such, the problem does not directly relate to the problem at hand, as we do not wish to focus on minimisation of setup, production and holding costs, but rather a minimisation of the penalties and transport costs.

Bin packing problem
According to Bódis et al. (2019), the bin packing problem (BPP) in its original form consist of *n* items, each with a known size. These items have to be assigned to bins with a given capacity, such that the minimal number of bins is used. As such, in its original definition the bin packing problem is one-dimensional. Research has also been performed in the direction of two-dimensional bin packing problems, in which items have a given width and height instead of volume (Côté et al., 2021). Similarly, the three-dimensional packing problem consists of a set of three-dimensional items, with a given width, height and depth (Lodi et al., 2002). Like the other C&P problems, the bin packing problem is NP-hard (Abdul-Minaam et al., 2020), and as such mostly heuristic methods are applied to solve the problem.

The bin packing problem is relevant as it considers a fixed capacity packing problem, which is the case at hand. Moreover, since the loading of the transport units is only limited by the pallet capacity (and weight capacity) and is as such one-dimensional, the many applications of the one-dimensional BPP can be of use during the research. Finally, the heuristic methods that are applied to solve the bin packing problem can be used as inspiration for the heuristic method developed for the problem at hand, as the methods again consider the limited capacity. However, the bin packing problem differs in terms of its objective. In case of the bin packing problem, all items that are demanded in a certain week are transported in such a way that a minimum number of bins is used. However, for the problem at hand, all items must be transported on or before their demand point, in a given number of bins with fixed capacity, in such a way that the total penalties and transport costs are minimised. Concluding, the objective of the bin packing problem does not fully align with the objective of the research problem.

0-1 Knapsack problem
The Knapsack Problem is a well-known combinatorial optimization problem that has been widely discussed in literature. Many adaptions of the problem have been studied and applied in various fields. According to Garey and Johnson (1978), the Knapsack Problem is NP-hard.

In its original form, the Knapsack Problem aims to maximise the total profit as a result of items in the Knapsack (Kellerer et al., 2004). The model considers n items that can be added to the knapsack. Each item has its own profit and weight, and the decision that must be made is whether or not to place the item in the knapsack with a fixed capacity. This formulation of the knapsack problem is also called the 0-1 knapsack problem, because of the binary decision variable. The 0-1 Knapsack problem relates to the bin packing problem in the sense that in both cases items need to be assigned to a larger item with a fixed capacity, and both problems consider one dimension.

The 0-1 Knapsack problem relates to the research problem. First of all, the objective of the knapsack problem is to maximise the profit of the assigned items to the knapsack. This objective is similar to the research problem, as in this case the objective is to minimise the penalties and transport costs. This effectively also means that the profit is maximised, as the profit of the items that are sold remain the same and subtracted costs are minimised. Moreover, in the case of the 0-1 knapsack problem items are assigned to a knapsack of fixed capacity. This also relates to the research problem, as items need to be assigned to a transport unit of fixed capacity. However, it is possible to leave certain items behind (out of the knapsack) and not transport them. As in the case of ADIL all demands must be met, this should not be possible, so in this respect the Knapsack Problem differs from the problem at hand.

Variants of the Knapsack Problem

In the following section, the different variants of the 0-1 Knapsack Problem are discussed. These selected variants are those that relate the most to the case at hand, based on the characteristics of the problem such as the fact that multiple TUs are considered and multiple constraints must be taken into consideration. The section concludes with their relevance and differences to the research problem.

An often-researched adaption of the Knapsack Problem is the Multiple Knapsack Problem (MKP). In the MKP we need to assign n items to m multiple knapsacks. Every knapsack i has an individual capacity c_i, and each item j has a size s_j and a profit p_j (Chekuri & Khanna, 2005). Similarly to the KP, items must be added to the m knapsacks such that the profit is maximised. An extension of the MKP, is the Multiple Knapsack Assignment Problem (MKAP). Differently from the MKP, in the MKAP the items are divided into K mutually disjoint subsets of items N_k (Kataoka & Yamada, 2014). According to Kataoka and Yamada (2014), in the MKAP the assignment of knapsacks to each subset must be determined and items from the subset must be selected such that the total profit is maximised.

The multi-dimensional knapsack problem is also an adaption of the knapsack problem, where again a subset of given items is selected in such a way that the total profit is maximised, but now a set of knapsack constraints must be satisfied as well (Deep & Bansal, 2008). This multi-dimensional adaption of the knapsack problem should not be confused with allocating three-dimensional items to the knapsack. This problem is considered to be strongly NP-hard (Angelelli et al., 2010). Several exact and heuristic algorithms are available in the literature to solve this problem.

The multi-dimensional multiple knapsack problem (MDMKP) is a combination of the MKP and MDKP. The MDMKP considers multiple knapsacks, and each knapsack consists of multiple constraints (Mancini et al., 2021). There is little research available on the MDMKP in literature, however, there are relevant instances to which an integer program has been applied to a problem that can be defined as an MDMKP.

As for the case at hand items need to be assigned to multiple transport units, this relates the most to the multiple knapsack application of the 0-1 KP. However, important to note is that similarly to the 0-1 Knapsack Problem, the formulation allows items to be left behind which is not allowed in the case of ADIL. For the research problem, more than one constraint needs to be taken into consideration, which is most similar to the multi-dimensional KP. The multi-dimensional multiple knapsack problem combines both the fact that multiple knapsacks need to be filled and the fact that multiple constraints must be taken into consideration. Therefore, this particular application of the knapsack problem is the most relevant. The heuristic methods as described can be used as inspiration for solving the model. However, it is important to note that the 0-1 knapsack problem does not directly relate to the problem at hand, as the 0-1 decision variable is not applicable in this case, since the volume of a certain item that is assigned to a transport unit needs to be determined.

Container loading problem

The container loading problem is a generalisation of the 0-1 Knapsack problem, and as such has similar characteristics as both the 0-1 Knapsack Problem and the bin packing problem. In its original form, the container loading problem (CLP) is a three-dimensional packing problem, in which items have to be loaded into a container of a given size subject to several constraints (Gajda et al., 2022). However, according to Pisinger (2002) there are several variations of the container loading problem, such as strip packing, knapsack loading, bin-packing and multi-container loading. This again displays the strong relation between these different C&P problems.

As stated in Gehring and Bortfeldt (1997), the original application of the CLP aims to maximise the total value of the loaded items under the relevant constraints by selecting a subset of all items available to load in the container. The value of items can be described as the volume or the freight rate (Gehring & Bortfeldt, 1997).

The CLP is considered to be NP-hard, as such it is often solved using a heuristic approach (Scheithauer, 1992). Various heuristic approaches have been described in the literature, including genetic algorithms, tertiary tree-based approaches, randomized constructive heuristics, neighborhood structures and many more (Gehring & Bortfeldt, 1997; Parreño et al., 2010; Scheithauer, 1992; Wang et al., 2008; D. Zhang et al., 2012).

The container loading problem is relevant since it considers the loading of items into a container of a certain size (capacity). Moreover, the CLP takes multiple relevant constraints into consideration which also relates strongly to the problem at hand, in which not only capacity constraints must be taken into consideration, but also constraints related to the demand of items, limitation on the weeks items are allowed to be transported in advance, etc. In addition, the objective of the CLP aligns partly with the objective of the problem at hand, as maximising the value of loaded items relates to the minimisation of penalties and transport costs, since this also means the profit of the problem is maximised. The CLP differs from the problem at hand, since it is a three-dimensional problem in its original form. However, there are also one-dimensional versions of the CLP available.

3.3.2 Applications to Transportation Planning

The models and methods described find variant applications in literature. One instance in which an MDMKP has been formulated is by Cao et al. (2012). The problem maximises the total profit as a result of the accepted freight bookings for goods over a multi-period planning horizon under limited shipping and loading capacities (Cao et al., 2012). The problem, as described by Cao et al. (2012), considers one origin and multiple destinations. The paper proposes two heuristic algorithms to approximate the optimal solutions. The first heuristic algorithm is based on the algorithms provided by Loulou and Michaelides (1979) and Toyoda (1975) and is called HA (Heurisitc Algorithm) (Cao et al., 2012). In the formulation of HA as provided by Cao et al. (2012), the algorithm starts empty and adds the item with the highest profitability iteratively and one at a time, as long as the constraints do not get violated. Here the profitability is formulated as an adaption of the formulation of Toyoda (1975), where the profitability is based on an effective gradient. The value of this gradient is dependent on the item, the mode of transport, and the period in which this item is transported via a transport mode (Cao et al., 2012). To improve the accuracy of the heuristic algorithm, Cao et al. (2012) formulate an algorithm named IHA (improved heuristic algorithm). In the IHA, three methods are used to obtain solutions based on which the best solution is selected (Cao et al., 2012).

Another relevant application is described by Ang et al. (2007) for a cargo mix problem with a multi-period planning horizon. Similar to the paper by Cao et al. (2012), it aims to maximise the "total profit generated by all freight bookings accepted in a multi-period planning horizon subject to constraints, such as available volume capacity, available weight capacity, and the number of available empty containers at the port of origin" (Ang et al., 2007, p. 1383). Again, the model considers one origin and multiple destinations. As no similar problem has been studied in literature (at that time), Ang et al.

(2007) suggest two heuristic algorithms to solve the problem. The first algorithm formulated by Ang et al. (2007) is called HAM (heuristic algorithm for MDMKP). HAM starts with no items and evaluates the profitability of each item, after which the most profitable item is accepted, one item at a time. Here, the profitability is based on the procedure as described by Toyoda (1975), by formulation an adaption G_{kt} of the effective gradient G_k, where the rate of profit depends on the item k and the period in which it is shipped (Ang et al., 2007). This procedure of selecting the item with the highest profitability is repeated as long as the solution is feasible. The second heuristic as formulated by Ang et al. (2007) is called MHA (modified heuristic algorithm). In this algorithm, solutions are obtained by six methods from which the best solution is chosen.

The paper on lot sizing by Lee et al. (2005) allows for the simultaneous determination of lot sizes and the transportation policy. The bin packing problem and approach as described by Côte et al. (2021) can be applied to production, warehouse management and transportation. The heuristic algorithm for the multiple knapsack problem as formulated by Kataoka and Yamada (2014) can be used by marine shipping companies for drawing up a cargo plan. Mancini et al.'s exact algorithm applies to the resource management of distributed computing contexts and service-oriented architecture (2021). Loulou and Michaelides's greedy-like algorithms are of use for capital budgeting problems (1979). The formulation by Cao et al. (2012) is used to define an optimal multi-period rail container shipment planning problem in multimodal transportation, whereas the related formulation by Ang et al. (2007) is applied to a multi-period sea cargo mix problem. The papers on the container loading problem all apply to real-world packing and container loading problems (Gajda et al., 2022; Parreño et al., 2010; Pisinger, 2002; Scheithauer, 1992; Wang et al., 2008; D. Zhang et al., 2012).

Next to the applications to transportation planning of the papers discussed in Section 3.3.1, some of the research sparked additional research that describes other applications of the literature in transportation planning. An example is the paper by Xu et al. (2015) where the container allocation problem with random freight demands in synchromodal transportation network form the container carriers' perspective is investigated. Related to the Multidimensional Knapsack Problem, Kress et al. (2007) introduce a Minmax Multi-Dimensional Knapsack Problem that finds its application in a military logistics problem, for ground operations such as resupply of ammunition to an artillery battalion. Moreover, Ang et al. wrote another paper on a multiperiod sea cargo mix problem for the container shipping industry (2009). Another application of the Multi-Dimensional Knapsack Problem finds its use in the oil industry, in an optimisation problem that aims to find the optimal two-dimensional positioning of deck cargoes (Seixas et al., 2016).

There are many more applications available, but the main applications can be found in truck, train, sea and air transportation for the loading of the transport units themselves or the containers that are transported on these transport units. Next to applications in transportation, applications are also common in warehousing and other forms of logistics, such as military logistics.

3.3.3 Solution approaches

In Section 3.3.1, the Lot Sizing Problem, Bin Packing Problem, Knapsack Problem and its relevant variants and the Container Loading Problem are discussed. Table 1 provides an overview of these different solution approaches described in the papers discussed in the previous section. The dash indicates unknown. From the relation between the described models and the research problem at hand, the appropriate solution approach can be based on the solution approaches of these papers.

From Table 1, it can be concluded that almost all papers describe a heuristic approach to solving the problems. This can be explained by the fact that the problems are NP-hard, and thus complex to solve in a reasonable amount of time through an exact approach. Two models and their solving methods specifically stand out as being applicable to solving the research problem and describe the heuristic approaches for solving an MDMKP.

Table 1: Overview of solution approaches

Paper	**Problem type**	**Solution method described**	**R/A?**	**Scenario size?**
Latha et al. (2021)	Lot sizing problem	Continuous review models	A	n.a.
Lee et al. (2005)	Lot sizing problem	Heuristic algorithm with adjustment mechanism	A	3-10
M. Zhang (2015)	Lot sizing problem	Dynamic programming-based algorithm	n.a.	n.a.
Bódis et al. (2019)	Bin Packing Problem	Heuristics: Next-Fit, First-Fit and harmonic algorithm	A	100-100,000
Côte et al. (2021)	Bin Packing Problem	Branch-and-Cut algorithm	A	20-100
Lodi et al. (2002)	Bin Packing Problem	Height first-Area second heuristic algorithm and Tabu search	A	10-100
Abdul-Minaam et al. (2020)	Bin Packing Problem	Optimised swarm algorithm and fitness-dependent optimiser	A	50-500
Kellerer et al. (2004)	Knapsack Problem	Exact algorithms and approximation algorithms	/	/
Chekuri and Khanna (2005)	Multiple Knapsack Problem	Generalised assignment problem	n.a.	n.a.
Kataoka and Yamada (2014)	Multiple Knapsack Problem	Heuristic algorithm	A	200-6,400,000
Deep and Bansal (2008)	Multi-Dimensional Knapsack Problem	Socio-cognitive particle swarm optimisation	A	60-250
Angelelli et al. (2010)	Multi-Dimensional Knapsack Problem	Kernel search framework (heuristic framework)	A	500
Mancini et al. (2021)	Multiple Multi-Dimensional Knapsack Problem	Exact algorithm based on a specific combinatorial Benders’ cut approach	A	1,200-6,000
Cao et al. (2012)	Multiple Multi-Dimensional Knapsack Problem	Heuristic algorithms: adaption of effective gradient method	A	624- 930

Paper	**Problem type**	**Solution approach described**	**R/A?**	**Size of scenarios?**
Loulou and Michaelides (1979)	Multi-Dimensional Knapsack Problem	Greedy-like heuristic methods	A	200-2,400
Toyoda (1975)	0-1 Programming Problem	Heuristic: primal effective gradient method	A	100-300
Ang et al. (2007)	Multiple Multi-Diemsnional Knapsack problem	Heuristic algorithms: adaption of the effective gradient method	A	123-25,992
Gajda et al. (2022)	Container Loading Problem	Randomised constructive heuristic	R	2-442
Pisinger (2002)	Container Loading Problem	Heuristics based on the wall-building approach	A	50-150
Gehring and Bortfeldt (1997)	Container Loading Problem	Hybridised genetic algorithm	A	100
Parreño et al. (2010)	Container Loading Problem	Variable neighbourhood search	A	100
Scheithauer (1992)	Container Loading Problem	Heuristic algorithm based the “ forward state strategy” of dynamic programming	/	100-500
Wang et al. (2008)	Container Loading Problem	Heuristic: tertiary-tree-based dynamic space decomposition approach	/	/
D. Zhang et al. (2021)	Container Loading Problem	Heuristic block-loading algorithm based on multi-layer search	A	100

3.4 CONCLUSION

This chapter described the transportation network principle and planning levels, and investigated the current state on item allocation models and methods in literature in order to find the most suitable approach to the research problem.

From Section 3.1, it can be concluded that ADIL’s direct truck transport follows the direct link network design. All intermodal train transport and intermodal sea transport can be identified as hub-and-spoke networks, in which all transport movements pass through at least one hub.

The planning levels that will be considered in this research, as described in Section 3.2, are the strategic planning level for the determination of the levelled and fixed number of transport units, since this decision is related to capacity dimensioning and has long-term implications. Furthermore, the tactical planning level is considered for the item allocation method since decisions are made on a (shorter) weekly basis and relate to the performance improvement through efficient allocation of items to the existing resources.

In Section 3.3.1, different item allocation models and methods are discussed that relate to the research problem, namely the lot sizing problem, the bin packing problem, the 0-1 knapsack problem and its variants, including the multiple multi-dimensional knapsack problem, and finally, the container loading problem. From all problems described there is not a single problem that proves to be the exact/best fit. However, from all problems parts can be taken that can be used to formulate the model and solving approach for the research problem. The lot sizing problem allows for the consideration of multiple periods. Moreover, all demand must be met, which is also the case in the container loading problem. The relevant capacity constraints are a part of the bin packing, knapsack, and container loading problem formulations. Both the container loading problem and the knapsack problem have the same objective that can be related to the research problem, namely value/profit maximisation of the assigned/transported items (as for the problem at hand the objective is to minimise the penalties and transportation costs, which leads to an increase in the profit as the profit of items remains equal due to the fact that all items must be transported). The fact that multiple constraints can be added to the multi-dimensional KP, and the container loading problem is relevant, because multiple constraints need to be added to the research problem’s model, like demand fulfilment constraints (next to capacity related constraints). The fact items need to be allocated to multiple transport units is reflected in the multiple KP. The multiple multi-dimensional knapsack problem ensures that items can be added to multiple knapsacks (TUs) under multiple constraints. Concluding, the relevant parts of the different models described will be used to formulate the model for the case at hand.

With regards to the solving methods, Section 3.3.2 shows that almost all models described in Section 3.3.1 are solved via a heuristic approach. The heuristic approaches that can best be used as inspiration to solve the problem at hand use an adaption of the effective gradient method to iteratively add the items with the highest profitability as long as the constraints do not get violated. The modified/improved version of the algorithm uses multiple methods to generate solutions from which the best is chosen. Naturally, the solving method needs to be adjusted to fully fit the model. For example, instead of a gradient method, a constructive method can be used, as long as it iteratively adds the item that results in the highest profitability. As such, the idea behind the approach, iterative item allocation that results in the highest profitability, remains intact. In addition, the other heuristic methods can serve as inspiration to solve the model.

4. MODEL DESCRIPTION

This chapter provides the model description and thus answers Research Question 3: “How should the assignment of items to transport units be designed?”. Section 4.1 answers Sub-Question 3a (“What is the scope of the model?”) and describes the scope of the model. In Section 4.2, the assumptions that are made are described and motivated, in order to answer Sub-Question 3b: “What assumptions are made?”. The mathematical formulation, which includes the indexes, parameters, variables, objective function, and constraints, is discussed in Section 4.3. As such, this section answers Sub-Question 3c: “What is the final model formulation?”. Finally, in Section 4.5 Sub-Question 3d: “What is the solving method?” is answered.

4.1 SCOPE OF THE MODEL

As the model will be run with historical data (from 2021) for the number of transport units and items, only minor changes will be made to the number of transport units of each type. The reason for this is the fact that all items from 2021 must be assigned and the transport unit type they can be assigned to is fixed. As such, the number will not vary a lot from the known number of TUs of each type in 2021 (as found in the historical data). The historical data will determine the initial solution for the number of TUs of each type, and based on the experimental results this number may be altered. Despite the fact that the actual number of transport units of each type might fluctuate slightly, the decision between different types of transport units for a certain location is fixed (i.e. the TU’s size for a certain supplier is fixed) and out of the scope. The model is formulated to perform one run for the entire year, despite making decisions on a weekly basis.

It is known with which transport mode(s) items were transported from a certain origin in 2021. This mode of transport is often reflected in the type of transport unit, but no special attention is paid to the transport mode. Concluding, the decision on the mode of transport is left out of the scope.

4.2 ASSUMPTIONS AND REQUIREMENTS

The model has to meet several requirements, which are listed below. Moreover, due to the complexity of the model, some assumptions are made to keep the model tractable while still capturing all important features of the problem faced by ADIL. Important to note is that next to these requirements and assumptions, the model is also subject to several constraints, as discussed in Section 2.6.

- The allocation of items to available transport units is done such that it would be feasible in reality. In order to ensure feasibility, the known demand cannot be adjusted. Moreover, the resulting inbound flow of each item should be feasible for the distribution centre. Specifically, the constraints on transport unit capacity and demand fulfilment are hard constraints. The weight and pallet capacities of transport units should always be respected, as otherwise the result would not be feasible. The demand fulfilment constraint cannot be violated as this would lead to significant losses, due to lost sales.

- No intermediate stops are allowed, apart from stops that are made to consolidate orders. With this it is meant that the origins of orders cannot be adjusted. Items travel directly from this origin to the destination unless they are allowed to and need to be consolidated for further transport. Consolidation can only be done for transport from specified regions/suppliers and transport unit types.

- Weekly demand values are defined by the last available forecast of that week for each week of the year 2021. With the last available forecast it is meant that we consider the forecast that is available the week before, i.e. the forecast that is available in week 52 2020 for week 1 2021, in week 1 for week 2, in week 2 for week 3, and so on. This assumption is made as the forecast strongly reflects the information the planner has available at the time of ordering. Therefore, it strongly corresponds to the actual order that is made, apart from the additions that the planners make to the order when a FTL is not yet attained by transporting only the forecasted demand. The forecast is thus used as the fixed input for the weekly demand values.

- Items are assumed to be available at the time of ordering. Since the last available forecast for each week is assumed to be the demand, there might be a slight discrepancy between the orders as assumed as input for the model and the actual situation for the year 2021. When this difference becomes very large, additional research might be required to find the cause of the difference.
- The orders are made on a weekly basis. No distinction is made between the days of the week. It is assumed that if the weekly capacity is sufficient, the inbound flow will be divided over the days such that the daily capacity is sufficient as well. In principle, the model could be adjusted in the future in such a way that decisions are made on a daily basis.
- The decision between different types of transport units from an origin is out of the scope. It is assumed that the number of transport units from each origin of each type on a yearly basis is equal to the number of transport units from that origin of that type in 2021. As the number of transport units on a weekly basis will be levelled throughout the year in the new situation, the weekly number of transport unit of a specific type from an origin is fixed as well and is equal to the ceiling of the total number of that type from that origin divided by 52 weeks. This also means that the transport modes are fixed from a certain origin. As such, no decision needs to be made on the mode of transport.
- The the weeks items are transported in advance are penalised based on the items' distribution term and turnover rate. Moreover, there is a hard constraint that the number of weeks items are transported in advance cannot exceed their distribution term. However, the number of weeks items are allowed to be transported in advance should have an additional limitation. In discussion with ADIL, it is determined that it is undesirable that items are transported more than 6 weeks in advance. Therefore, this number is fixed in the additional constraint.
- The algorithm has a warm-up and cool-down period. The warm-up and cool-down period are equal to the number of weeks items are allowed to be transported in advance. As only one year is considered during this research, during the warm-up period, items can still be transported in the year before that is not considered. In addition, during the cool-down period, there could have been items from the year after, that were transported in the final period of the considered year that now are not shown. Therefore, it is important for the analysis to take this warm-up and cool-down period into account.

4.3 MATHEMATICAL FORMULATION

A mathematical model for the item allocation to a number of transport units on a weekly basis for one year is developed in this section. The problem formulation combines the relevant aspects of the different formulation as described in Section 3.3. In the item allocation problem, we have a set of I items, $\tilde{I}$, that have to be allocated to a set of n transport units, $\tilde{N}$. In doing so, the capacity constraints related to the pallet and weight capacity of the transport units need to be taken into consideration, as well as the demand fulfilment constraints. The objective is to minimize the penalties for items that are transported in advance of their demand point in a multi-period planning horizon and the costs of the occupied transport units.

In order to present the mathematical formulation of the problem for a given planning horizon, some notations are introduced below:

Index sets

$\tilde{I}$ Set of items $\{1, 2,\ldots,i,\ldots,I\}$

$\tilde{T}$	Set of weeks {1,2,…,t,…,T}
$\tilde{O}$	Set of origins {1,2,…,o,…,O}
$\tilde{U}$	Set of transport unit types {1,2,…,u,…, U}
$\tilde{N}$	Set of transport unit number {1,2,…,n,…,N}

Parameters

$d_{i,o}$	demand of item *i* from origin *o* (in number of pallets)
δ_i	due date of item *i*
w_i	weight per pallet of item *i* (in kg)
wc_u	weight capacity of transport unit type *u* (in kg)
c_u	pallet capacity of transport unit type *u*
$\Omega_{u,o}$	yearly number of transport units of type *u* in origin *o*
k_u	cost of transport unit type *u*
s_i	penalty for early arrival of item *i* in period *t*
G_i	distribution term of item *i*
B	maximum number of weeks items are allowed to be transported in advance
$z_{i,j}$	$\begin{cases} 1 & \text{if item } i \text{ cannot be transported with item } j \\ 0 & \text{otherwise} \end{cases}$
$q_{n,u}$	$\begin{cases} 1 & \text{if transport unit number } n \text{ is of transport unit type } u \\ 0 & \text{otherwise} \end{cases}$

Decision variables

$a_{u,o}$	number of transport units of type *u* used at origin *o* for each time period
$v_{o,n,t}$	$\begin{cases} 1 & \text{if from origin } o \text{ transport unit } n \text{ is used in period } t \\ 0 & \text{otherwise} \end{cases}$
$y_{i,t}$	number of pallets of item *i* transported in period *t* beyond $d_{i,t}$
$x_{i,o,n,t}$	number of pallets of item *i* transported from origin *o* in transport unit number *n* in period *t*

Objective function

$$\min \sum_{i=1}^{I} \sum_{t=1}^{T} (\delta_i - t) * s_i * y_{i,t} + \sum_{u=0}^{U} \sum_{o=1}^{O} k_u * a_{u,o}$$

Constraints

$$\sum_{i=1}^{I} x_{i,o,n,t} \leq M * v_{o,n,t} \qquad \forall o, n, t \ (1)$$

$$\sum_{i=1}^{I} x_{i,o,n,t} \leq \sum_{u=1}^{14} q_{n,u} * c_u \qquad \forall o, n, t \ (2)$$

$$\sum_{i=1}^{I} w_i * x_{i,o,n,t} \leq \sum_{u=1}^{14} q_{n,u} * wc_u \qquad \forall o,n,t \ (3)$$

$$\sum_{n=1}^{N} v_{o,n,t} * q_{n,u} = a_{u,o} \qquad \forall o,u,t \ \ (4)$$

$$a_{u,o} \leq \frac{\Omega_{u,o}}{52} \qquad \forall u,o \ (5)$$

$$\sum_{o=1}^{O} \sum_{n=1}^{N} \sum_{t=1}^{\delta_i} x_{i,o,n,t} = \sum_{o=1}^{O} d_{i,o} \qquad \forall i (6)$$

$$y_{i,t} = \sum_{o=1}^{O} \sum_{n=1}^{N} x_{i,o,n,t} \qquad \forall i,t < \delta_i \ (7)$$

$$y_{i,t} = \ 0 \qquad \forall i,t \geq \delta_i \ (8)$$

$$(\delta_i - t) * \ y_{i,t} \leq \ G_i * \ y_{i,t} \qquad \forall i,t \ (9)$$

$$(\delta_i - t) * \ y_{i,t} \leq \ B * \ y_{i,t} \qquad \forall i,t \ (10)$$

$$x_{i,o,n,t}, y_{i,t}, a_{u,o} \geq 0, integer \qquad (11)$$

$$v_{o,n,t} \in \{0,1\} \qquad (12)$$

Constraint 1 is formulated such that the variable $v_{o,n,t}$ takes the value 1 if items are transported from origin *o* in transport unit number *n* in period *t*, i.e. if the sum of the number of pallets of all items that will be transported assigned to that transport unit with number *n* is higher than 0. Constraint 2 ensures that the sum of all items that are transported in a particular transport unit does not exceed the capacity of the transport unit type. Constraint 3 is formulated such that the total weight of the assigned volume to a transport unit does not exceed the weight capacity of that transport unit's type. Constraint 4 ensures that the number of transport units of type *u* at origin *o* in period *t* is equal to the decided number of transport units of type *u* at origin *o* on a weekly basis. This decided number of weekly transport unit of type *u* at origin *o* cannot exceed the total number of transport units of type *u* in origin *o* used for the entire reference year divided by 52 (weeks), as per constraint 5. With constraint 6, it is ensured that the expected demand of an item is fulfilled in time. Constraint 7 defines the value of the number of pallets that are transported in advance of demand of item *i* in period *t*. No pallets of item *i* can be transported in advance of demand, once the demand week of item *i* has passed, as defined in constraint 8. Constraints 9 and 10 ensure that items cannot be transported more in advance than their demand week than allowed, both in terms of their distribution term and the maximum number of weeks all items are allowed to be transported in advance, respectively. Constraint 11 defines the values the integer decision variables can take. Constraint 12 defines the value the binary decision variable can take.

4.4 SOLUTION APPROACH

This section describes the approach that is taken to arrive at a solution. The problem at hand can be reduced to the 0-1 Knapsack Problem, which is *NP*-hard as demonstrated in Chapter 3: Literature Review. Therefore, the problem at hand is considered to be *NP*-hard as well. Due to the large number of integer variables, the problem becomes intractable for large instances. Therefore, it must be solved with a heuristic algorithm instead of exact methods. The problem is decomposed in two subproblems that are solved independently and sequentially. First, the number of transport units is determined, as described in Section 4.4.1, after which the item allocation to these transport units takes place, according to the methods as described in Section 4.4.2. Then the TU heuristic, as described in Section 4.4.1, is applied again. The entire process, as described above, is visualised in Figure 14. It is important to note that as the number of weekly TUs are determined for each origin, the model can be decomposed for all countries of origin and solved separately (only for the countries of origin that meet the requirements).

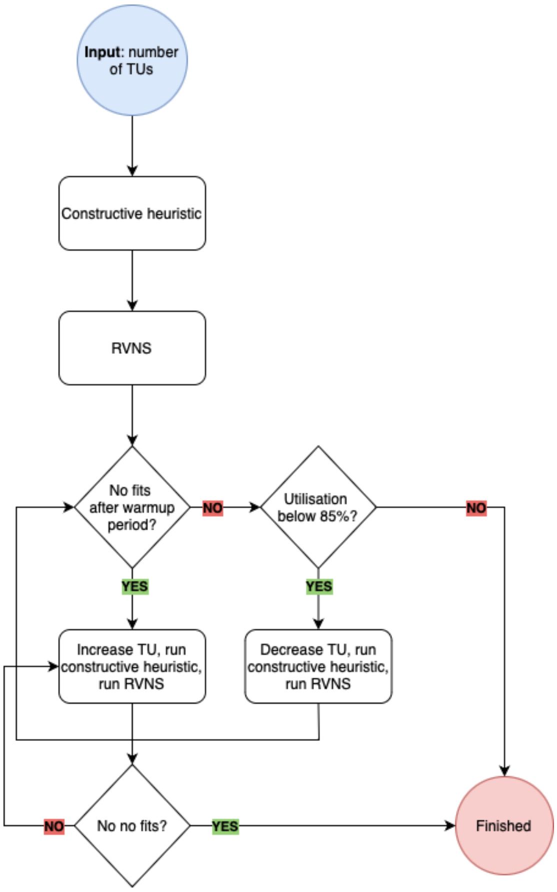

Figure 14: Flowchart two-phase solution approach

4.4.1 Determination fixed number of transport units

The levelled and fixed number of transport units on a weekly basis is determined through a heuristic approach. The number of transport unit type u at origin o is equal to the ceiling of the total number of transport units of type u transported from origin o for the entire reference year divided by 52 weeks. The total number is divided by 52 as we want to spread the number of transport units evenly throughout the year. The resulting number is used as an input to the algorithm (i.e. the number of transport units of each TU type is an input variable, that later can be adjusted). There are three scenarios that can occur during the runs, namely:

1. All items fit within the available number of transport units and the utilisation of the available transport units is sufficient, namely higher than or equal to 85%. Then, no further iterations are needed.
2. There are several items (after the warmup period) that cannot be transported in the available transport units. If this is the case, the number of transport units is increased, and another iteration is performed.
3. All items fit within the available number of transport units, however the utilisation levels are too low. In this instance, the number of transport units of the type for which this is the case is decreased by one and another iteration is performed.If both scenario 2 and scenario 3 are true, scenario 2 is performed until all items fit within the available number of transport units, since demand always has to be met.

4.4.2 Item allocation to transport units

The solution approach to allocate items to the available transport units is a heuristic method. Since the aim is to minimise item-dependent penalties based on the weekly turnover rate and distribution term of an item, the heuristic should allocate items to transport units such that the solution has an as low total penalty value as possible.

Some items have to be transported in advance of their demand point to allow for levelling of the inbound flow. This requires distinguishing between the different items in some way, as some items are preferred to be transported in advance compared to others. To aid the decision-making process, this distinction is made in the item-dependent penalty. This item-dependent penalty is the determining factor in which items are transported when, as the aim is to minimize the penalties for items that are transported in advance. The item-dependent penalty should reflect the turnover rate and distribution term. When items with a higher turnover rate are assigned lower penalties, they are prioritised over items with a lower turnover rate. This ensures that the items that already remain in the warehouse for a longer period of time get chosen later or with lower likeliness. It is important that this happens as this ensures that the inventory at the distribution centre increases over time as little as possible. Constantly transporting items with low turnover rates has the opposite effect. The distribution term should be taken into consideration as items with a long distribution term are more suitable for transportation ahead of their demand point compared to items with a shorter distribution term. If items with a short distribution term are transported in advance, there is an increased risk that these items pass their distribution term in the warehouse and can no longer be sold.

The method that will be applied consists of a constructive heuristic and a Reduced Variable Neighbourhood Search (RVNS) to improve on the initial solution, and is inspired by the heuristic methods discussed in Section 3.3, specifically the methods described by Ang et al. (2007) and Cao et al. (2012). The methods as described by Ang et al. (2007) and Cao et al. (2012) do not consider the use of a meta-heuristic to improve on the initial solution.

Constructive heuristic

The constructive heuristic generates the first solution of the model. Figure 15 shows the flowchart of the constructive heuristic, in which the steps taken in the model to generate the initial solution are shown. First, the idea behind the strategy is explained, after which the exact step by step approach is elaborated.

The constructive heuristic adds items to the transport units based on the week in which they have demand and their penalty in case of early transportation. First, items are added as early as possible, while not exceeding the number of weeks they are allowed to be transported in advance. If an item cannot be assigned before its moment of demand it is added to a NoFit list. The items on this list initially do not fit within the available capacity. As all demand must be met, this NoFit list is used to attempt to fit the items again at a later stage (after adjustments have been made) and to monitor whether after the algorithm has finished, there are still items that have not been allocated to TUs. If we consider an item before the week in which it has demand, the decision to add it or not is based on its penalty, under the condition that it does not exceed the number of weeks the item is allowed to be transported in advance. If we consider an item that still has to be added in the week of its demand, it is added immediately, naturally under the condition that it fits. After all items that could be added are added, an improvement step takes place in which items are moved to the week in which they have demand if that is possible. Once this is done, if there are items in the NoFit list, a second attempt is made to add these items to TUs.

More in detail, the constructive heuristic works as follows. Items are assigned to the transport units iteratively, starting from week 1 to week 52, and from the first transport unit of the respective week to the last. A minimum is initialised at 10,000, that is later used to find the best fit. The following conditions are checked: at least one pallet of the selected item fits within the selected transport unit in terms of the pallet and weight capacity, and the transport unit type the selected item must be transported in is equal to the transport unit type of the selected transport unit. In addition, if the transport unit type is a truck, and the selected truck has already been assigned items, the supplier of the selected item should be equal to that of the item's in the selected truck (only 1 supplier is allowed to be transported in the same truck). If the demand of the selected item from the list fits the transport unit in the considered week, and the selected item has the demand in the considered week, then the item is directly added to the transport unit, as the items always need to be transported no later than their demand point. If only a fraction of the demand fits in the TU, either limited by the pallet capacity or weight capacity of the TU, this fraction is added. If the selected item has demand during a later week than the considered week, and the difference between the considered week and the item's week is smaller than the maximum number of weeks items are allowed to be transported early and the distribution term of an item, the potential penalty for early transportation of a pallet times the number of pallets is calculated. If this total penalty is lower than the current noted minimum, the minimum is assigned the value of the generated penalty, and the selected item is stored. After all items that are left to be assigned have been considered, the selected item that results in the minimum penalty is assigned to the transport unit. If all demand of the selected item fits the selected TU, this is added. If only a fraction of demand fits the remaining pallet or weight capacity, only this fraction is added. This process is repeated as long as there is an item in the list that still fits the TU. In case there are items that do not fit fully into the weeks of or before their demand point, these items are added to a no fit list and removed from the list of items that still need to be assigned. These items will not be assigned, as they would generate lost sales.

When there are no more items in the list of items that need to be assigned, for all weeks and all transport units within these weeks, a check is performed in case the considered transport units are of the type truck. The check determines whether these trucks both transport items of the same supplier. If this is the case, and the contents of both trucks can be consolidated in one truck (both in terms of pallet and weight capacity), this consolidation is performed.

As for the generated solution items are always assigned as early as possible (up to a limited number of weeks earlier), the resulting solution might end up with some remaining capacity for the final weeks (depending on the number of items that must be assigned). As the aim is to generate an as low penalty as possible, items should be transported as close to their demand point as possible. Since this is not always the case for generated solution, an improvement is made to further optimise the initial solution. The improvement phase goes over the initial generated solution and first checks whether an item assigned to a transport unit in a specific week has its demand in a later week. If so, it is checked whether this item can be moved to the week in which it has demand, by checking for each available transport unit in that week whether the demand fits in the remaining capacity of that TU. If the item can be moved, it is removed from the TU it was originally assigned to and added to the new TU. If not, it is checked whether the item can be assigned in the week before its demand week, and so on.

Again, after the items are moved as close to their demand week as possible, an additional attempt is made to consolidate trucks with contents from the same supplier in the same week.

After this process is finished for all weeks, all TUs and all items, a second attempt is done to fit the items that were originally placed in the 'No Fit List'. For all items in the list, for all weeks and all available TUs in those weeks, it is checked whether the week in which the item has demand is equal to or later than the considered week. If that is the case, it is then checked if the item's demand fits the remaining capacity of the considered TU. If this is the case, the item is added to the considered TU and removed from the 'No Fit List'. If only a fraction of the item's demand fits the TU, again either limited by the pallet or weight capacity of the TU, this fraction is added to the TU and the demand that remains to be added is decreased by this fraction. If no more items on the 'No Fit List' can be added, the heuristic is finished and the results are printed. The final result shows the allocation of all items over the available transport units.

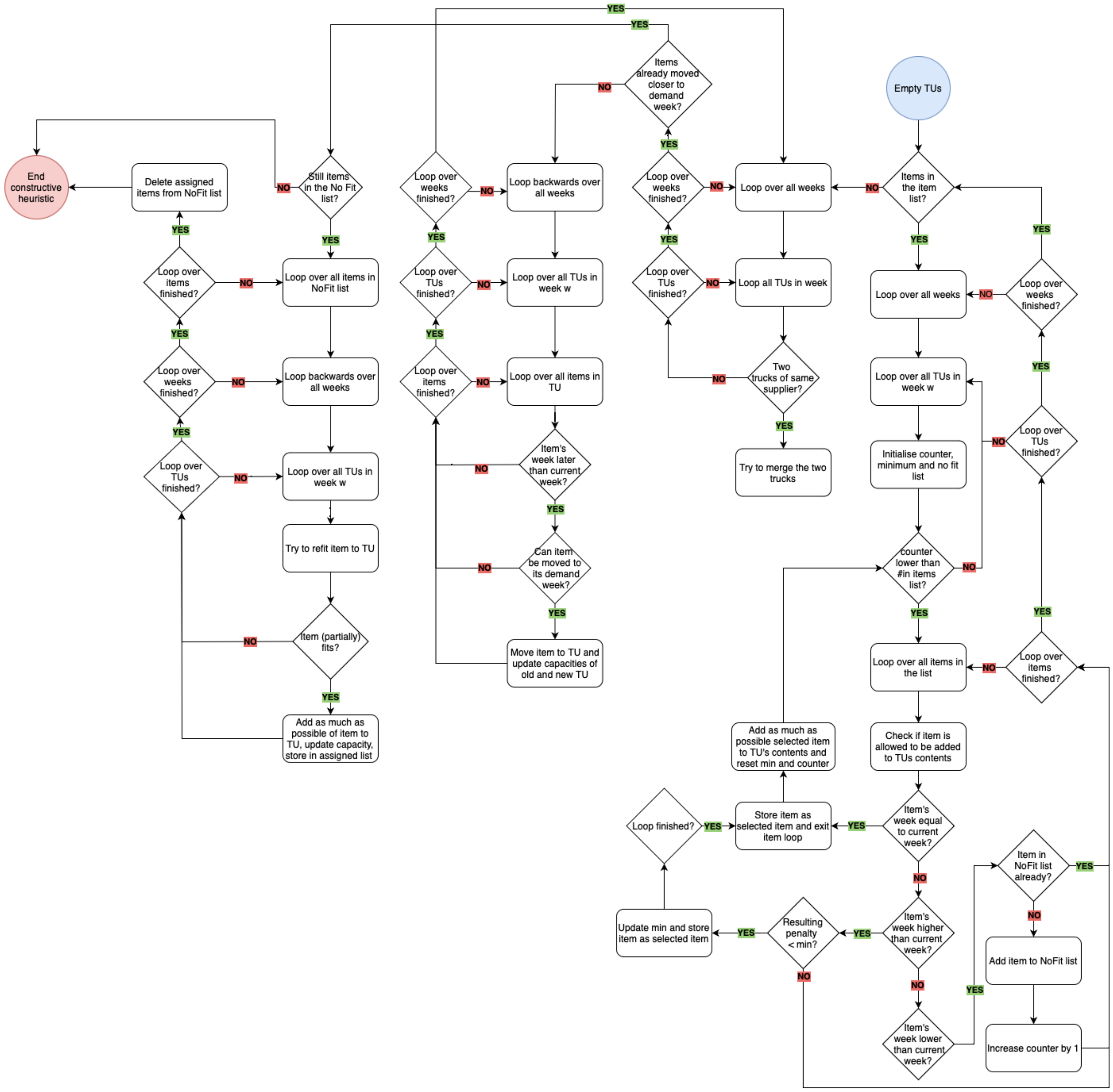

Figure 15: Flowchart constructive heuristic describing the step-by-step approach in which an initial solution is created

Reduced Variable Neighbourhood Search

The solution that results from the constructive heuristic is improved through a Reduced Variable Neighbourhood Search (RVNS). RVNS systematically exploits the idea of a neighbourhood change, making it possible to descent to local optima and escape the valleys that contain them (Hansen & Mladenovic, 2014). The RVNS algorithm follows the following approach, according to Hansen and Mladenovic (2014):

1. Initialisation:
    1) Select the neighborhood structures N_k, for k = 1, …, k_{max}
    2) Find an initial solution x
    3) Set a stopping condition
2. Repeat the following steps until the stopping condition is met:
    1) Set $k \leftarrow 1$;
    2) Repeat the following steps until $k = k_{max}$:
        i. Shake procedure: generate at random a starting solution $x' \in N_k(x)$
        ii. Move or not: If x'' is better than the incumbent x, move there ($x \leftarrow x''$), and continue the search with N_1 $(k \leftarrow 1)$; otherwise, set $k \leftarrow k + 1;$

Figure 16 shows the flowchart for the RVNS algorithm for this specific instance. At the start of the algorithm two stopping conditions are defined: the algorithm is stopped once the computation time exceeds a defined value, and once there is no improvement for a predefined computation time. Like in the RVNS, an operator is selected based on a generated random number. This can either be a move, swap or two-swap operator. The functionality of the operators is elaborated below:

- Move operator: Two random transport units are selected, that cannot differ more than the predefined maximum number of weeks items are allowed to be transported in advance, and their contents is stored, such that the change that will be made can be reversed if it does not result in a better solution. From both TUs, two items are selected. The two selected items are swapped, and the solution is checked for its feasibility. This feasibility check ensures that the change does not result in capacity violations for the considered TUs, the TU type an item is moved to is equal to the TU type it is allowed to be transported in and the weeks during which an item is allowed to be transported aligns with the week to which it is moved. Furthermore, if the TU type is a truck, only items from the same supplier can be swapped (as a TU is only allowed to consist of items from the same supplier). The operator finishes with the improvement check, that is, if the changed solution is feasible and leads to lower penalties, the change remains in place and this solution and its penalties are stored as the new current solution. Moreover, the time without improvement is reset. If the changed solution is infeasible or leads to higher penalties, the change is reversed.
- Swap operator: Like fore the move operator, two random transport units are selected. From both TUs, two items are selected. The first selected item from TU1 is moved to the location of the second selected item from TU2. Again, the same feasibility checks are done. Like for the move operator, the improvement check is performed.
- 2-Swap operator: Similarly to the move and swap operator, again two random transport units are selected. Two adjacent items are selected from both TUs for the 2-swap operator. The two items from the first TU are swapped with the two items from the second TU. Both sets of items

are reinserted at the location of the items that were previously there. Naturally, the feasibility check is also performed. Finally, also the improvement check is done.

Once one of the stopping criteria is reached, the RVNS finishes and a final attempt is done to fit the items that are still in the NoFit list. It is important to note that the results of the RVNS are subject to randomness, as a random number generator is used in the approach. The randomness asks for multiple replications, to obtain a higher certainty of the mean results/performance.

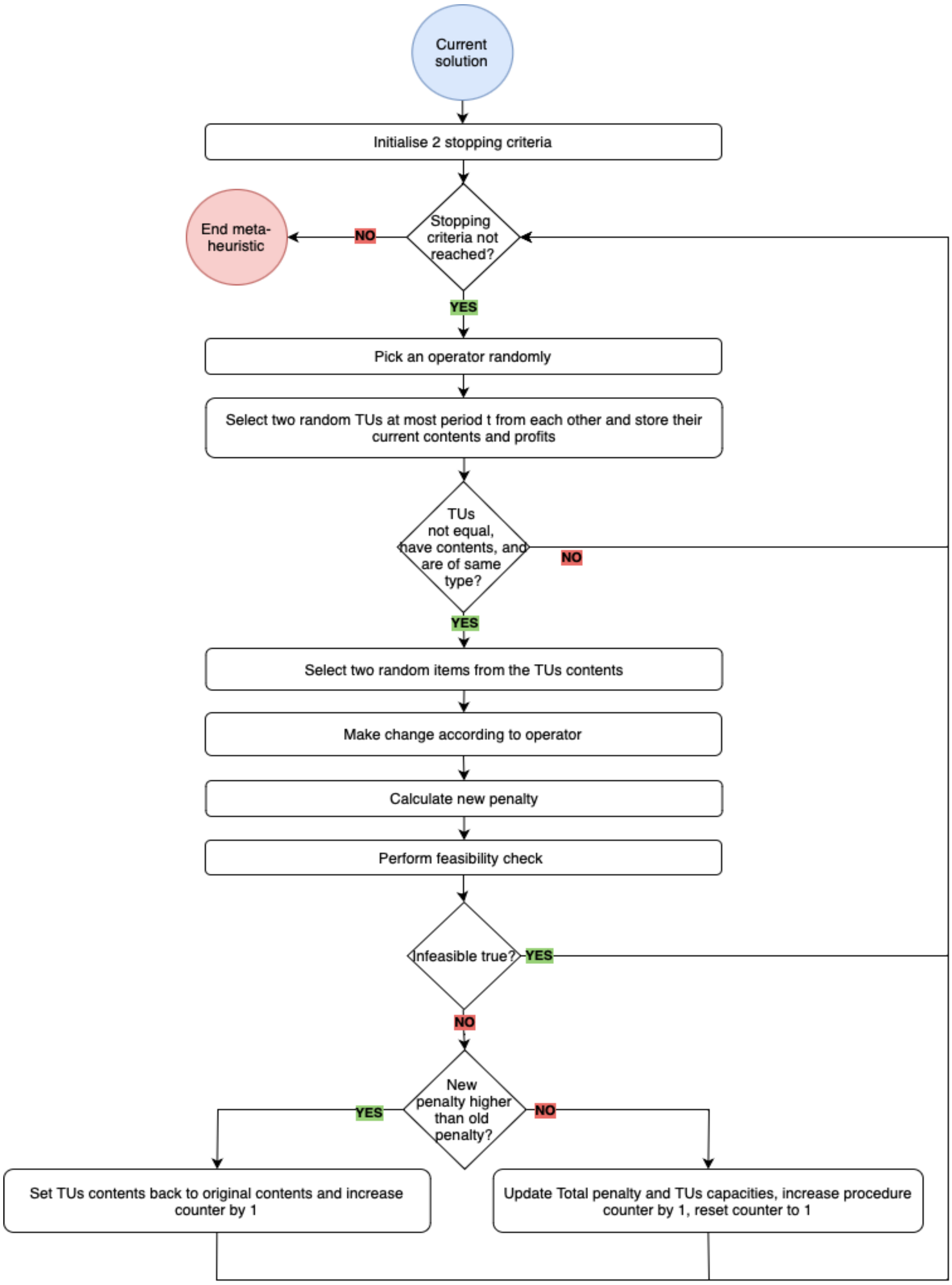

Figure 16: Flowchart meta-heuristic describing the approach of the RVNS to improve the initial solution

5. NUMERICAL EXPERIMENTS

This chapter discusses the numerical experiments and thus answers Research Question 4: “What are the effects of levelling the inbound flow throughout the year on Ahold Delhaize Inbound Logistics’ operations, costs and inventory?”. Section 5.1 describes the scope of the numerical experiments. Section 5.2 elaborates on the experimental design, which includes an overview of the scenarios that are used and how the different experiments are constructed. In Section 5.3, the results of the four parameter tuning experiments are analysed. Section 5.4 discusses the results of the fifth experiment, and includes an extensive analysis of the performance. As such, this section answers Sub-Question 4a: “What are the main changes in the performance of the KPIs of the solution compared to the current performance?”. To evaluate the robustness of the model, in Section 5.5 a sensitivity analysis is performed on the impact of different penalty values on the decision making and performance of the model. The chapter ends with a conclusion, which includes the answer to Research Question 4.

5.1 SCOPE OF NUMERICAL EXPERIMENTS

The scope of this research is limited to the inbound transport commissioned by the ADIL department to ADIL’s largest national distribution centre. The Simon Loos DC in Tiel experiences the most capacity related problems and accounts for the largest part of ADIL’s operations. Only the year 2021 is considered, and orders that are placed before the year 2021 are left out of the scope.

The countries of origin that have a sufficient number of inbound transport units that allow for levelling, i.e. over 52 transport units, are taken into consideration. As such, countries with a limited flow are not taken into consideration. The same holds for transport unit types that are used on an irregular basis. From the countries of origin that remain, no further origins are excluded. Moreover, all items that were transported from these countries are included in the scope of the research and as such should be assigned to the related number of transport units.

5.2 EXPERIMENTAL DESIGN

The algorithm is implemented in Python and all experiments are performed on a computer with an Apple M2 processor of 8 x 2.4-3.5 GHz and 16.0 GB RAM. The experiments are run separately for the different scenarios that are indicated in Section 5.2.1. As there is randomness involved in the results, due the RVNS as described in Section 4.4.2, 5 replications will be performed for each scenario to obtain a better estimate of the mean performance. The experiments can be divided in three different categories, listed below:

- Parameter tuning: The proposed algorithms have ruling parameters resulting in a different performance. Thus, the aim of this experiment type is to find the best configuration, such that the solving performance of the algorithm can be increased.
- Performance evaluation: The second experiment type serves to compare the performance of the model after the Reduced Variable Neighbourhood Search to the original solution from the constructive heuristic and the current situation.
- Sensitivity analysis: The last round of experiments serves as a sensitivity analysis of the model. By performing a sensitivity analysis, the effects of the input parameters on the performance of the model are analysed. Specifically, a sensitivity analysis is performed to find the effects of adjusting the weight of the penalty factors. That way the robustness of the model can be determined.

A more in depth description of the experiments that are performed and the questions they aim to answer are described in Sections 5.2.2, 5.2.3, 5.2.4 for the parameter tuning, performance evaluation and sensitivity analysis experiments, respectively.

5.2.1 Scenarios

The scenarios are defined by the countries of origin and are of different sizes and configurations. An overview of the scenarios that will be used can be found in Table 2. Both the number of items that need to be assigned and the total number of pallets are displayed. This gives an indication of the average number of pallets an item order consists of. The original number of trucks and containers are those used as an input parameter to the algorithm. The number of containers is expressed for each type of container from the original calculation with the historical data. The container types are abbreviated as follows: 20ft (20' container), 40ft (40' container), 40ftw (40' wide container), 45ftw (45' wide container).

Table 2: Scenario overview

Scenario	Number of items	Total number of pallets	Original number of weekly trucks	Original number of weekly containers
1	254	2,773	2	0
2	1,324	12,117	11	0
3	4,472	25,612	30	0
4	5,220	32,266	20	0
5	222	4,667	2	0
6	257	2,283	0	1 (20ft)
7	9,293	65,613	6	25 (45ft)
8	929	2,657	3	0
9	677	15,037	15	0
10	827	7,101	1	3 (40ftw)
11	3,861	30,822	22	1 (40ft), 1 (40ftw)
12	1,111	5,765	3	0
13	831	3,434	0	2 (20ft), 2 (40ft)
14	806	5,475	0	2 (40ft)
15	1,052	9,184	7	0

Due to the different sizes and configurations for each scenario, the evaluation will be performed for both the separate scenarios and for all scenarios together. This is done as it is valuable to provide an insight in the performance of levelling the inbound flow as a whole, as this is the main aim of the research. However, the performance of the contributing countries should also be analysed separately, as this might show which countries are less suited for the levelling of inbound flow as described and attempted in this research due to their characteristics. This could also indicate possibilities for further research into ways in which the levelling could also be applied to these countries.

5.2.2 Parameter tuning

First, the parameters that determine the probability with which an operator will be chosen during the RVNS. Secondly, the stopping criteria settings are determined.

Experiments 1 and 2 are performed, such that in the end the following question can be answered: ‘Which neighbourhood selection approach results in the lowest penalty values?’. The Reduced Variable Neighbourhood Search picks one of the operators (swap, move or two-opt) based on a generated random number. Depending on the value of the generated random number and the probability with which a certain operator is chosen, the decision is made for a specific operator. Altering the probability with which a certain operator is used will therefore change the performance of the RVNS. The parameter tuning in experiment 1 is done such that the effects of using particular neighbourhoods on the performance can be evaluated, i.e. consider all neighbourhoods (operators), only two (and if so which) or only one (and if so which). The aim of the second experiment is to set the probabilities of selecting a particular operator such that the performance of the RVNS is as optimal as possible, i.e. the highest improvement on penalties.

In the second experiment a decision is made between picking an operator at random or exploring the neighbourhood through one operator, until no further improvements can be found for a longer period of time, before moving on to the next operator and so on. Through this experiment, the neighbourhood exploration is set such that the RVNS results in the biggest possible improvement.

Finally, in experiment 3, different stopping criteria settings are tested to determine the optimal performance. These stopping criteria settings are defined by the run time of the RVNS and the run time during which no improvement was found. Tuning these stopping criteria shows whether it is required to run the algorithm for a longer period of time to improve the solution, or whether the same result can be achieved for a shorter computation time. Moreover, an assessment can be made on the necessity of computational speed compared to improved results. After experiment 3 has been performed, the following question should have been answered: ‘How does the model react under different stopping criteria settings?’

5.2.3 Performance evaluation

The fourth experiment is performed to analyse in detail the results to assess its performance, in terms of its objective value (and its components) and utilisation levels of the TUs. Experiment 4 is run with the settings found in experiments 1 to 3. After the analysis a comparison can be made to the current situation, in order to answer the following question: ‘How does the model perform compared to the current situation?’. All KPIs, the standard deviation of the inventory level and DC capacity utilisation, as well as the objective value, are evaluated, in order to find potential improvements or deteriorations of the new situation compared to the current situation.

5.2.4 Sensitivity analysis

It is important to know how the model reacts to different weight values for the two factors that make up the penalty, namely the weekly turnover and the time an item is allowed to stay in the DC. These penalties are the leading part in the optimisation of the model since the penalties together with the transportation costs determine the objective function value. As such, adjusting the weights assigned to both factors that together determine the penalties could have an impact on the decision making of the model. The question that should be answered in experiment 5 is: ‘How does a different composition of the penalty factors influence the robustness of the results of the algorithm?’.

Finally, in experiment 6, the question that should be answered is: ‘What impact does the number of weeks items are allowed to be transported in advance of their demand have on the objective value?’ The number of weeks items are allowed to be transported in advance is a parameter that is used in both the constructive heuristic as well as the RVNS. The performance might change under different values for the constraint on the number of weeks items are allowed to be transported in advance. Setting this constraint for a low number of weeks might result in lower penalties, while it also could result in a higher number of items that do not fit in the available transport units, leading to an increase in the total number of transport units. Despite the fact that ADIL has a practical limitation on this constraint, it is still relevant to learn for other cases what changes in the performance occur if this number is adjusted, to establish the sensitivity of the algorithm to this parameter.

5.3 PARAMETER TUNING: EXPERIMENTS 1, 2, AND 3

5.3.1 Experiment 1: decision for RVNS operators and selection probability

For conducting experiment 1, the stopping criterion for the RVNS is set for a maximum running time of 10 minutes (600 seconds) and a maximum of 1 minute (60 seconds) without improvement. During the first experiment, several parameter settings will be tested. An overview of the different settings is shown in Table 3. The table indicates which operators are considered and with what probability. As shown in Table 3, when more than one operator is considered, each operator is considered with an equal probability.

Table 3: Operator settings including probabilities for picking an operator

Setting	Operators considered	Probabilities
0	Swap, Move, 2-Swap	0.33, 0.33, 0.34
1	Swap, Move	0.5, 0.5
2	Swap, 2-Swap	0.5, 0.5
3	Move, 2-Swap	0.5, 0.5
4	Swap	1.0
5	Move	1.0

Table 4 shows the results of experiment 1, a more elaborate overview of the results can be found in Appendix A in Tables 15-20. In Table 4, for all settings and scenarios, the minimum, maximum and average objective are shown. The best average objective across all settings for each scenario is indicated with a *.

From Table 4, it can be concluded that not all settings show the same performance for the different scenarios. This can be explained by the characteristics of the scenario. If the scenario consists of more items that have a higher demand it becomes harder to for example have a more efficient two-swap operator (not only but also because the transport units often are completely or almost entirely filled with the demand from a single item). Also, when a move is attempted with a lower number of pallets, it is often more successful, leading to lower penalties.

When all scenarios are considered together, the lowest penalty occurs when setting 1: Swap and Move is implemented. Since the number of TUs and related costs remain the same, this setting also results in the lowest objective value. Therefore, when the neighbourhood exploration is done through a random selection of an operator, setting 1 should be implemented.

Table 4: Results experiment 1 – parameter tuning decision between RVNS operators under equal selection probabilities

	Setting 0: Swap, Move, 2-Swap			**Setting 1: Move, Swap**			**Setting 2: Swap, 2-Swap**		
Scenario	**Min objective**	**Max objective**	**Avg objective**	**Min objective**	**Max objective**	**Avg objective**	**Min objective**	**Max objective**	**Avg objective**
1	468,465.121	468,465.471	468,465.191*	468,465.121	468,465.471	468,465.191*	468,468.546	468,468.896	468,468.616
2	1,721,230.673	1,721,382.679	1,721,273.299*	1,721,239.243	1,721,392.848	1,721,334.422	1,721,699.851	1,721,808.271	1,721,761.313
3	3,596,175.554	3,596,313.296	3,596,250.827	3,595,986.461	3,596,049.616	3,596,005.366*	3,596,444.339	3,596,449.151	3,596,446.684
4	3,128,471.313	3,128,507.413	3,128,488.312	3,128,064.077	3,128,144.393	3,128,114.238*	3,128,459.106	3,128,528.511	3,128,499.221
5	469,773.537	469,774.628	469,774.410*	469,773.537	469,774.628	469,774.192	469,784.242	469,784.242	469,784.242
6	910,018.961	910,051.291	910,025.921*	910,019.587	910,051.291	910,032.513	910,035.396	910,039.767	910,037.583
7	4,566,846.870	4,567,167.104	4,567,048.354	4,566,604.396	4,566,739.029	4,566,664.160	4,567,012.603	4,567,078.366	4,567,051.532
8	781,447.146	781,452.040	781,448.909	781,444.828	781,448.424	781,446.587*	781,453.106	781,457.599	781,454.679
9	1,876,302.531	1,876,936.166	1,876,645.295	1,876,287.094	1,876,934.350	1,876,592.323*	1,876,698.196	1,876,820.811	1,876,749.967
10	1,638,163.675	1,638,178.400	1,638,168.400*	1,638,164.700	1,638,175.900	1,638,170.705	1,638,174.775	1,638,185.900	1,638,178.140
11	4,866,142.381	4,866,302.430	4,866,242.285	4,865,943.760	4,866,021.519	4,865,975.975*	4,866,273.679	4,866,315.271	4,866,287.000
12	468,037.473	468,054.850	468,043.802	468,039.563	468,044.992	468,042.682	468,038.120	468,044.594	468,041.101*
13	988,015.171	988,015.171	988,015.171*	988,015.171	988,015.171	988,015.171*	988,015.171	988,015.171	988,015.171*
14	1,040,593.735	1,040,607.958	1,040,600.823	1,040,589.195	1,040,611.522	1,040,598.908*	1,040,610.257	1,040,630.105	1,040,622.038
15	1,249,401.012	1,249,426.909	1,249,413.640	1,249,400.200	1,249,411.584	1,249,406.421*	1,249,458.658	1,249,479.333	1,249,467.798
Total	**27,769,085.153**	**27,770,635.806**	**27,769,904.639**	**27,768,036.933**	**27,769,280.739**	**27,768,638.852**	**27,770,626.045**	**27,771,105.990**	**27,770,865.087**

	Setting 3: Move, 2-Swap			Setting 4: Move			Setting 5: Swap		
Scenario	**Min objective**	**Max objective**	**Avg objective**	**Min objective**	**Max objective**	**Avg objective**	**Min objective**	**Max objective**	**Avg objective**
1	468,490.621	468,490.621	468,490.621	468,468.546	468,468.896	468,468.756	468,490.621	468,490.621	468,490.621
2	1,722,415.074	1,722,420.747	1,722,417.557	1,721,690.580	1,721,904.057	1,721,789.428	1,722,445.442	1,722,445.646	1,722,445.558
3	3,596,386.078	3,596,414.351	3,596,399.695	3,596,344.764	3,596,385.689	3,596,368.691	3,596,343.078	3,596,412.978	3,596,383.110
4	3,128,651.931	3,128,676.870	3,128,661.331	3,128,344.070	3,128,411.560	3,128,367.747	3,128,344.489	3,128,434.009	3,128,391.113
5	469,849.009	469,849.009	469,849.009	469,784.242	469,786.426	469,784.679	469,849.009	469,849.009	469,849.009
6	910,063.912	910,063.912	910,063.912	910,036.198	910,039.767	910,037.517	910,063.912	910,063.912	910,063.912
7	4,567,779.312	4,567,796.838	4,567,789.738	4,566,502.868	4,566,637.636*	4,566,589.757	4,567,784.472	4,567,789.619	4,567,787.604
8	781,477.340	781,481.923	781,480.041	781,455.422	781,457.166	781,456.485	781,485.968	781,485.968	781,485.968
9	1,877,588.852	1,877,588.852	1,877,588.852	1,876,663.892	1,876,896.167	1,876,800.923	1,877,591.088	1,877,591.088	1,877,591.088
10	1,638,212.150	1,638,212.150	1,638,212.150	1,638,165.500	1,638,184.275	1,638,175.950	1,638,212.150	1,638,212.150	1,638,212.150
11	4,866,493.148	4,866,535.660	4,866,516.817	4,866,222.920	4,866,276.323	4,866,247.267	4,866,502.448	4,866,581.952	4,866,537.673
12	468,067.922	468,069.217	468,068.261	468,039.620	468,053.806	468,043.941	468,070.909	468,070.909	468,070.909
13	988,015.171	988,015.171	988,015.171*	988,015.171	988,015.171	988,015.171*	988,015.171	988,015.171	988,015.171*
14	1,040,717.369	1,040,717.369	1,040,717.369	1,040,608.646	1,040,623.619	1,040,615.877	1,040,717.369	1,040,717.370	1,040,717.369
15	1,249,534.002	1,249,539.302	1,249,536.892	1,249,455.958	1,249,479.083	1,249,471.146	1,249,546.902	1,249,548.927	1,249,547.947
Total	**27,773,741.891**	**27,773,871.992**	**27,773,807.415**	**27,769,798.397**	**27,770,619.640**	**27,770,233.335**	**27,773,463.027**	**27,773,709.329**	**27,773,589.203**

5.3.2 Experiment 2: neighbourhood exploration

In experiment 2, the exploration of neighbourhoods in the RVNS is done in such a way that first a neighbourhood is exhausted. When no improvement can be found for an extended period of time, the neighbourhood exploration changes to the next operator. Again, the operator is applied until no improvement is found for a longer period of time, after which the final operator is applied to the solution. Two different exploration settings are tested, namely (1) Swap, Move and then 2-Swap and (2) Move, Swap and then 2-Swap. Here also, a stopping criterion is in place in the RVNS that checks the total computation time. After this time has passed, it immediately stops the RVNS, independent of which operator it applies at that time. This stopping criterion is set to 10 minutes and the second stopping criterion that checks the time no improvement has been found is set to 10% of that time, namely 1 minute.

A summary of the results of experiment 2 are shown in Table 5, a more elaborate overview can be found in Appendix A, Tables 21 and 22. The results should be compared to the best performing setting that was found for the neighbourhood selection in experiment 1. The best performing setting is the setting that results in the lowest average objective. The number of TUs, related costs and utilisations remain equal for both approaches. When comparing the objectives of experiment 2 setting 1 (Swap, Move, 2-Swap), it is found that for most scenarios the neighbourhood exploration as done in experiment 1 with setting 1 results in a lower penalty than for experiment 2 setting 1. For the three scenarios that improve in experiment 2 (scenarios 6, 7 and 8), this improvement is only minor, namely 1.388, 2.584 and 1.615 respectively. When looking at the experiment 2 setting 2, the setting performs better than experiment 2 setting 1, but still results in a total objective that is higher than experiment 1 setting 1. There are again three scenarios that do improve, namely scenarios 8, 9 and 12, but the improvements remain minor, 9.552, 1.429 and 3.172 respectively.

This leads to the conclusion that, as the average objective value is the lowest for experiment 1 setting 1, this is the approach that should be taken in the RVNS to ensure the lowest objective values.

Table 5: Results experiment 2 - neighbourhood exploration through neighbourhood exhaustion

	Swap → Move → 2-Swap			**Move → Swap → 2-Swap**		
Scenario	**Minimum objective**	**Maximum objective**	**Average objective**	**Minimum objective**	**Maximum objective**	**Average objective**
1	468,465.121	468,465.471	468,465.191	468,468.546	468,468.896	468,468.616
2	1,721,402.030	1,721,561.432	1,721,489.484	1,721,685.476	1,721,783.712	1,721,734.795
3	3,596,368.564	3,596,422.589	3,596,386.245	3,596,083.961	3,596,139.611	3,596,116.652
4	3,128,348.090	3,128,490.169	3,128,418.129	3,128,424.867	3,128,731.741	3,128,641.609
5	469,777.016	469,777.016	469,777.016	469,784.242	469,784.242	469,784.242
6	910,031.915	910,037.024	910,033.901	910,036.198	910,041.899	910,039.557
7	4,566,592.510	4,566,726.493	4,566,661.576	4,566,620.954	4,566,689.445	4,566,654.608
8	781,444.797	781,445.152	781,444.972	781,444.793	781,446.063	781,445.158
9	1,876,502.692	1,876,786.143	1,876,625.126	1,876,708.892	1,876,855.503	1,876,755.899
10	1,638,165.700	1,638,179.525	1,638,171.550	1,638,165.850	1,638,176.175	1,638,171.575
11	5,087,239.508	5,087,316.133	5,087,277.783	4,866,065.724	4,866,137.400	4,866,105.297
12	468,038.120	468,043.402	468,041.331	468,037.473	468,042.607	468,039.509
13	988,015.171	988,015.171	988,015.171	988,015.171	988,015.171	988,015.171
14	1,040,599.867	1,040,609.442	1,040,603.912	1,040,610.554	1,040,633.498	1,040,620.628
15	1,249,405.719	1,249,427.019	1,249,418.119	1,249,435.538	1,249,452.713	1,249,445.211
Total	**27,990,396.819**	**27,991,302.182**	**27,990,829.504**	**27,769,588.239**	**27,770,398.677**	**27,770,038.526**

5.3.3 Experiment 3: Stopping criteria settings

As described in Section 5.2.2, the aim of experiment 3 is to learn how the model reacts under different stopping criteria settings. Experiment 3 is conducted with the parameter settings that were found in experiments 1 and 2, experiment 1 setting 1: Swap, Move that are selected at random through a random number generator with equal probability during the RVNS.

The RVNS algorithm consists of two stopping criteria that can be tuned as explained before. The first stopping criterion considers the total computation time that is allowed. An additional stopping criterion is added that monitors the time period in which no improvement takes place. Since the algorithm should not continue to attempt to make improvements, when there are virtually no improvement options available, the additional stopping criterion is added to ensure that no unnecessary time is wasted. The settings that will be tested during the fourth experiment are shown in Table 6.

Table 6: Settings experiment 4 for criterion 1: computation time and criterion 2: time without improvement

	Setting 1	**Setting 2**	**Setting 3**	**Setting 4**	**Setting 5**	**Setting 6**	**Setting 7**	**Setting 8**
Criterion 1	5 minutes	5 minutes	10 minutes	10 minutes	15 minutes	15 minutes	20 minutes	20 minutes
Criterion 2	10% (30 seconds)	20% (60 seconds)	10% (1 minute)	20% (2 minutes)	10% (90 seconds)	20% (3 minutes)	10% (2 minutes)	20% (4 minutes)

It is important to determine the appropriate balance between additional computation time and gain. If the computation time is increased significantly, but the objective value does not improve significantly, the additional computation time could be considered not worthwhile.

In Table 7, the average penalties for the different settings are displayed, as well as the computation times for the RVNS for each setting. A more extensive overview including the minimum and maximum penalties, and the related objective values and transport units can be found in Tables 23-30 in Appendix A. After conducting experiment 3, all settings have the same number of TUs and thus TU costs and therefore the difference in objective value is only determined by the penalty values.

From Table 7, it can be concluded that the scenarios that are of a larger size are stopped by criterion 1. The smaller scenarios are more likely to be stopped by criterion 2. This can be explained by the fact that for the larger scenarios there are more feasible configurations that can be made for the item allocation. Therefore, the chance no improvements occur for an extended period of time is lower.

Looking at the total penalty values, it can be concluded from Table 7, that an increase in the computation time from 5 to 10 minutes and from 10 to 15 minutes, decreases the average penalty value significantly. However, the difference between 15 minutes computation time and 20 minutes computation time becomes negligible, independent of the second stopping criterion on the time without improvement. Furthermore, it can be observed in the results that setting criterion 2 at 20% instead of 10% does not necessarily improve the results. This is also related to the randomness of the RVNS.

Since the algorithm will not have to be implemented in the daily practice of the ADIL department, there is no strong limitation on the computation time it may take. Based on the fact that an increase in the computation time beyond these 15 minutes and 90 seconds does not necessarily result in a lower penalty, it is decided that the appropriate stopping criteria settings are those of setting 5, namely 15 minutes maximum computation time, and at most 90 seconds without improvement.

Table 7: Results experiment 3 – parameter tuning stopping criteria settings

Scenario	5 minutes – 10%	CT (s)	5 minutes – 20%	CT (s)	10 minutes – 10%	CT (s)	10 minutes – 20%	CT (s)	15 minutes – 10%	CT (s)	15 minutes – 20%	CT (s)	20 minutes – 10%	CT (s)	20 minutes – 20%	CT (s)
1	465.121	31.444	465.261	61.775	465.191	64.156	465.191	122.175	465.191	92.325	465.331	180.455	465.191	490.621	465.261	244.016
2	5,313.600	169.195	5,393.028	300.000	5,334.422	384.318	5,317.999	480.246	5,312.664	408.986	5,281.267	634.106	5,283.406	567.545	5,330.284	678.347
3	8,245.834	300.000	8,241.816	300.000	8,005.366	600.000	7,993.960	600.000	7,925.006	900.000	7,996.770	900.000	7,972.783	1,200.000	7,942.087	1,200.000
4	8,427.033	300.000	8,473.478	300.000	8,114.238	600.000	8,139.046	600.000	8,041.142	900.000	8,052.843	900.000	8,069.239	1,200.000	8,030.878	1,200.000
5	1,776.643	32.562	1,775.033	64.345	1,774.192	62.273	1,774.192	123.152	1,775.947	92.819	1,775.688	183.623	1,774.192	128.730	1,774.192	244.246
6	19.462	38.835	25.677	66.562	32.513	62.613	38.548	126.258	19.462	93.618	38.353	188.272	25.866	131.936	25.872	243.826
7	3,909.096	300.004	3,806.887	300.002	3,664.160	600.003	3,680.601	600.001	3,607.656	900.000	3,495.250	900.001	3,521.967	1,200.001	3,559.720	1,200.001
8	1,449.353	127.888	1,446.361	162.497	1,446.587	118.920	1,444.742	209.850	1,444.792	246.730	1,445.204	347.925	1,444.851	263.840	1,444.787	362.188
9	4,568.756	30.000	4,664.148	60.003	4,592.323	60.002	4,519.660	120.002	4,507.807	90.001	4,588.323	180.006	4,548.136	120.007	4,512.477	240.002
10	173.080	85.550	168.325	87.736	170.705	130.282	172.285	208.399	170.500	126.335	169.270	334.581	171.270	224.579	174.610	327.579
11	4,210.492	300.003	4,228.383	300.002	3,975.975	600.002	3,988.165	600.003	3,967.147	900.000	3,952.747	900.000	3,985.308	1,200.005	3,932.006	1,200.006
12	43.291	84.697	41.800	80.385	42.682	127.870	42.736	135.392	41.666	111.454	41.285	210.156	42.425	134.119	41.401	361.350
13	15.171	30.005	15.171	60.002	15.171	60.002	15.171	120.000	15.172	90.000	15.171	180.000	15.171	120.000	15.171	240.005
14	600.225	109.629	600.272	102.452	598.908	97.673	605.848	171.042	602.373	156.668	600.390	236.195	598.051	177.299	600.591	307.355
15	1,412.114	175.805	1,408.737	237.149	1,406.421	258.879	1,413.147	295.149	1,406.218	246.793	1,408.752	407.328	1,407.692	305.632	1,412.307	528.928
Total	**40,629.271**	**n.a.**	**40,754.378**	**n.a.**	**39,638.852**	**n.a.**	**39,611.291**	**n.a.**	**39,302.742**	**n.a.**	**39,326.645**	**n.a.**	**39,325.546**	**n.a.**	**39,261.643**	**n.a.**

5.4 PERFORMANCE EVALUATION: EXPERIMENT 4

As the appropriate parameter settings have been found in experiments 1 through 3, the algorithm can be run with these settings in order to evaluate its performance. Hence, the code is run with the maximum improvement time of the RVNS set at 15 minutes, the maximum time without improvement set at 90 seconds, and the RVNS set to pick the Swap or Move operator with equal probability based on a random number generator.

The average objective of the optimisation problem amounts to 27,768,302.74. For the current situation, the objective amounts to 21,864,000.00, so experiment 4 shows that the objective increases with roughly 27%. This increase can be explained by the fact that for the current situation, no penalties occur as items are not transported in advance of their demand. Moreover, the number of required TUs on a yearly basis to allow for levelling of the peaks over a specified number of weeks (6), is higher than the yearly number that is required when levelling is not applied, which explains the increase in transportation costs.

In Figure 17, the algorithm's number of weekly inbound pallets throughout the year (2021) for each scenario is shown. The two black vertical lines indicate the warm-up and cool-down period. The figure shows that the largest number of inbound pallets is accounted for by scenario 7. This can be explained by the fact that this scenario also has the highest number of pallets that need to be allocated. Furthermore, it becomes evident that scenarios 4, 11 and 3, the scenarios with the next three largest number of pallets, display the largest fluctuations (standard deviation). This is in part caused by the fact that for scenarios 4 and 11 the number of pallets that need to be assigned at the beginning of the year on a weekly basis is higher compared to later in the year. For scenario 3 this effect is less strong, but still the number of pallets that must be transported during the weeks at the end of the year decreases. However, it can be seen that for the smaller scenarios the inbound number of pallets on a weekly basis is much more stable. This can be explained by the fact that when the difference between the number of pallets that must be transported on a weekly basis is smaller, levelling can be more easily applied. As a result, the number of required TUs does not increase as much and therefore, items are less likely to be spread out evenly.

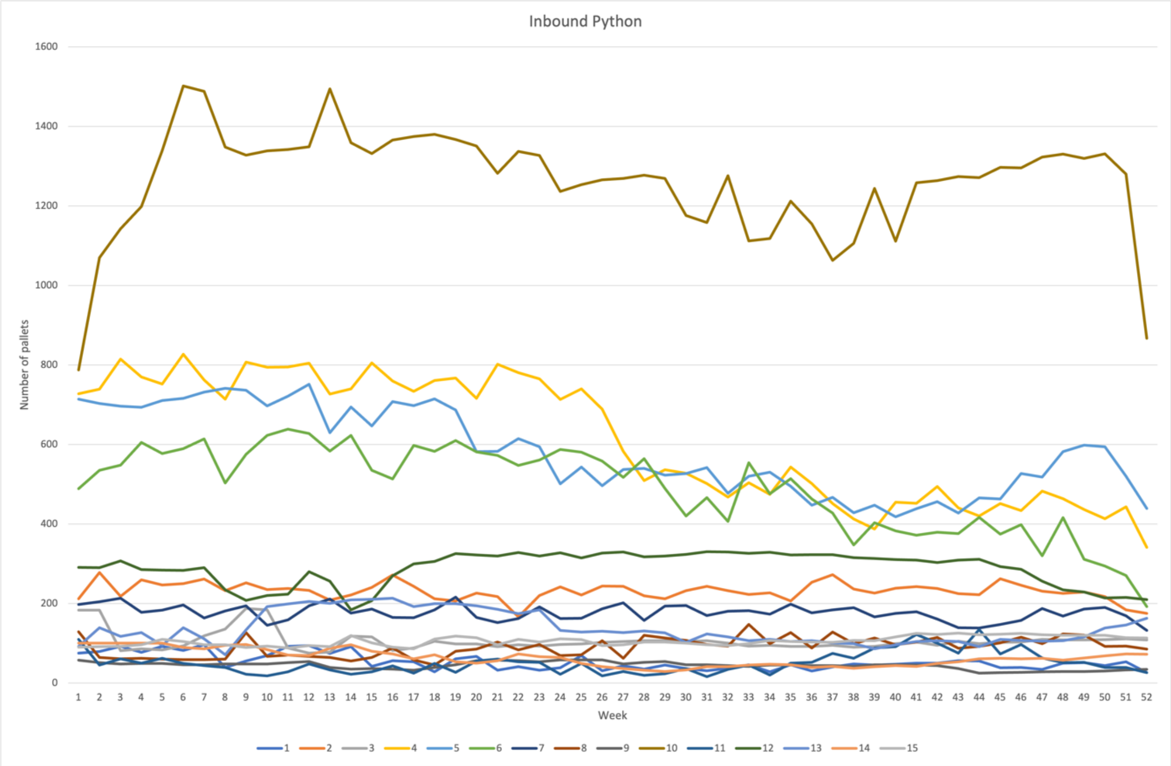

Figure 17: Weekly number of pallets for each scenario throughout the year 2021 at the Simon Loos DC in Tiel

Figure 18 displays the course of the number of pallets over the year (2021) for the input that is used to run the Python script, the actual inbound flow (based on historical data), and the results of running the Python code for the 15 scenarios (countries of origin) that are taken into consideration. The result of the python code displays the sum of the average number of weekly pallets that are found for each country after five replications are performed. Figure 18 shows that the inbound flow expressed in the number of pallets experiences the least fluctuation for the outcome. The period after the warm-up period and before the cool-down period, as described in Section 4.2, is displayed between the two lines in Figure 18. Especially when the warm-up and cool-down period are taken into consideration, the result demonstrates significantly less fluctuation.

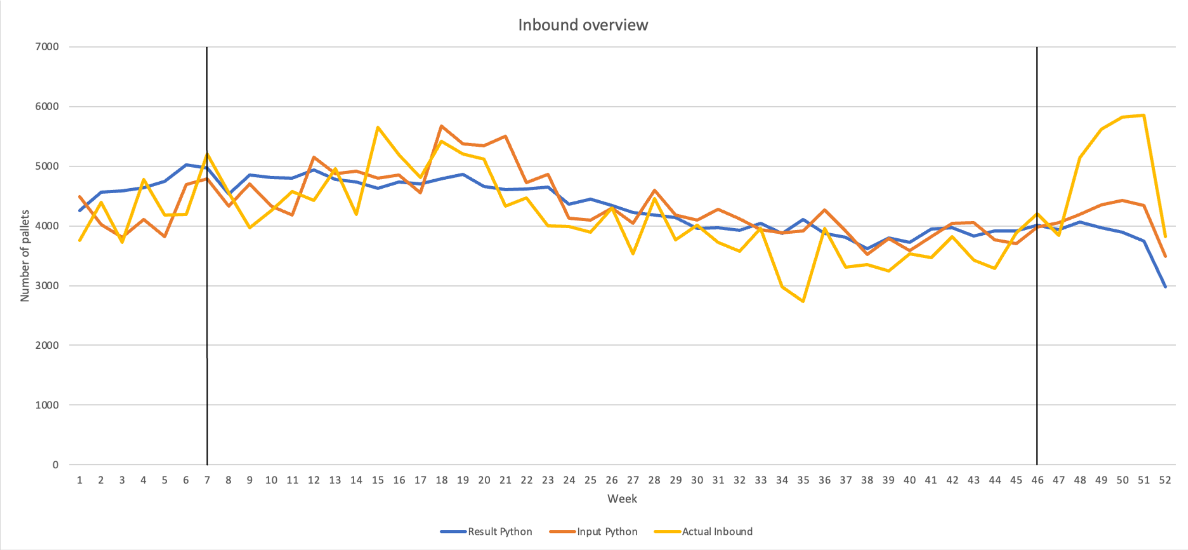

Figure 18: Weekly number of inbound pallets at the Simon Loos DC in Tiel

This is also shown in Table 8, where the standard deviation values are displayed for these three cases. Table 8 confirms that the result of performing experiment 4 has lowest standard deviation of the number of weekly pallets.

Table 8: Standard deviation values for the input used for the Python script, the actual inbound and results of experiment 5 excluding warm-up and cool-down period

	Actual Inbound	**Input Python**	**Result Python**
Standard Deviation	698.2071	548.5632	411.4628

However, what can also be concluded from the data as shown in Table 8, is that the standard deviation values are not equal for the actual inbound and the script input. This implies that the actual inbound is not equal to the input (which is defined by the last available forecast for each week, as described in Section 4.2). This is also shown by the total number of pallets that the actual inbound amounts to, namely 219,915 and the total number of pallets that the input data amounts to which equals 224,838. This 4,923-pallet difference can be explained by the availability issues ADIL experienced during 2021, which meant that, for a number of items, orders could not be placed to meet the forecasted demand. Naturally, this discrepancy between the current situation and the input to for the Python script might need to be taken into consideration when comparisons are made, to ensure that the discrepancy does not cloud the comparison. When this is the case, the assumptions, changes or considerations that are made will be mentioned specifically.

In Figure 19, an overview of the utilisation rates for the scenarios (countries) with road transport is shown. The figure shows that almost all countries demonstrate variable behaviour. The reason for this variable behaviour is the fluctuation in demand and the fact that, while the number of available TUs is equal for each week, this fluctuating demand is only allowed to be transported a limited number of weeks in advance. Moreover, from the figure it becomes evident that for example scenario 10 does not have demand that should be transported in trucks during the first couple of weeks, leading to lower utilisation rates as well. In addition, this effect of fluctuating demand gets impacted even more by the fact that also items from different suppliers are not allowed to be transported together in case of road transport. While Figure 18 shows that overall, the inbound number of pallets levels out, Figure 19 shows a different situation when the analysis is performed on a scenario/country level. This implies that this fully levelled number of weekly TUs throughout the year, leads to a higher number of TUs on a weekly basis and lower utilisation levels, in addition to the fact that this also results in the fact that the number of inbound pallets remains, while less, variable throughout the year.

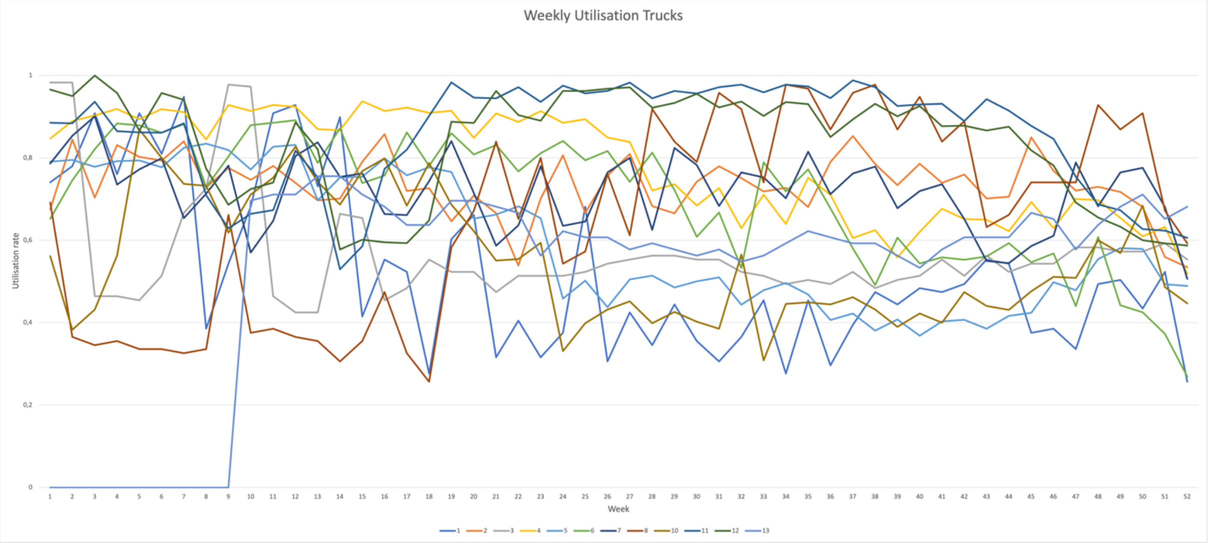

Figure 19: Weekly utilisation rates of trucks

Figure 20 shows the weekly utilisation rates of containers for the scenarios (countries) that transport in this TU type. From the figure, it becomes evident that, especially for scenario 11 where the first 21 weeks the demand for items that should be transported in a container is equal to 0, the low utilisation rates occur when the demand fluctuates highly. In addition, it also shows that scenarios 7 and 14 have less variable and higher utilisation rates compared to the other scenarios.

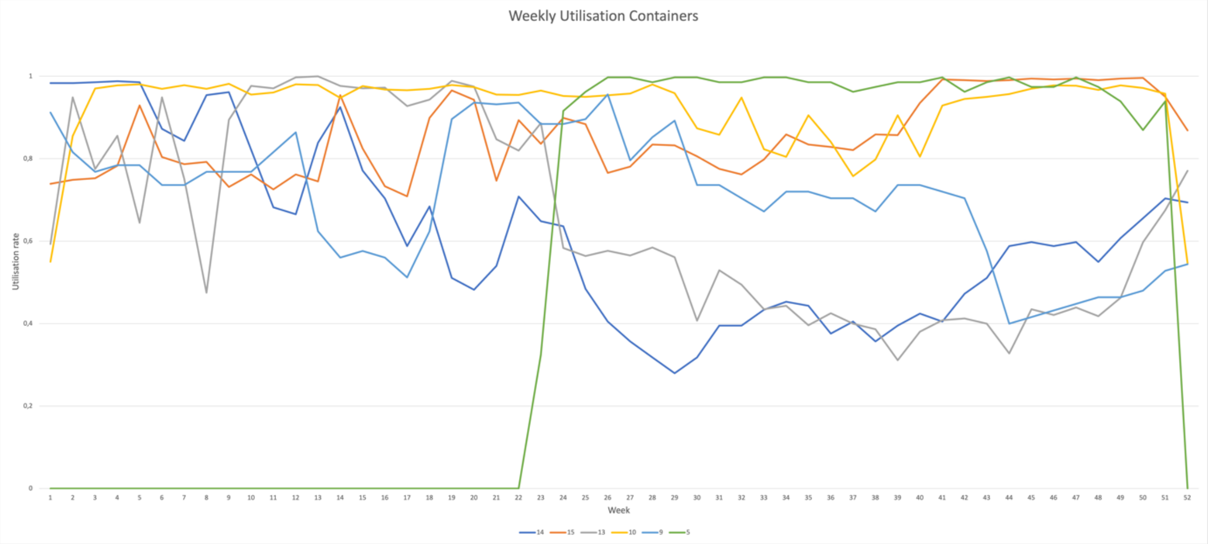

Figure 20: Weekly utilisation rates of containers

In Table 9, the resulting number of transport units of each type and their average utilisations throughout the year after performing the experiment are displayed. From the table, it is evident that the average utilisation rate is too low, especially for road transport (in trucks). As of right now, no consolidation is allowed on this type of transport. Allowing for some form of consolidation, either through actual consolidation of orders from different suppliers in the same country, or through considering the total number of transport units for multiple countries at the same time, could potentially drastically increase the utilisation rates of trucks. Also, looking at the utilisation rates of containers it also becomes apparent that for some countries, the utilisation rates are too low. Again, approaching the problem at hand in a different way, such as considering multiple countries at once and setting one weekly number of containers for these countries together, might prove to be a solution to this problem. A more elaborate discussion of these suggestions can be found in Section 6.3.

Table 9: Results experiment 4 - overview number of transport units of each type and their utilisations

Scenario	Number of trucks	Number of containers	Truck utilisation	Container utilisation
1	3	0	0.5242	0.0000
2	11	0	0.7349	0.0000
3	23	0	0.7009	0.0000
4	20	0	0.7815	0.0000
5	3	0	0.6526	0.0000
6	0	5 (20ft)	0.0000	0.7087
7	6	31 (45ftw)	0.5507	0.9223
8	5	0	0.2934	0.0000
9	12	0	0.8567	0.0000
10	2	6 (40ftw)	0.5231	0.6528
11	27	1 (40ft), 2 (40ftw)	0.5978	0.5313
12	3	0	0.5671	0.0000
13	0	2 (20ft), 3 (40ft)	0.0000	0.6148
14	0	5(40ft)	0.0000	0.8546
15	8	0	0.7177	0.0000
Total	**123**	**55**	**0.6752**	**0.8501**

Table 10 provides an insight into the utilisations of the inbound capacity at the distribution centre. It is important to note that there are a number of countries that are not taken into consideration during this research, hence the utilisation levels are lower than might be expected. Nonetheless, based on the countries that are taken into consideration, conclusions can still be drawn on the performance of the potential new situation compared to the current and the expected situation according to the input to the Python script. A lower standard deviation of the utilisation of DC capacity is more desirable, as this implies that the fluctuations in inbound flow, that now cause capacity problems at the distribution centre, decrease. Here, again, it is shown that the algorithm (new situation) has the most optimal performance in terms of the fluctuation of utilisation of DC capacity.

Table 10: Utilisation levels DC capacity

	Actual inbound	**Input Python**	**Result Python**
Minimum utilisation DC capacity	0.5384	0.5402	0.4730
Maximum utilisation DC capacity	0.2602	0.3358	0.3446
Variation utilisation DC capacity	0.0665	0.0522	0.0392

Figure 21 shows an overview of how often items arrive during their demand week and in advance of their demand week. The figure clearly shows that most of the time items arrive at the time they are demanded (72.08%). 10.21% of the pallets are transported 1 week in advance of its demand week, 5.90% of the total number of pallets are transported 2 weeks in advance. The remaining 11.8% of all pallets arrive 3 to 6 weeks in advance of their demand.

Figure 21 also shows that most items that are transported in advance of demand come from scenario 6. In addition, the other countries that account for a large part of the pallets that arrive before their demand week are scenarios 7, 11, 3 and 4, the four scenarios of the largest size (the highest number of pallets to be assigned). The arrival of items in advance of their demand implies that items do not fit within their original demand week, i.e. there is high fluctuation in demand. This can also be seen when the data for these scenarios is analysed. However, as discussed before, there can be other contributing factors that result in an item being transported in advance, such as more items which have demand for a higher number of pallets, truck transport with suppliers that have irregular demand, and more.

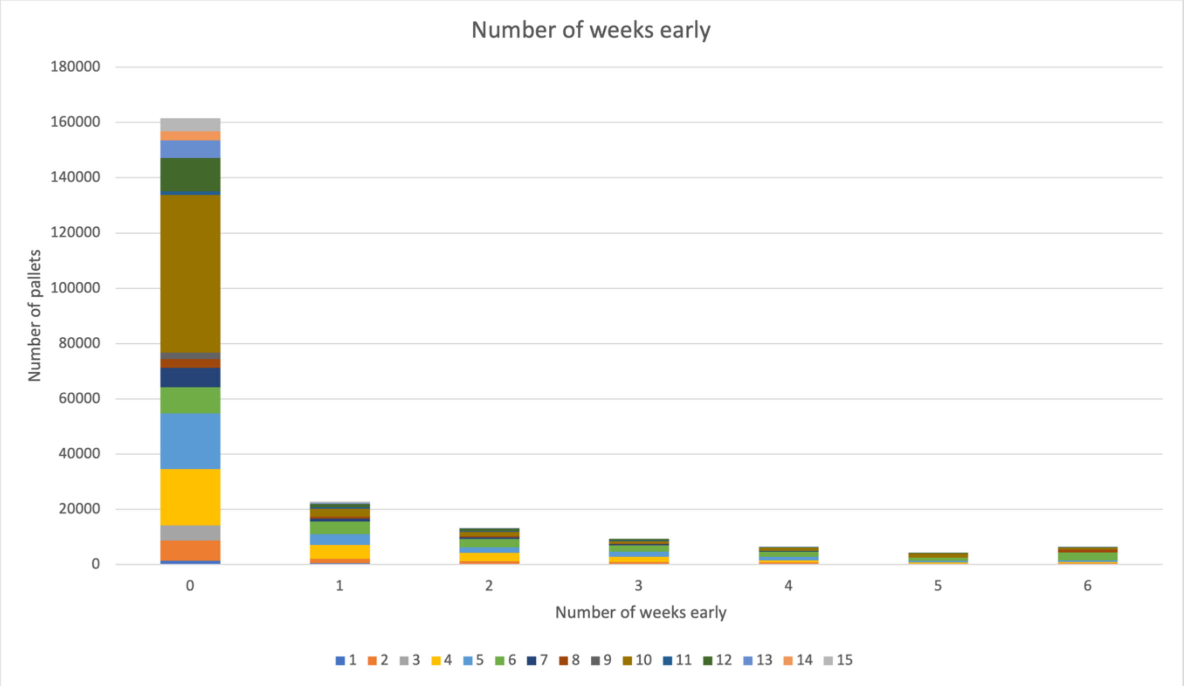

Figure 21: Count of number of items transported in advance of demand

The inventory development is displayed in Figure 22. This development does not show the actual inventory level, but rather the development of the inventory level compared to the baseline of week 52 of year 2020. The development is calculated based on the inbound and outbound values for both the current state as well as the tested scenarios for experiment 4. The inventory development shows the accumulated inbound minus outbound flow for all 15 scenarios.

As mentioned, the discrepancy between the actual inbound and input data for the experiment leads to the fact that, in order to determine the appropriate inventory level for the new scenario, it is not possible to use the actual outbound data. This assumption is based on the fact that the items that did not arrive (as displayed in the actual inbound data) due to availability issues, also can't leave the DC and therefore are also not part of the actual outbound data. Therefore, inventory level development (i.e. the difference between inbound and outbound) for the current situation is calculated by subtracting the total outbound flow expressed in number of pallets up to point t in time, from the total inbound flow expressed in the number of pallets up to point t in time. The inventory level development is calculated by subtracting the accumulated input data (which we assume to be demanded upon arrival) up to point t in time from the total inbound flow as found during experiment 4 up to point t in time.

It is important to note that the fall in the inventory level at the end of year 2021 for the new scenario can be explained by the number of pallets that are not transported due to the warm-up period (according to the number of weeks items are allowed to be transported in advance, these pallets can be transported in 2020 in advance of their demand in 2021). Furthermore, the large increase in the inventory level that is shown during the weeks 15-42 for the current situation can be explained by the fact that the safety stock for items was increased significantly during this period in 2021 due to the availability issues ADIL was experiencing at that time.

When the warm-up and cool-down period are not considered, the total inventory level on the first of January is assumed to be roughly 20,550 pallets, under the inventory costs per week per pallet as currently agreed, the total additional inventory costs for the new situation decrease with 2.71% compared to the current scenario. While this implies that the new scenario as tested in this experiment outperforms the current scenario, this conclusion cannot be drawn directly. The input data that is used to perform the experiment is based on the last available forecast for each week. However, the additional stock that ADIL imported to ensure availability is not represented in this forecast, and therefore Figure 22 might present an inaccurate picture. If the weeks during which this significant increase in the inventory level is displayed are left out of consideration, and the average 'inventory level development' is calculated, this information can be used to paint a more realistic picture of what the inventory level development might have looked like if the safety stocks had not been increased. If the additional inventory costs are recalculated with this data, the costs lower with almost 4.73%. This demonstrates that, if the safety stock had not been increased during 2021, there is a large chance the additional inventory costs would have been roughly 2.12% lower than for the new scenario. However, already less than a 1% decrease of the transportation cost is required to outweigh these increased inventory costs for the new scenario. Due to the fact that the number of TUs is fixed on a weekly basis, it is likely that lower prices can be negotiated with the logistics providers due to the fixed purchasing commitments ADIL will be able to make.

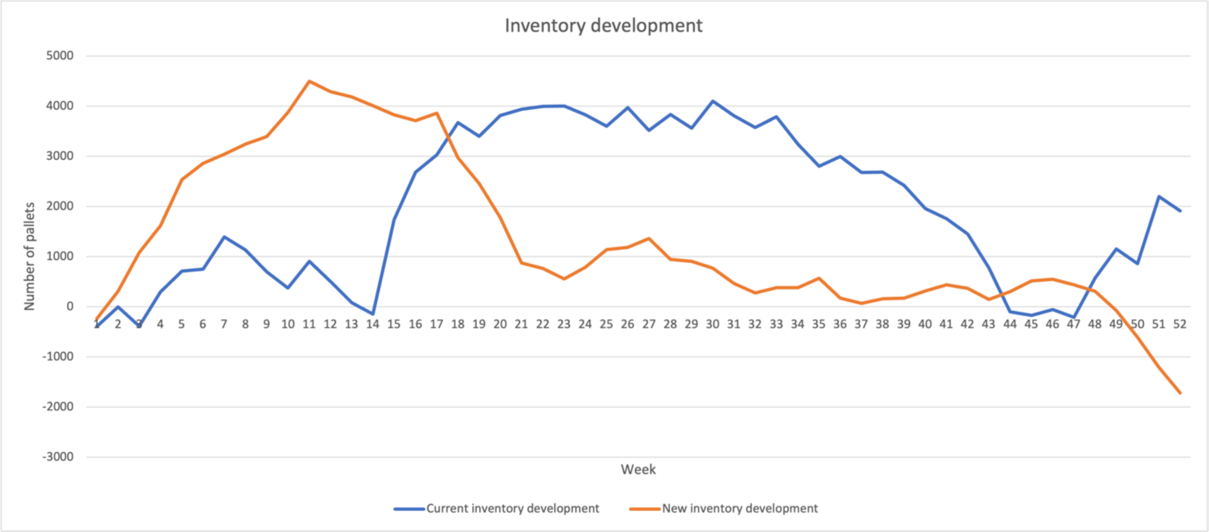

Figure 22: Inventory development over time

One of the KPIs, namely the standard deviation of the inventory levels for the current situation, the potential case in which there would not have been an increase in safety stock, and new situation is displayed in Table 11. From the table, it becomes evident that the standard deviation is slightly larger for the new case compared to the current case. This can be explained by the fact that the inventory level in the first quartile increases rather drastically and decreases to almost the original level later in the year. While for the current case an increase in the inventory level can also be seen, this increased inventory level remains for a longer period of time. However, while the performance of the KPIs for the current and new case does not differ strongly, the potential value for the standard deviation of the inventory level in the case the safety stock had not been increased shows a very different picture. If the assumption is made that the drastic increase in the safety stock had not occurred, and only the weeks before and after the increase are considered, the current case would strongly outperform the new scenario in terms of the standard deviation of the current inventory level. Still, this is to be expected, as in the current situation the inbound and outbound flow of goods follow roughly the same pattern, but in the new situation the inbound flow would display a more levelled pattern, while the outbound remains highly variable. Naturally, this leads to higher variability in the inventory level.

Table 11: Standard deviation of inventory level of the current and new situation

Standard deviation current inventory level	1,463.1688
Standard deviation potential inventory level excl. increased safety stock	708.2308
Standard deviation new inventory level	1,515.921

5.5 SENSITIVITY ANALYSIS: EXPERIMENT 5 AND 6

5.5.1 Experiment 5: Sensitivity analysis on the penalty values and factor weights

For experiment 5, the aim of the experiment is to find the effects of different penalty values on the robustness of the model. Again, the experiment is conducted with the parameter settings as found in the parameter tuning experiments 1 through 3.

First of all, it is important to note that during experiment 5, only the impact of different weights of the two factors that make up the penalty value are analysed. This is done as a factor increase of the penalty value does not impact the decision making of the algorithm. The reason for this is that the solution approach first minimises the number of TUs, and then minimises the penalty for that number. Therefore, an increase in the penalty value, while resulting in a different objective value, will not impact the decision making of the model, i.e. the same items will be assigned to the same TUs (apart from some randomness that is involved in the RVNS). Proof of this can be found in Appendix A Table 32, where the results of the constructive heuristic are shown, since there is no randomness in the initial solution. For each scenario the penalty increases with a factor 1,000 if the individual penalty values of items are increased by a factor 1,000.

Next, the experiment is performed with different weight factors for the two factors that make up the penalty: the ABC classification of the turnover rate and the distribution term. An overview of the tested weight settings can be found in Table 12.

Table 12: Overview of the experiment settings of experiment 5

Setting	Weight turnover	Weight DT
Original	0.5	0.5
1	0.6	0.4
2	0.4	0.6
3	1.0	0.0
4	0.0	1.0

The results are shown in Figure 23, the warm-up and cool-down windows are again indicated by the vertical black lines in the figure. The figure displays the number of weekly inbound pallets for the different settings. It is important to note that the range of the y-axis has been adjusted, such that the changes are more clearly visible. From the figure, it becomes apparent that the model's decision making does get impacted by adjusting the weights of the penalty factors. The standard deviations found for each setting can be found in Table 13. From the table, it can be concluded that the performance in terms of levelling the inbound flow remains relatively equal for all 5 settings, but the results do differ slightly. This again confirms that the decision making of the model does get impacted by different weights for the two penalty factors. Both the fact that the decision making gets impacted and the effects remain limited can be explained by the characteristics of the model. Due to the hard constraints on the number of weeks items are allowed to be transported in advance and the fact that all items (apart from the items in the warm-up period) must be transported, the number of pallets that are transported in a week can only deviate by a relatively small amount. In essence, the hard constraints limit the sensitivity of the model to large changes in the input data, and therefore increase the model's robustness. The fact that the decision making still gets affected can be explained by the way in which decisions are currently made. As described in Section 4.4.2, items that are transported in advance of demand are chosen such that the penalty is minimised. If the ratio between the penalty values of different items changes, due to the change in settings as tested in this experiment, the item that has the lowest penalty will likely also change. In conclusion, if the penalty values of the items get changed such that the ratio between them also changes, the decision making of the model will be impacted. However, the model displays robust behaviour despite these changes.

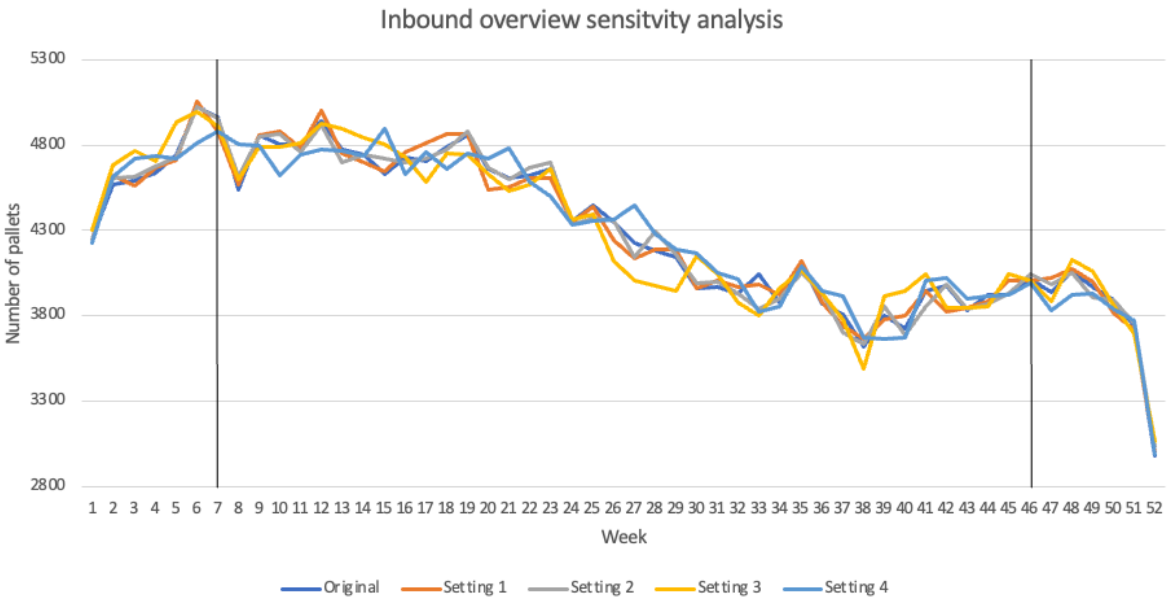

Figure 23: Sensitivity analysis experiment results - overview of the weekly number of inbound pallets for the year 2021

Table 13: Sensitivity analysis experiment results - standard deviations of the weekly number of inbound pallets for all settings

Setting	Standard deviation of weekly number of inbound pallets
Original	411.4628
1	412.6806
2	420.4595
3	415.7932
4	396.5104

5.5.2 Experiment 6: Sensitivity analysis on the number of weeks of transportation in advance

The decision on the number of weeks items are allowed to be transported in advance impacts the way in which items are allocated to the available transport units. This decision depends on the case at hand, such as the characteristics of the company that wishes to apply the solution approach as described in this research. As such, it is important to learn how the algorithm reacts under different settings.

Experiment 6 is performed for 3 different values of the number of weeks items are allowed to be transported in advance, namely 3 weeks, 6 weeks, 10 weeks. The choice for these experiment settings is based on a combination of academic relevance and practical relevance. In practice, in discussion with ADIL it is determined that it is undesirable that items are transported more than 6 weeks in advance. However, for academic relevance it is relevant to see how the algorithm reacts when transportation further in advance is allowed, as this will allow to spread the items even better throughout the year if the peaks are very high (as more possibilities are allowed), which could ultimately lead to a lower number of transport units and/or increased utilisation rates. Moreover, we also want to learn what the effects are of allowing a relatively short period for transportation in advance of demand: can the peaks in demand be spread out evenly throughout the year using such a short period?

A summary of the results of experiment 6 can be found in Table 14, on page 61. A more in-depth overview of the results, including the minimum and maximum penalty and objective values of all iterations, are shown in Tables 33-35 in Appendix A. Table 14 indicates the average penalty, TU costs, the truck and container utilisation values, and the number of unassigned items (UI). All four of these values are directly related to the number of TUs.

From Table 14, it can be concluded that there can be changes in the penalty cost when items are allowed to be transported further in advance, while the number of TUs remain the same. An increase in the penalty can be expected when the number of TUs is decreased, as that forces items to be spread out more evenly. However, a change in penalty costs for the same number of transport units could be considered more unexpected. Still, there are many different aspects that contribute to the performance on the penalty for each scenario.

First of all, the transport unit type that items must be transported in plays an important role. Increases in the penalty costs can occur when items are allowed to be transported further in advance, but have to be transported in a truck. In the constructive heuristic, items are assigned as early as possible in a TU (a truck in this case) where they fit according to all constraints. However, when we try to move them closer to their demand week, the truck we move them to is only allowed to transport items from the same supplier. In case there are a number of items that are transported from a supplier that has low demand/occurs less frequently, this move is often unsuccessful. This is also due to the fact that in the constructive heuristic, the attempt to move an item closer to their demand week is conducted starting at the final week. In that case, when the number of weeks an item is transported in advance is higher it is possible that the attempt is made at a later time when all available TUs have already been filled by items from other suppliers. This scenario can lead to the penalty costs increasing.

A similar principle holds for items that are transported in containers. When items are allowed to be transported further in advance, it might result in an unsuccessful attempt to refit the items at a later time compared to when it would have been attempted at an earlier stage, as items are moved closer to their demand week starting from the final week.

Finally, a decrease in the penalty value can also occur when items are allowed to be transported further in advance. This happens with a higher probability for scenarios (i.e. countries) in which items are (mostly) transported in a container, as here the attempted change made in the constructive heuristic as described before is successful more often. This decrease is a result of the following scenario: assume there are a few weeks that are currently at full capacity for setting 1: 3 weeks. Let us consider item 1 in week 5 that officially has 5 pallets of demand in week 8 and a penalty of 0.1. Item 2 is currently transported in week 4, has a demand of 5 pallets in week 7 and a penalty of 0.4. The total penalty of both items amounts to 7.5 (3*5*0.1 + 3*5*0.4). In case we consider setting 1, item 2 cannot be transported in week 8 instead of 7 as this would cause item 1 to not fit within the available capacity. However, when the same scenario is considered for setting 2: 6 weeks, this would result in item 1 (at least) swapping with item 2, resulting in a lower penalty of 6 (4*5*0.1 + 2*5*0.4).

In Table 14 it is shown that, as expected, the lowest penalties occur for setting 1: 3 weeks. The average penalty increases for setting 2: 6 weeks with 8.45% compared to setting 1: 3 weeks, while the TU costs decrease with 6.37%, as the total number of trucks and containers fall from 131 to 123 and 58 to 55 respectively. This is also reflected in the utilisation levels of the trucks and containers, as they both increase. The penalty values for setting 3: 10 weeks increase with 16.05% compared to setting 2: 6 weeks, while the TU costs only decrease with 1,69% due to a lowering of the number of trucks by 3.

This shows us that the algorithm is sensitive to changes under different settings for the number of weeks items are allowed to be transported in advance. As a result, the decision should be made with careful consideration, as it will have large implications for the performance. It is important to note that, in line with the hypothesis, the algorithm is able to spread the inbound flow more evenly and thus lower the number of transport units further in case items are allowed to be transported further in advance of their demand point. For different companies, or in different contexts, this theory could be applied to gain a more optimal performance of the model (in special cases where transportation in advance has no significant disadvantages and thus items can be transported even more than 10 weeks in advance for example). Finally, it is important to note that not only the objective value shows a better performance for a higher number of weeks items are allowed to be transported in advance, but also the utilisation rates for trucks and containers both increase significantly due to the lower number of TUs. Naturally, a higher utilisation rate of the truck and containers is more desirable, as this means that the available capacity is used in a more efficient manner. In addition, an increase in penalty value indicates that more items are transported (potentially further) in advance of their demand week, implying that inbound flow is spread out more evenly.

In summary, the results show that the algorithm is sensitive to changes in the number of weeks items are allowed to be transported in advance and that as such the decision for this constraint should be well-balanced and considered.

Table 14: Results experiment 6 - sensitivity analysis on number of weeks items are allowed to be transported in advance

	Setting 1: 3 weeks					Setting 2: 6 weeks					Setting 3: 10 weeks				
Scenario	**Penalty (avg)**	**TU costs**	**Truck utilisation**	**Container utilisation**	**UI**	**Penalty (avg)**	**TU costs**	**Truck utilisation**	**Container utilisation**	**UI**	**Penalty (avg)**	**TU costs**	**Truck utilisation**	**Container utilisation**	**UI**
1	372.803	468,000.00	0.5242	0.0000	1	465.191	468,000.00	0.5242	0.0000	1	406.739	468,000.00	0.5242	0.0000	1
2	4,711.785	1,716,000.00	0.7349	0.0000	10	5,312.664	1,716,000.00	0.7349	0.0000	10	5,734.500	1,716,000.00	0.7349	0.0000	10
3	4,446.702	4,524,000.00	0.5567	0.0000	14	7,925.006	3,588,000.00	0.7009	0.0000	26	8,211.281	3,588,000.00	0.7009	0.0000	26
4	6,748.826	3,276,000.00	0.7456	0.0000	45	8,041.142	3,120,000.00	0.7815	0.0000	55	9,423.403	3,120,000.00	0.7815	0.0000	55
5	1,532.253	468,000.00	0.6526	0.0000	0	1,775.947	468,000.00	0.6526	0.0000	0	1,640.898	468,000.00	0.6526	0.0000	0
6	12.658	910,000.00	0.0000	0.7087	0	19.462	910,000.00	0.0000	0.7087	0	32.013	910,000.00	0.0000	0.7087	0
7	6,929.003	4,563,000.00	0.5507	0.9223	2	3,607.656	4,563,000.00	0.5507	0.9223	2	2,526.722	4,563,000.00	0.5507	0.9223	2
8	1,399.216	780,000.00	0.2934	0.0000	13	1,444.792	780,000.00	0.2934	0.0000	13	2,386.761	624,000.00	0.3634	0.0000	32
9	4,093.146	1,872,000.00	0.8567	0.0000	3	4,507.807	1,872,000.00	0.8567	0.0000	3	5,727.797	1,872,000.00	0.8567	0.0000	3
10	234.975	1,638,000.00	0.5231	0.6528	0	170.500	1,638,000.00	0.5231	0.6528	0	116.150	1,638,000.00	0.5231	0.6528	0
11	3,071.433	5,239,000.00	0.5774	0.3942	30	3,967.147	4,862,000.00	0.5978	0.5313	39	4,134.897	4,862,000.00	0.5978	0.5313	39
12	41.934	468,000.00	0.5671	0.0000	33	41.666	468,000.00	0.5671	0.0000	22	1,654.342	312,000.00	0.8264	0.0000	39
13	61.540	1,404,000.00	0.0000	0.4264	0	15.171	988,000.00	0.0000	0.6148	41	15.171	988,000.00	0.0000	0.6148	41
14	531.630	1,040,000.00	0.0000	0.8546	0	602.373	1,040,000.00	0.0000	0.8546	0	607.106	1,040,000.00	0.0000	0.8546	0
15	1,794.212	1,248,000.00	0.7177	0.0000	0	1,406.218	1,248,000.00	0.7177	0.0000	0	2,993.504	1,092,000.00	0.8106	0.0000	9
Total	**35,982.116**	**29,614,000.00**	**0.6345**	**0.7739**	**151**	**39,302.742**	**27,729,000.00**	**0.6752**	**0.8180**	**212**	**45,611.282**	**27,261,000.00**	**0.6910**	**0.8180**	**257**

5.6 CONCLUSION

Experiment 1 shows that only using the Swap and Move operator with equal probabilities resulted in the lowest penalties compared to the other settings. Moreover, by comparing experiment 1 and both settings of experiment 2, it was found that the lowest penalties (with equal TU costs) occurred when the operator was chosen at random, compared to first exploring one neighbourhood until no further improvements can be made before moving to the next. Finally, in experiment 3, the conclusion is drawn that the first stopping criterion (maximum computation time) should be set at 15 minutes and the second stopping criterion (maximum computation time without improvement) should be set at 10% of that time (90 seconds). This setting shows better results than shorter computation times, and also demonstrated the performance remained similar for longer computation time settings.

Experiment 4 discusses the performance of the solution. On a scenario level, it can be seen that the variation in inbound flow is much lower for the smaller scenarios, which can be explained by the fact that often the absolute fluctuation in demand is also less high for these smaller scenarios. Moreover, when the utilisation levels of trucks and containers are analysed, it can be seen that for some scenarios the utilisation level in some periods is equal to or near 0, as there is no demand for an extended period of time. This indicates that these scenarios, at least for the year 2021, were not suited for levelling. It is found that the solution has a lower standard deviation of inbound flow compared to the current situation, and it can be said that for the new scenario the inbound flow is better spread throughout the year, as was intended. However, it is also shown that the utilisation levels for almost all trucks and some containers in the different scenarios are lower than desired. This is due to the fact that items are not allowed to be spread infinitely in advance, leading to a higher number of total weekly TUs to ensure that all items can be transported, resulting in lower utilisations during the weeks with lower demand. There are multiple approaches that might provide a solution to this issue, which are discussed in more depth in Section 6.3. Moreover, as expected due to the lower standard deviation in the inbound flow, the standard deviation of the inbound capacity also demonstrates the lowest values for the new scenario.

In addition, the overview of the number of pallets that are transported in advance of their demand week demonstrate that over 70% of the total number of pallets remain to be transported in their demand week, while roughly 10% of all pallets are transported 1 week in advance of their demand. The remaining pallets are transported either 2, 3, 4, 5 or 6 weeks in advance. The fact that most of the items arrive in their demand week also links to the fact that the many TUs have poor utilisation levels. Due to the fact that the number of available TUs is often higher than the demand, the items with demand for the weeks in which this is the case can mostly be transported in their desired week. Moreover, the inventory level development displayed an increase in the safety stock for the current situation during an extend period in 2021. This increase in safety stock was due to the fact that ADIL experienced a lot of availability issues, which led them to increase their stocks in order to ensure that they would be able to fulfil demand better. Comparing the current situation to the new situation, the inventory costs lower with 2.71%. When an estimation is made of what the inventory level would have looked like had the safety stock not been increased, the comparison to the new situation shows a different picture. In that case, the inventory costs would be 2.12% higher for the new scenario. Finally, the standard deviation of the inventory level is found to be the highest for the new scenario compared to the original new scenario as well as the original scenario without the increase in safety stock.

The sensitivity analysis in experiment 5 demonstrates that a factor increase in the penalty values does not impact the decision making of the model, while the weight of the two factors that make up the penalty does influence the decision making. However, the impact on the robustness of the model is limited due to the two hard constraints that ensure that all items (outside of the warm-up period) are transported and the limitation on the number of weeks items are allowed to be transported in advance. Experiment 6 shows that the algorithm is strongly sensitive to changes in the number of weeks items are allowed to be transported in advance. As such, this decision should be made with careful consideration as it will have a big impact on the performance of the algorithm.

6. CONCLUSIONS AND RECOMMENDATIONS

This chapter aims to provide the conclusions and answer to Research Question 5: ‘What are the conclusions and recommendations for the Ahold Delhaize Inbound Logistics department?’, and as such answer the main research question: ‘How should the number of transport units and item allocation to them be determined such that the inbound flow is levelled and costs are minimised?’. The conclusions and answer to the research question can be found in Section 6.1. The practical and scientific relevance are discussed in Section 6.2. The recommendations and suggestions for further research are described in Section 6.3.

6.1 CONCLUSIONS

To answer the main research question, first a context analysis is performed in order to gain a proper understanding of the current situation. The DCs currently experience large fluctuations in inbound flow, leading to capacity problems. These capacity problems are the motivation for this research. It is not only important to understand how items are currently transported, namely via road, intermodal train or intermodal sea transport, but also how items are ordered and allocated to transport units. As levelling the inbound flow impacts the decision making on what items are transported when, it is important to understand the current decision making as well as the constraints related to the item allocation. Currently, items are ordered on a weekly basis, based on the inventory level and forecasted demand. When the inventory level of an item is expected to fall below the safety stock, the item is ordered. Orders are made such that mostly only full truck loads (FTLs) are transported, which means that in some cases items that officially do not have to be ordered yet are added to the order to ensure that this is the case. Furthermore, there are a number of constraints that must be taken into consideration, like the fact that all demand must be met, and the number of items that can be transported in a truck are limited by a weight and pallet capacity. Also, items should not be transported too far in advance, therefore the decision for transport in advance should be based on the distribution term and the turnover rate of an item.

During the literature review, it is found that there is not a single item allocation model or method that is an exact fit to the problem. Therefore, the relevant parts from all problems that are reviewed are taken to create an approach that meets all requirements. These parts are the consideration of multiple periods, the fact that all demand must be met, and the item allocation is constrained by the pallet and weight capacity, showing the need for multiple constraints. Moreover, multiple transport units items need to be assigned to are considered, which is reflected in the multiple Knapsack Problem. The literature review demonstrates that almost all models are solved via a heuristic approach. The heuristic approaches that show the closest link to the problem at hand iteratively add the items with the highest profitability as long as the constraints do not get violated. The approach needs to be adjusted, to fit the problem, but idea behind the heuristic remains intact.

Based on the models found during the literature review, the model is formulated. In addition, the approach to solve the item allocation is described based on the heuristic methods found in the literature review. Based on the historic data, first the weekly number of transport units of each type for each scenario are calculated. This number can be adjusted after executing the constructive and improvement heuristic by the TU heuristic, that increases or decreases the weekly number of available TUs based on items that do not fit or utilisation rates. The constructive heuristic assigns the items to the available number of transport units, based on their demand week and their penalty in case of early transportation. Items are first assigned as early as possible. If an item cannot be added before its demand week, it is added to a NoFit list. After all items that could have been added are added, an improvement step takes place in which items are moved to the week in which they have demand if that is possible. Once this improvement step has taken place, a second attempt is made to add the items in the NoFit list to the TUs. The result of the constructive heuristic is an initial solution, after which a Reduced Variable Neighbourhood Search (RVNS) attempts to improve the solution. As described by Hansen and

Mladenovic (2014), RVNS systematically exploits the idea of a neighbourhood change, making it possible to descent local optima and escape the valleys that contain them. Three operators are used to generate solutions, namely a Swap operator, Move operator and 2-Swap operator.

For running the experiments, 15 scenarios are generated. These scenarios consist of the items that must be ordered, and the required information (such as the number of demanded pallets, the demand week, transport unit type, etc) of 15 countries, and are of different sizes and configurations. In addition, for each country separately the required number of weekly transport units is calculated, as described above. Next, three parameter tuning experiments are performed to find the behaviour of the algorithm under different parameter settings. The tested parameter settings that result in the best performance of the algorithm are set to conduct a fourth experiment, with the purpose of evaluating the performance.

The results of the fourth experiment show that the performance in terms of the objective value, utilisation rates, and deviation in the number of weekly inbound pallets vary for the different scenarios. The reason for this are the characteristics of the different scenarios, both in terms of their size and their composition (such as the demand variability throughout the year). The varying performance shows that in some cases the scenario might not be best suited for levelling with the parameter settings found in experiment 1 through 3, or in general, for levelling through the approach as described in this research.

Overall, from this experiment, the conclusion can be drawn that in some respects the new situation in which the inbound flow of items is levelled through using the same number of TUs for each week outperforms the current situation. First of all, with respect to the standard deviation of the inbound flow and the KPI standard deviation of the DC capacity utilisation the algorithm shows a 41.05% lower standard deviation when compared to the current situation. This shows that levelling the inbound flow could indeed improve the current problems the DC is experiencing with its capacity due to high peaks in the inbound flow. The results also show that for example the standard deviation of the inventory level is higher when the inbound flow is levelled compared to the current situation, but this is expected as the outbound remains variable while the inbound flow levels out. When the inbound and outbound flow of goods don't follow the same pattern anymore, the pattern of the inventory level will demonstrate more variable behaviour. Moreover, from the historical data, it can be concluded that the inventory levels rose for a number of months during 2021 due to an increase in safety stock that was initiated because of the availability issues ADIL was experiencing. When this increase in safety stock is removed from the data and the inventory level development without this additional safety stock is estimated, it is also found that the inventory costs are 2.12% higher when the inbound flow is levelled. Despite this, since the levelling of inbound flow is done through having a fixed number of TUs on a weekly basis, this likely allows ADIL to negotiate a lower price with its logistic partners based on their fixed purchasing. When the transportation costs lower by 1% this can already account for the increase in the inventory costs. Finally, the results demonstrate that for many scenarios, and especially when considering truck transport, the utilisation levels of the TUs are too low. This can be explained by the limitation on the number of weeks items are allowed to be transported in advance and the fact that all items must be transported to meet demand. In order to fulfil these constraints, the number of fixed TUs will be increased to deal with periods of increased demand, leaving them with much lower utilisation levels for the periods with lower demand. This is also reflected in the objective of the optimisation problem. For the case in which the inbound flow is levelled, naturally the objective is higher than for the current situation, namely roughly 27%. This is explained by the fact that for the current situation, no penalties are assigned and the total number of transport units on a yearly basis is lower.

In short, the answer to the main research question 'What are the effects of levelling the inbound flow throughout the year on Ahold Delhaize Inbound Logistics' operations, costs, and inventory?' is as follows: the approach as described in this research is able to resolve the large fluctuations in inbound flow at the distribution centre that are the cause of the capacity problems ADIL experiences, and thus has a positive effect on the operations, there are some down falls. The utilisation levels of the TUs in many cases are too low, leading to resources being wasted and the transportation costs being higher than strictly required. As expected, the inventory levels rise slightly in case the inbound flow is levelled throughout the year, but these additional costs can be outweighed easily by only a minor decrease in the transportation costs. This decrease in transportation costs is likely to occur, as when the inbound flow is levelled throughout the year, commitments can be made with the logistic providers for a fixed number of weekly TUs, resulting in lower transportation costs.

6.2 PRACTICAL AND SCIENTIFIC CONTRIBUTION

6.2.1 Practical contribution

This study contributes to the operations of the Ahold Delhaize Inbound Logistics department and Ahold Delhaize as a whole, but can also be applied to other companies with similar characteristics. The ways in which this is done are elaborated below.

Through levelling the inbound flow and, thus, decreasing the peaks in inbound flow, the capacity problems that ADIL currently experiences can be resolved. This ensures that all actions that are required for the processing of the inbound flow can be conducted fully and without delays, demonstrating a significant improvement in the operations at ADIL’s Distribution Centres.

However, these improvements do require a trade-off to be made, as the inventory costs increase and the utilisation levels lower. Thus, the resolution of the capacity problems, as described in this research, does lead to other issues that require careful consideration and attention, and potentially further optimisation or a different approach.

6.2.2 Scientific contribution

As of right now, there is little to no literature available on optimization and transportation with the goal of evenly spreading the inbound flow in the form of the number of inbound transport units, instead of the goal of inventory minimisation. The effects of this untraditional approach to inbound logistics can be demonstrated more clearly for a large multinational such as Ahold Delhaize, due to the size of (fluctuations in) the inbound flow. The research has shown that the approach is able to offer solution for the capacity problems that can occur due to peaks in inbound flow. However, while feasible solutions have been found and the research has demonstrated that only a minor decrease in the transportation costs can already account for the increase in inventory costs for scenarios with similar costs per TU, the research has also shown that the approach as taken now has some limitations. These limitations relate to the low utilisation levels when an equal number of TUs are used on a weekly basis. This also offers opportunities for further research, which will be discussed in Section 6.3.

Moreover, even though a lot of research has been conducted in the direction of the lot sizing problem, the bin packing problem, the 0-1 knapsack problem and its variants, including the multiple multi-dimensional knapsack problem, and finally, the container loading problem, little research has been performed in the direction of a combination of these problems. This research has demonstrated that a combination of these problems allows for creating a model that displays the case at hand, such that it can be solved to generate feasible solutions through a heuristic approach.

6.3 RECOMMENDATIONS AND FUTURE RESEARCH

This research has shown that spreading the inbound flow evenly throughout the year is able to resolve the capacity problems the DC in Tiel currently faces at times of increased inbound flow. However, it also poses a number of challenges that prevent a recommendation to directly implement the approach as discussed in this research. As the approach has demonstrated promising results in terms of resolving the capacity problems at the DC in Tiel, it is recommended to conduct further research to improve the approach to attempt to increase the performance. There are a number of directions in which further research might prove worthwhile.

As mentioned during the discussion of the performance of the algorithm, the utilisation rates for the transport units are rather low. This can be explained by the fact that the number of transport units should remain equal for all weeks, while the peaks in inbound flow cannot be spread out infinitely, due to the fact that there is a limitation on the number of weeks items are allowed to be transported in advance of their demand week. As a result of this limitation, it occurs more often that items do not fit within the available number of transport units, leading to an increase of this number through the transport unit heuristic that is currently applied in the algorithm. One can conclude that, due to the assumptions that were made at the beginning of the research, the results are not optimal, but offer an opportunity to potentially be improved through other methods.

The first suggestion for further research is to not fully fix the number of transport units throughout the year, but work with more of a 'bandwidth' approach. The number of transport units should then be within this bandwidth but is allowed to fluctuate a little during periods of increased demand. This will then potentially allow the DC to cope better with the periods of increased flow, as still some levelling takes place, while also allowing items to be transported closer to their demand week during times of increased demand compared to the completely levelled approach as discussed in this research. Through this approach, the ADIL department would still be able to negotiate with the logistic providers on the number of transport units that will minimally be used each week, and the DC experiences a lot less fluctuations in the inbound flow. Implementation of this approach does require a large change to the mathematical model and the solution approach. In terms of changes to the mathematical model, it would entail that the current decision variable $a_{u,o}$ has an additional index *t*. As a result, the decision on the number of transport units of each type *u* from origin *o* is made for every period *t*. In addition, this number would have to be limited by the bandwidth, both in terms of its lowest value and its highest value. In terms of the solution approach, the values for the minimum and maximum of this bandwidth can be based on the historical data. For example, a 40% increase from the lowest number of used TUs in a week and a 40% decrease from the highest number of TUs. This 40% is a parameter that could be tuned to determine the effects on its performance. Moreover, the TU heuristic would require a large adjustment to determine the value for $a_{u,o,t}$. One way to determine the initial value for $a_{u,o,t}$ could be to also base this number on the historical data. When the number of TUs of type u in origin o in a particular week falls below the set minimum this number should be set to this minimum and, similarly, when this number exceeds the maximum, it should be set to this maximum. With these numbers, the item allocation could be performed as it is currently done and afterwards it should again be evaluated whether there are items that do not fit within the available capacity, or whether potentially in some weeks there is increased idle capacity. An approach that can be taken here is to increase the number of transport units of type for origin o in week t by 1 if there are items that do not fit within that week, as long as the current number of TUs does not exceed the maximum. If the maximum is exceeded, it should be checked if the number can be increased for the week before, if not, the week before that, and so on. If the utilisation is too low, the number of TUs in a week should be decreased by 1. If this change results in items that do not fit, the change should be reversed and not be allowed to change again. Naturally, next to the described change in the solution approach, there are many more possibilities to change the solution approach such that the bandwidth approach can be applied. All of these possibilities should be part of the further research in this direction.

Moreover, another approach that could be researched further is still fixing the number of TUs of type *u* from origin *o* for a longer period of time, but not for the whole year. For example, in case of the demonstrated case for scenario 11 in Figure 20. If up to week 21 the number of weekly containers of all types would be set at 0 and from week 22 to week 52 to the original number of containers would be set (1 40ft and 2 40ft wide containers), the average container utilisation level increases from 53.13% to 89.13%. Naturally, this scenario shows an extreme case, however it also shows that the utilisation level can improve once this approach is implemented. Furthermore, research could be conducted in the direction of the number of different TU levels that should be implemented, and how often they should be allowed to change. An example could be having only 2 TU levels but allowing changes to the number of TUs 4 times a year, but many more options could be researched to positively impact the performance throughout the year. For this case also, fluctuations could still be limited, and it is known in advance what capacity should be available at the DCs. In addition, fixed purchasing commitments could still be made with ADIL's logistics partners based on the minimum number of weekly TUs.

The third suggestion for further research relates to not considering the countries of origin separately with each their own weekly number of transport units, but rather considering one total fixed number of weekly transport units, that can be divided over the countries according to their demand. That way items might be able to arrive closer to their demand points compared to the current situation, while still maintaining a stable inbound flow. This could be the case when during week 1 country 1 has a higher demand, while country 2 has a lower demand, and in week 2 the same situation occurs but the other way around. Through aggregating the countries, at times of increased demand for one country and lower demand for the other country, the demand for each country can be transported under the fixed inbound number of TUs/flow. When the European countries are considered together, it is shown that the utilisation rate for trucks for the current algorithm improves from 67.52% to 76.68%, as the total number of trucks decreases from 123 to 108 on a weekly basis. However, by making changes or improvements to the algorithm this number could be improved further.

In addition, allowing for consolidation on truck transport on shorter distances could lower the number of required trucks and therefore also increase the utilisation levels. This suggestion is tested for one of the scenarios from this research which demonstrates low utilisation rates and in which the different suppliers are located in relatively close proximity, namely for scenario 8. Through running the algorithm, without the constraint of a single supplier per truck (i.e. allowing for consolidation), it is found that the number of trucks required to transport all items in advance of their demand can be decreased from 5 trucks per week to 2 trucks per week. Moreover, the utilisation levels increase from roughly 29.34% to 73.91%. This clearly demonstrates the potential benefit that could be gained through allowing consolidation in areas in which suppliers are located with close proximity. Combining both the third and fourth suggestion could also prove to even further improve the separate improvements that can be made, as the third suggestion is currently also still strongly constrained by the fact that no consolidation can take place between the different trucks.

Furthermore, the model could be used to evaluate the effects of moving from road transport towards intermodal train transport for other European countries such as Spain, France and Germany. As shown during the experiments, levelling the inbound flow while transporting items via road transport often results in lower utilisation rates, compared to transported modes that better allow for consolidation. By testing the effects of making these adjustments on the inbound flow (as items can then be consolidated before they are transported), it could potentially be found that a large gain can be made, next to potential financial and sustainability benefits.

Finally, the company strives strongly to make their operations more sustainable as they have already made commitments for the coming years (Ahold Delhaize, 2021c). Levelling the inbound flow of goods as done in this research through a fixed weekly number of TUs allows for the option of making purchasing commitments with ADIL's logistic providers. These commitments will provide an incentive to the logistic providers to purchase more eco-friendly trucks for example. Potentially, the ADIL department could also demand these changes during the negotiation phase of the contract. Further research is required to determine in which way this can be achieved. Increasing the sustainability of their modes of transport allows ADIL to aid the company in meeting its sustainability commitments.

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APPENDIX A

Table 15: Results experiment 1 setting 0 – Swap, Move, 2-Swap with equal probabilities

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.191	468,465.121	468,465.471	468,465.191	3	0	0.5242	0.0000	1
2	5,230.673	5,382.679	5,273.299	1,721,230.673	1,721,382.679	1,721,273.299	11	0	0.7349	0.0000	10
3	8,175.554	8,313.296	8,250.827	3,596,175.554	3,596,313.296	3,596,250.827	23	0	0.7009	0.0000	26
4	8,471.313	8,507.413	8,488.312	3,128,471.313	3,128,507.413	3,128,488.312	20	0	0.7815	0.0000	55
5	1,773.537	1,774.628	1,774.410	469,773.537	469,774.628	469,774.410	3	0	0.6526	0.0000	0
6	18.961	51.291	25.921	910,018.961	910,051.291	910,025.921	0	5 (20ft)	0.0000	0.7087	0
7	3,846.870	4,167.104	4,048.354	4,566,846.870	4,567,167.104	4,567,048.354	6	31 (45ftw)	0.5507	0.9223	2
8	1,447.146	1,452.040	1,448.909	781,447.146	781,452.040	781,448.909	5	0	0.2934	0.0000	13
9	4,302.531	4,936.166	4,645.295	1,876,302.531	1,876,936.166	1,876,645.295	12	0	0.8567	0.0000	3
10	163.675	178.400	168.400	1,638,163.675	1,638,178.400	1,638,168.400	2	6 (40ftw)	0.5231	0.6528	0
11	4,142.381	4,302.430	4,242.285	4,866,142.381	4,866,302.430	4,866,242.285	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	37.473	54.850	43.802	468,037.473	468,054.850	468,043.802	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	593.735	607.958	600.823	1,040,593.735	1,040,607.958	1,040,600.823	0	5(40ft)	0.0000	0.8546	0
15	1,401.012	1,426.909	1,413.640	1,249,401.012	1,249,426.909	1,249,413.640	8	0	0.7177	0.0000	0
Total	**40,085.153**	**41,635.806**	**40,904.639**	**27,769,085.153**	**27,770,635.806**	**27,769,904.639**	**123**	**55**	**0.6752**	**0.8180**	**212**

Table 16: Results experiment 1 setting 1 – Swap, Move with equal probabilities

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.191	468,465.121	468,465.471	468,465.191	3	0	0.5242	0.0000	1
2	5,239.243	5,392.848	5,334.422	1,721,239.243	1,721,392.848	1,721,334.422	11	0	0.7349	0.0000	10
3	7,986.461	8,049.616	8,005.366	3,595,986.461	3,596,049.616	3,596,005.366	23	0	0.7009	0.0000	26
4	8,064.077	8,144.393	8,114.238	3,128,064.077	3,128,144.393	3,128,114.238	20	0	0.7815	0.0000	55
5	1,773.537	1,774.628	1,774.192	469,773.537	469,774.628	469,774.192	3	0	0.6526	0.0000	0
6	19.587	51.291	32.513	910,019.587	910,051.291	910,032.513	0	5 (20ft)	0.0000	0.7087	0
7	3,604.396	3,739.029	3,664.160	4,566,604.396	4,566,739.029	4,566,664.160	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.828	1,448.424	1,446.587	781,444.828	781,448.424	781,446.587	5	0	0.2934	0.0000	13
9	4,287.094	4,934.350	4,592.323	1,876,287.094	1,876,934.350	1,876,592.323	12	0	0.8567	0.0000	3
10	164.700	175.900	170.705	1,638,164.700	1,638,175.900	1,638,170.705	2	6 (40ftw)	0.5231	0.6528	0
11	3,943.760	4,021.519	3,975.975	4,865,943.760	4,866,021.519	4,865,975.975	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	39.563	44.992	42.682	468,039.563	468,044.992	468,042.682	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	589.195	611.522	598.908	1,040,589.195	1,040,611.522	1,040,598.908	0	5(40ft)	0.0000	0.8546	0
15	1,400.200	1,411.584	1,406.421	1,249,400.200	1,249,411.584	1,249,406.421	8	0	0.7177	0.0000	0
Total	**39,036.933**	**40,280.739**	**39,638.852**	**27,768,036.933**	**27,769,280.739**	**27,768,638.852**	**123**	**55**	**0.6752**	**0.8180**	**212**

Table 17: Results experiment 1 setting 2 – Swap, 2-Swap with equal probabilities

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	468.546	468.896	468.616	468,468.546	468,468.896	468,468.616	3	0	0.5242	0.0000	1
2	5,699.851	5,808.271	5,761.313	1,721,699.851	1,721,808.271	1,721,761.313	11	0	0.7349	0.0000	10
3	8,444.339	8,449.151	8,446.684	3,596,444.339	3,596,449.151	3,596,446.684	23	0	0.7009	0.0000	26
4	8,459.106	8,528.511	8,499.221	3,128,459.106	3,128,528.511	3,128,499.221	20	0	0.7815	0.0000	55
5	1,784.242	1,784.242	1,784.242	469,784.242	469,784.242	469,784.242	3	0	0.6526	0.0000	0
6	35.396	39.767	37.583	910,035.396	910,039.767	910,037.583	0	5 (20ft)	0.0000	0.7087	0
7	4,012.603	4,078.366	4,051.532	4,567,012.603	4,567,078.366	4,567,051.532	6	31 (45ftw)	0.5507	0.9223	2
8	1,453.106	1,457.599	1,454.679	781,453.106	781,457.599	781,454.679	5	0	0.2934	0.0000	13
9	4,698.196	4,820.811	4,749.967	1,876,698.196	1,876,820.811	1,876,749.967	12	0	0.8567	0.0000	3
10	174.775	185.900	178.140	1,638,174.775	1,638,185.900	1,638,178.140	2	6 (40ftw)	0.5231	0.6528	0
11	4,273.679	4,315.271	4,287.000	4,866,273.679	4,866,315.271	4,866,287.000	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	38.120	44.594	41.101	468,038.120	468,044.594	468,041.101	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	610.257	630.105	622.038	1,040,610.257	1,040,630.105	1,040,622.038	0	5(40ft)	0.0000	0.8546	0
15	1,458.658	1,479.333	1,467.798	1,249,458.658	1,249,479.333	1,249,467.798	8	0	0.7177	0.0000	0
Total	**41,626.045**	**42,105.990**	**41,865.087**	**27,770,626.045**	**27,771,105.990**	**27,770,865.087**	**123**	**55**	**0.6752**	**0.8180**	**212**

Table 18: Results experiment 1 setting 3 – Move, 2-Swap with equal probabilities

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	490.621	490.621	490.621	468,490.621	468,490.621	468,490.621	3	0	0.5242	0.0000	1
2	6,415.074	6,420.747	6,417.557	1,722,415.074	1,722,420.747	1,722,417.557	11	0	0.7349	0.0000	10
3	8,386.078	8,414.351	8,399.695	3,596,386.078	3,596,414.351	3,596,399.695	23	0	0.7009	0.0000	26
4	8,651.931	8,676.870	8,661.331	3,128,651.931	3,128,676.870	3,128,661.331	20	0	0.7815	0.0000	55
5	1,849.009	1,849.009	1,849.009	469,849.009	469,849.009	469,849.009	3	0	0.6526	0.0000	0
6	63.912	63.912	63.912	910,063.912	910,063.912	910,063.912	0	5 (20ft)	0.0000	0.7087	0
7	4,779.312	4,796.838	4,789.738	4,567,779.312	4,567,796.838	4,567,789.738	6	31 (45ftw)	0.5507	0.9223	2
8	1,477.340	1,481.923	1,480.041	781,477.340	781,481.923	781,480.041	5	0	0.2934	0.0000	13
9	5,588.852	5,588.852	5,588.852	1,877,588.852	1,877,588.852	1,877,588.852	12	0	0.8567	0.0000	3
10	212.150	212.150	212.150	1,638,212.150	1,638,212.150	1,638,212.150	2	6 (40ftw)	0.5231	0.6528	0
11	4,493.148	4,535.660	4,516.817	4,866,493.148	4,866,535.660	4,866,516.817	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	67.922	69.217	68.261	468,067.922	468,069.217	468,068.261	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	717.369	717.369	717.369	1,040,717.369	1,040,717.369	1,040,717.369	0	5(40ft)	0.0000	0.8546	0
15	1,534.002	1,539.302	1,536.892	1,249,534.002	1,249,539.302	1,249,536.892	8	0	0.7177	0.0000	0
Total	**44,741.891**	**44,871.992**	**44,807.415**	**27,773,741.891**	**27,773,871.992**	**27,773,807.415**	**123**	**55**	**0.6752**	**0.8180**	**212**

Table 19: Results experiment 1 setting 4 – Swap

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	468.546	468.896	468.756	468,468.546	468,468.896	468,468.756	3	0	0.5242	0.0000	1
2	5,690.580	5,904.057	5,789.428	1,721,690.580	1,721,904.057	1,721,789.428	11	0	0.7349	0.0000	10
3	8,344.764	8,385.689	8,368.691	3,596,344.764	3,596,385.689	3,596,368.691	23	0	0.7009	0.0000	26
4	8,344.070	8,411.560	8,367.747	3,128,344.070	3,128,411.560	3,128,367.747	20	0	0.7815	0.0000	55
5	1,784.242	1,786.426	1,784.679	469,784.242	469,786.426	469,784.679	3	0	0.6526	0.0000	0
6	36.198	39.767	37.517	910,036.198	910,039.767	910,037.517	0	5 (20ft)	0.0000	0.7087	0
7	3,502.868	3,637.636	3,589.757	4,566,502.868	4,566,637.636	4,566,589.757	6	31 (45ftw)	0.5507	0.9223	2
8	1,455.422	1,457.166	1,456.485	781,455.422	781,457.166	781,456.485	5	0	0.2934	0.0000	13
9	4,663.892	4,896.167	4,800.923	1,876,663.892	1,876,896.167	1,876,800.923	12	0	0.8567	0.0000	3
10	165.500	184.275	175.950	1,638,165.500	1,638,184.275	1,638,175.950	2	6 (40ftw)	0.5231	0.6528	0
11	4,222.920	4,276.323	4,247.267	4,866,222.920	4,866,276.323	4,866,247.267	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	39.620	53.806	43.941	468,039.620	468,053.806	468,043.941	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	608.646	623.619	615.877	1,040,608.646	1,040,623.619	1,040,615.877	0	5(40ft)	0.0000	0.8546	0
15	1,455.958	1,479.083	1,471.146	1,249,455.958	1,249,479.083	1,249,471.146	8	0	0.7177	0.0000	0
Total	**40,798.397**	**41,619.640**	**41,233.335**	**27,769,798.397**	**27,770,619.640**	**27,770,233.335**	**123**	**55**	**0.6752**	**0.8180**	**212**

Table 20: Results experiment 1 setting 5 – Move

Scenario	**Min. penalty**	**Max. penalty**	**Avg. penalty**	**Min. objective**	**Max. objective**	**Avg. objective**	**Number trucks**	**Number containers**	**Truck utilisation**	**Container utilisation**	**UI**
1	490.621	490.621	490.621	468,490.621	468,490.621	468,490.621	3	0	0.5242	0.0000	1
2	6,445.442	6,445.646	6,445.558	1,722,445.442	1,722,445.646	1,722,445.558	11	0	0.7349	0.0000	10
3	8,343.078	8,412.978	8,383.110	3,596,343.078	3,596,412.978	3,596,383.110	23	0	0.7009	0.0000	26
4	8,344.489	8,434.009	8,391.113	3,128,344.489	3,128,434.009	3,128,391.113	20	0	0.7815	0.0000	55
5	1,849.009	1,849.009	1,849.009	469,849.009	469,849.009	469,849.009	3	0	0.6526	0.0000	0
6	63.912	63.912	63.912	910,063.912	910,063.912	910,063.912	0	5 (20ft)	0.0000	0.7087	0
7	4,784.472	4,789.619	4,787.604	4,567,784.472	4,567,789.619	4,567,787.604	6	31 (45ftw)	0.5507	0.9223	2
8	1,485.968	1,485.968	1,485.968	781,485.968	781,485.968	781,485.968	5	0	0.2934	0.0000	13
9	5,591.088	5,591.088	5,591.088	1,877,591.088	1,877,591.088	1,877,591.088	12	0	0.8567	0.0000	3
10	212.150	212.150	212.150	1,638,212.150	1,638,212.150	1,638,212.150	2	6 (40ftw)	0.5231	0.6528	0
11	4,502.448	4,581.952	4,537.673	4,866,502.448	4,866,581.952	4,866,537.673	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	70.909	70.909	70.909	468,070.909	468,070.909	468,070.909	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	717.369	717.370	717.369	1,040,717.369	1,040,717.370	1,040,717.369	0	5(40ft)	0.0000	0.8546	0
15	1,546.902	1,548.927	1,547.947	1,249,546.902	1,249,548.927	1,249,547.947	8	0	0.7177	0.0000	0
Total	**44,463.027**	**44,709.329**	**44,589.203**	**27,773,463.027**	**27,773,709.329**	**27,773,589.203**	**123**	**55**	**0.6752**	**0.8180**	**212**

Table 21: Results experiment 2 setting 1 – Swap, Move, 2-Swap

Scenario	**Min. penalty**	**Max. penalty**	**Avg. penalty**	**Min. objective**	**Max. objective**	**Avg. objective**	**Number trucks**	**Number containers**	**Truck utilisation**	**Container utilisation**	**UI**
1	465.121	465.471	465.191	468,465.121	468,465.471	468,465.191	3	0	0.5242	0.0000	1
2	5,402.030	5,561.432	5,489.484	1,721,402.030	1,721,561.432	1,721,489.484	11	0	0.7349	0.0000	10
3	8,368.564	8,422.589	8,386.245	3,596,368.564	3,596,422.589	3,596,386.245	23	0	0.7009	0.0000	26
4	8,348.090	8,490.169	8,418.129	3,128,348.090	3,128,490.169	3,128,418.129	20	0	0.7815	0.0000	55
5	1,777.016	1,777.016	1,777.016	469,777.016	469,777.016	469,777.016	3	0	0.6526	0.0000	0
6	31.915	37.024	33.901	910,031.915	910,037.024	910,033.901	0	5 (20ft)	0.0000	0.7087	0
7	3,592.510	3,726.493	3,661.576	4,566,592.510	4,566,726.493	4,566,661.576	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.797	1,445.152	1,444.972	781,444.797	781,445.152	781,444.972	5	0	0.2934	0.0000	13
9	4,502.692	4,786.143	4,625.126	1,876,502.692	1,876,786.143	1,876,625.126	12	0	0.8567	0.0000	3
10	165.700	179.525	171.550	1,638,165.700	1,638,179.525	1,638,171.550	2	6 (40ftw)	0.5231	0.6528	0
11	4,239.508	4,316.133	4,277.783	4,866,239.508	4,866,316.133	4,866,277.783	27	1 (40ft), 2 (40ftw)	0.5978	0.5313	39
12	38.120	43.402	41.331	468,038.120	468,043.402	468,041.331	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft), 3 (40ft)	0.0000	0.6148	41
14	599.867	609.442	603.912	1,040,599.867	1,040,609.442	1,040,603.912	0	5(40ft)	0.0000	0.8546	0
15	1,405.719	1,427.019	1,418.119	1,249,405.719	1,249,427.019	1,249,418.119	8	0	0.7177	0.0000	0
Total	**40,396.819**	**41,302.182**	**40,829.504**	**27,769,396.819**	**27,770,302.182**	**27,769,829.504**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 22: Results experiment 2 setting 2 - Move, Swap, 2-Swap

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	468.546	468.896	468.616	468,468.546	468,468.896	468,468.616	3	0	0.5242	0.0000	1
2	5,685.476	5,783.712	5,734.795	1,721,685.476	1,721,783.712	1,721,734.795	11	0	0.7349	0.0000	10
3	8,083.961	8,139.611	8,116.652	3,596,083.961	3,596,139.611	3,596,116.652	23	0	0.7009	0.0000	26
4	8,424.867	8,731.741	8,641.609	3,128,424.867	3,128,731.741	3,128,641.609	20	0	0.7815	0.0000	55
5	1,784.242	1,784.242	1,784.242	469,784.242	469,784.242	469,784.242	3	0	0.6526	0.0000	0
6	36.198	41.899	39.557	910,036.198	910,041.899	910,039.557	0	5 (20ft)	0.0000	0.7087	0
7	3,620.954	3,689.445	3,654.608	4,566,620.954	4,566,689.445	4,566,654.608	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.793	1,446.063	1,445.158	781,444.793	781,446.063	781,445.158	5	0	0.2934	0.0000	13
9	4,708.892	4,855.503	4,755.899	1,876,708.892	1,876,855.503	1,876,755.899	12	0	0.8567	0.0000	3
10	165.850	176.175	171.575	1,638,165.850	1,638,176.175	1,638,171.575	2	6 (40ftw)	0.5231	0.6528	0
11	4,065.724	4,137.400	4,105.297	4,866,065.724	4,866,137.400	4,866,105.297	27	1 (40ft), 2 (40ftw)	0.5978	0.5313	39
12	37.473	42.607	39.509	468,037.473	468,042.607	468,039.509	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft), 3 (40ft)	0.0000	0.6148	41
14	610.554	633.498	620.628	1,040,610.554	1,040,633.498	1,040,620.628	0	5(40ft)	0.0000	0.8546	0
15	1,435.538	1,452.713	1,445.211	1,249,435.538	1,249,452.713	1,249,445.211	8	0	0.7177	0.0000	0
Total	**40,588.239**	**41,398.677**	**41,038.526**	**27,769,588.239**	**27,770,398.677**	**27,770,038.526**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 23: Results experiment 3 setting 1 - 5 minutes, 10%

Scenario	**Min. penalty**	**Max. penalty**	**Avg. penalty**	**Min. objective**	**Max. objective**	**Avg. objective**	**Number trucks**	**Number containers**	**Truck utilisation**	**Container utilisation**	**UI**
1	465.121	465.121	465.121	468,465.121	468,465.121	468,465.121	3	0	0.5242	0.0000	1
2	5,249.609	5,375.965	5,313.600	1,721,249.609	1,721,375.965	1,721,313.600	11	0	0.7349	0.0000	10
3	8,186.400	8,335.092	8,245.834	3,596,186.400	3,596,335.092	3,596,245.834	23	0	0.7009	0.0000	26
4	8,332.359	8,518.333	8,427.033	3,128,332.359	3,128,518.333	3,128,427.033	20	0	0.7815	0.0000	55
5	1,773.537	1,785.795	1,776.643	469,773.537	469,785.795	469,776.643	3	0	0.6526	0.0000	0
6	18.961	19.587	19.462	910,018.961	910,019.587	910,019.462	0	5 (20ft)	0.0000	0.7087	0
7	3,790.171	4,064.890	3,909.096	4,566,790.171	4,567,064.890	4,566,909.096	6	31 (45ftw)	0.5507	0.9223	2
8	1,446.867	1,450.605	1,449.353	781,446.867	781,450.605	781,449.353	5	0	0.2934	0.0000	13
9	4,356.039	4,916.785	4,568.756	1,876,356.039	1,876,916.785	1,876,568.756	12	0	0.8567	0.0000	3
10	165.750	182.325	173.080	1,638,165.750	1,638,182.325	1,638,173.080	2	6 (40ftw)	0.5231	0.6528	0
11	4,122.092	4,328.786	4,210.492	4,866,122.092	4,866,328.786	4,866,210.492	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	40.813	46.037	43.291	468,040.813	468,046.037	468,043.291	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	592.046	611.130	600.225	1,040,592.046	1,040,611.130	1,040,600.225	0	5(40ft)	0.0000	0.8546	0
15	1,406.147	1,420.759	1,412.114	1,249,406.147	1,249,420.759	1,249,412.114	8	0	0.7177	0.0000	0
Total	**39,961.082**	**41,536.381**	**40,629.271**	**27,768,961.082**	**27,770,536.381**	**27,769,629.271**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 24: Results experiment 3 setting 2 - 5 minutes, 20%

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.261	468,465.121	468,465.471	468,465.261	3	0	0.5242	0.0000	1
2	5,228.841	5,458.628	5,393.028	1,721,228.841	1,721,458.628	1,721,393.028	11	0	0.7349	0.0000	10
3	8,124.416	8,376.499	8,241.816	3,596,124.416	3,596,376.499	3,596,241.816	23	0	0.7009	0.0000	26
4	8,346.701	8,654.667	8,473.478	3,128,346.701	3,128,654.667	3,128,473.478	20	0	0.7815	0.0000	55
5	1,773.537	1,779.928	1,775.033	469,773.537	469,779.928	469,775.033	3	0	0.6526	0.0000	0
6	18.961	51.291	25.677	910,018.961	910,051.291	910,025.677	0	5 (20ft)	0.0000	0.7087	0
7	3,696.827	4,022.981	3,806.887	4,566,696.827	4,567,022.981	4,566,806.887	6	31 (45ftw)	0.5507	0.9223	2
8	1,445.525	1,447.167	1,446.361	781,445.525	781,447.167	781,446.361	5	0	0.2934	0.0000	13
9	4,278.526	4,841.878	4,664.148	1,876,278.526	1,876,841.878	1,876,664.148	12	0	0.8567	0.0000	3
10	160.825	177.650	168.325	1,638,160.825	1,638,177.650	1,638,168.325	2	6 (40ftw)	0.5231	0.6528	0
11	4,103.520	4,446.038	4,228.383	4,866,103.520	4,866,446.038	4,866,228.383	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	40.415	44.742	41.800	468,040.415	468,044.742	468,041.800	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	588.518	616.603	600.272	1,040,588.518	1,040,616.603	1,040,600.272	0	5(40ft)	0.0000	0.8546	0
15	1,403.484	1,416.209	1,408.737	1,249,403.484	1,249,416.209	1,249,408.737	8	0	0.7177	0.0000	0
Total	**39,690.388**	**41,814.924**	**40,754.378**	**27,768,690.388**	**27,770,814.924**	**27,769,754.378**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 25: Results experiment 3 setting 3 - 10 minutes, 10%

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.191	468,465.121	468,465.471	468,465.191	3	0	0.5242	0.0000	1
2	5,239.243	5,392.848	5,334.422	1,721,239.243	1,721,392.848	1,721,334.422	11	0	0.7349	0.0000	10
3	7,986.461	8,049.616	8,005.366	3,595,986.461	3,596,049.616	3,596,005.366	23	0	0.7009	0.0000	26
4	8,064.077	8,144.393	8,114.238	3,128,064.077	3,128,144.393	3,128,114.238	20	0	0.7815	0.0000	55
5	1,773.537	1,774.628	1,774.192	469,773.537	469,774.628	469,774.192	3	0	0.6526	0.0000	0
6	19.587	51.291	32.513	910,019.587	910,051.291	910,032.513	0	5 (20ft)	0.0000	0.7087	0
7	3,604.396	3,739.029	3,664.160	4,566,604.396	4,566,739.029	4,566,664.160	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.828	1,448.424	1,446.587	781,444.828	781,448.424	781,446.587	5	0	0.2934	0.0000	13
9	4,287.094	4,934.350	4,592.323	1,876,287.094	1,876,934.350	1,876,592.323	12	0	0.8567	0.0000	3
10	164.700	175.900	170.705	1,638,164.700	1,638,175.900	1,638,170.705	2	6 (40ftw)	0.5231	0.6528	0
11	3,943.760	4,021.519	3,975.975	4,865,943.760	4,866,021.519	4,865,975.975	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	39.563	44.992	42.682	468,039.563	468,044.992	468,042.682	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	589.195	611.522	598.908	1,040,589.195	1,040,611.522	1,040,598.908	0	5(40ft)	0.0000	0.8546	0
15	1,400.200	1,411.584	1,406.421	1,249,400.200	1,249,411.584	1,249,406.421	8	0	0.7177	0.0000	0
Total	**39,036.933**	**40,280.739**	**39,638.852**	**27,768,036.933**	**27,769,280.739**	**27,768,638.852**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 26: Results experiment 3 setting 4 - 10 minutes, 20%

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.191	468,465.121	468,465.471	468,465.191	3	0	0.5242	0.0000	1
2	5,281.582	5,399.857	5,317.999	1,721,281.582	1,721,399.857	1,721,317.999	11	0	0.7349	0.0000	10
3	7,946.355	8,044.006	7,993.960	3,595,946.355	3,596,044.006	3,595,993.960	23	0	0.7009	0.0000	26
4	8,123.819	8,166.766	8,139.046	3,128,123.819	3,128,166.766	3,128,139.046	20	0	0.7815	0.0000	55
5	1,773.537	1,774.628	1,774.192	469,773.537	469,774.628	469,774.192	3	0	0.6526	0.0000	0
6	19.587	51.291	38.548	910,019.587	910,051.291	910,038.548	0	5 (20ft)	0.0000	0.7087	0
7	3,663.718	3,704.056	3,680.601	4,566,663.718	4,566,704.056	4,566,680.601	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.328	1,445.662	1,444.742	781,444.328	781,445.662	781,444.742	5	0	0.2934	0.0000	13
9	4,271.083	4,702.027	4,519.660	1,876,271.083	1,876,702.027	1,876,519.660	12	0	0.8567	0.0000	3
10	167.150	175.450	172.285	1,638,167.150	1,638,175.450	1,638,172.285	2	6 (40ftw)	0.5231	0.6528	0
11	3,966.070	4,036.054	3,988.165	4,865,966.070	4,866,036.054	4,865,988.165	27	1 (40ft), 2 (40ftw)	0.5978	0.5313	39
12	40.415	44.742	42.736	468,040.415	468,044.742	468,042.736	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft), 3 (40ft)	0.0000	0.6148	41
14	591.091	621.143	605.848	1,040,591.091	1,040,621.143	1,040,605.848	0	5(40ft)	0.0000	0.8546	0
15	1,409.734	1,422.959	1,413.147	1,249,409.734	1,249,422.959	1,249,413.147	8	0	0.7177	0.0000	0
Total	**39,178.762**	**40,069.284**	**39,611.291**	**27,768,178.762**	**27,769,069.284**	**27,768,611.291**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 27: Results experiment 3 setting 5 - 15 minutes, 10%

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.191	468,465.121	468,465.471	468,465.191	3	0	0.5242	0.0000	1
2	5,228.177	5,441.687	5,312.664	1,721,228.177	1,721,441.687	1,721,312.664	11	0	0.7349	0.0000	10
3	7,902.661	7,937.886	7,925.006	3,595,902.661	3,595,937.886	3,595,925.006	23	0	0.7009	0.0000	26
4	7,941.605	8,147.362	8,041.142	3,127,941.605	3,128,147.362	3,128,041.142	20	0	0.7815	0.0000	55
5	1,773.537	1,782.315	1,775.947	469,773.537	469,782.315	469,775.947	3	0	0.6526	0.0000	0
6	18.961	19.587	19.462	910,018.961	910,019.587	910,019.462	0	5 (20ft)	0.0000	0.7087	0
7	3,590.344	3,638.717	3,607.656	4,566,590.344	4,566,638.717	4,566,607.656	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.328	1,445.723	1,444.792	781,444.328	781,445.723	781,444.792	5	0	0.2934	0.0000	13
9	4,293.455	4,775.541	4,507.807	1,876,293.455	1,876,775.541	1,876,507.807	12	0	0.8567	0.0000	3
10	162.575	176.625	170.500	1,638,162.575	1,638,176.625	1,638,170.500	2	6 (40ftw)	0.5231	0.6528	0
11	3,944.420	4,004.027	3,967.147	4,865,944.420	4,866,004.027	4,865,967.147	27	1 (40ft), 2 (40ftw)	0.5978	0.5313	39
12	39.563	44.197	41.666	468,039.563	468,044.197	468,041.666	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft), 3 (40ft)	0.0000	0.6148	41
14	597.992	609.301	602.373	1,040,597.992	1,040,609.301	1,040,602.373	0	5(40ft)	0.0000	0.8546	0
15	1,399.947	1,410.584	1,406.218	1,249,399.947	1,249,410.584	1,249,406.218	8	0	0.7177	0.0000	0
Total	**38,817.856**	**39,914.196**	**39,302.742**	**27,767,817.856**	**27,768,914.196**	**27,768,302.742**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 28: Results experiment 3 setting 6 - 15 minutes, 20%

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.331	468,465.121	468,465.471	468,465.331	3	0	0.5242	0.0000	1
2	5,176.951	5,350.598	5,281.267	1,721,176.951	1,721,350.598	1,721,281.267	11	0	0.7349	0.0000	10
3	7,924.386	8,041.114	7,996.770	3,595,924.386	3,596,041.114	3,595,996.770	23	0	0.7009	0.0000	26
4	7,907.762	8,134.824	8,052.843	3,127,907.762	3,128,134.824	3,128,052.843	20	0	0.7815	0.0000	55
5	1,774.628	1,779.928	1,775.688	469,774.628	469,779.928	469,775.688	3	0	0.6526	0.0000	0
6	19.587	51.291	38.353	910,019.587	910,051.291	910,038.353	0	5 (20ft)	0.0000	0.7087	0
7	3,466.743	3,562.597	3,495.250	4,566,466.743	4,566,562.597	4,566,495.250	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.328	1,446.503	1,445.204	781,444.328	781,446.503	781,445.204	5	0	0.2934	0.0000	13
9	4,235.596	4,796.325	4,588.323	1,876,235.596	1,876,796.325	1,876,588.323	12	0	0.8567	0.0000	3
10	161.250	178.100	169.270	1,638,161.250	1,638,178.100	1,638,169.270	2	6 (40ftw)	0.5231	0.6528	0
11	3,925.076	3,979.851	3,952.747	4,865,925.076	4,865,979.851	4,865,952.747	27	1 (40ft), 2 (40ftw)	0.5978	0.5313	39
12	40.165	43.617	41.285	468,040.165	468,043.617	468,041.285	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	1,404,015.171	1,404,015.171	1,404,015.171	0	2 (20ft), 3 (40ft)	0.0000	0.6148	41
14	590.403	608.361	600.390	1,040,590.403	1,040,608.361	1,040,600.390	0	5(40ft)	0.0000	0.8546	0
15	1,395.837	1,419.162	1,408.752	1,249,395.837	1,249,419.162	1,249,408.752	8	0	0.7177	0.0000	0
Total	**38,543.005**	**39,872.914**	**39,326.645**	**28,183,543.005**	**28,184,872.914**	**28,184,326.645**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 29: Results experiment 3 setting 7 - 20 minutes, 10%

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.191	468,465.121	468,465.471	468,465.191	3	0	0.5242	0.0000	1
2	5,219.489	5,328.458	5,283.406	1,721,219.489	1,721,328.458	1,721,283.406	11	0	0.7349	0.0000	10
3	7,947.911	7,994.861	7,972.783	3,595,947.911	3,595,994.861	3,595,972.783	23	0	0.7009	0.0000	26
4	8,006.471	8,122.723	8,069.239	3,128,006.471	3,128,122.723	3,128,069.239	20	0	0.7815	0.0000	55
5	1,773.537	1,774.628	1,774.192	469,773.537	469,774.628	469,774.192	3	0	0.6526	0.0000	0
6	19.587	50.981	25.866	910,019.587	910,050.981	910,025.866	0	5 (20ft)	0.0000	0.7087	0
7	3,477.366	3,563.735	3,521.967	4,566,477.366	4,566,563.735	4,566,521.967	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.328	1,445.723	1,444.851	781,444.328	781,445.723	781,444.851	5	0	0.2934	0.0000	13
9	4,360.156	4,960.929	4,548.136	1,876,360.156	1,876,960.929	1,876,548.136	12	0	0.8567	0.0000	3
10	166.575	177.075	171.270	1,638,166.575	1,638,177.075	1,638,171.270	2	6 (40ftw)	0.5231	0.6528	0
11	3,962.475	4,016.351	3,985.308	4,865,962.475	4,866,016.351	4,865,985.308	27	1 (40ft), 2 (40ftw)	0.5978	0.5313	39
12	40.915	43.697	42.425	468,040.915	468,043.697	468,042.425	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	1,404,015.171	1,404,015.171	1,404,015.171	0	2 (20ft), 3 (40ft)	0.0000	0.6148	41
14	593.457	604.940	598.051	1,040,593.457	1,040,604.940	1,040,598.051	0	5(40ft)	0.0000	0.8546	0
15	1,398.022	1,414.634	1,407.692	1,249,398.022	1,249,414.634	1,249,407.692	8	0	0.7177	0.0000	0
Total	**38,890.581**	**39,979.378**	**39,325.546**	**28,183,890.581**	**28,184,979.378**	**28,184,325.546**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 30: Results experiment 3 setting 8 – 20 minutes, 20%

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.261	468,465.121	468,465.471	468,465.261	3	0	0.5242	0.0000	1
2	5,275.896	5,382.360	5,330.284	1,721,275.896	1,721,382.360	1,721,330.284	11	0	0.7349	0.0000	10
3	7,909.210	8,003.841	7,942.087	3,595,909.210	3,596,003.841	3,595,942.087	23	0	0.7009	0.0000	26
4	7,913.738	8,161.726	8,030.878	3,127,913.738	3,128,161.726	3,128,030.878	20	0	0.7815	0.0000	55
5	1,773.537	1,774.628	1,774.192	469,773.537	469,774.628	469,774.192	3	0	0.6526	0.0000	0
6	19.307	51.291	25.872	910,019.307	910,051.291	910,025.872	0	5 (20ft)	0.0000	0.7087	0
7	3,479.668	3,613.766	3,559.720	4,566,479.668	4,566,613.766	4,566,559.720	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.328	1,445.063	1,444.787	781,444.328	781,445.063	781,444.787	5	0	0.2934	0.0000	13
9	4,206.163	4,913.464	4,512.477	1,876,206.163	1,876,913.464	1,876,512.477	12	0	0.8567	0.0000	3
10	169.000	181.250	174.610	1,638,169.000	1,638,181.250	1,638,174.610	2	6 (40ftw)	0.5231	0.6528	0
11	3,901.486	3,945.916	3,932.006	4,865,901.486	4,865,945.916	4,865,932.006	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	40.018	43.402	41.401	468,040.018	468,043.402	468,041.401	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	1,404,015.171	1,404,015.171	1,404,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	594.990	604.187	600.591	1,040,594.990	1,040,604.187	1,040,600.591	0	5(40ft)	0.0000	0.8546	0
15	1,407.372	1,418.759	1,412.307	1,249,407.372	1,249,418.759	1,249,412.307	8	0	0.7177	0.0000	0
Total	**38,615.005**	**40,020.297**	**39,261.643**	**28,183,615.005**	**28,185,020.297**	**28,184,261.643**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 31: Results experiment 4

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.191	468,465.121	468,465.471	468,465.191	3	0	0.5242	0.0000	1
2	5,228.177	5,441.687	5,312.664	1,721,228.177	1,721,441.687	1,721,312.664	11	0	0.7349	0.0000	10
3	7,902.661	7,937.886	7,925.006	3,595,902.661	3,595,937.886	3,595,925.006	23	0	0.7009	0.0000	26
4	7,941.605	8,147.362	8,041.142	3,127,941.605	3,128,147.362	3,128,041.142	20	0	0.7815	0.0000	55
5	1,773.537	1,782.315	1,775.947	469,773.537	469,782.315	469,775.947	3	0	0.6526	0.0000	0
6	18.961	19.587	19.462	910,018.961	910,019.587	910,019.462	0	5 (20ft)	0.0000	0.7087	0
7	3,590.344	3,638.717	3,607.656	4,566,590.344	4,566,638.717	4,566,607.656	6	31 (45ftw)	0.5507	0.9223	2
8	1,444.328	1,445.723	1,444.792	781,444.328	781,445.723	781,444.792	5	0	0.2934	0.0000	13
9	4,293.455	4,775.541	4,507.807	1,876,293.455	1,876,775.541	1,876,507.807	12	0	0.8567	0.0000	3
10	162.575	176.625	170.500	1,638,162.575	1,638,176.625	1,638,170.500	2	6 (40ftw)	0.5231	0.6528	0
11	3,944.420	4,004.027	3,967.147	4,865,944.420	4,866,004.027	4,865,967.147	27	1 (40ft), 2 (40ftw)	0.5978	0.5313	39
12	39.563	44.197	41.666	468,039.563	468,044.197	468,041.666	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft), 3 (40ft)	0.0000	0.6148	41
14	597.992	609.301	602.373	1,040,597.992	1,040,609.301	1,040,602.373	0	5(40ft)	0.0000	0.8546	0
15	1,399.947	1,410.584	1,406.218	1,249,399.947	1,249,410.584	1,249,406.218	8	0	0.7177	0.0000	0
Total	**38,817.856**	**39,914.196**	**39,302.742**	**27,767,817.856**	**27,768,914.196**	**27,768,302.742**	**123**	**55**	**0.6752**	**0.8501**	**212**

Table 32: Proof experiment 5: increased penalty by factor 1,000

Scenario	Original penalty	Increased penalty
1	490.6206	490,620.5686
2	6,523.7712	6,523,771.2375
3	70.9094	70,909.4482
4	8,967.5219	8,967,521.9064
5	4,834.5696	4,834,569.6488
6	8,848.6639	8,848,663.8796
7	1,581.9324	1,581,932.4415
8	1,849.0094	1,849,009.4482
9	63.9124	63,912.3746
10	4,347.8069	4,347,806.9398
11	1,886.1687	1,886,168.7291
12	5,591.0877	5,591,087.7090
13	213.2000	213,200.0000
14	15.1714	15,171.4047
15	718.2744	718,274.4147

Table 33: Results experiment 6 setting 1 - maximum 3 weeks transportation in advance

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	372.803	372.803	372.803	468,372.803	468,372.803	468,372.803	3	0	0.5242	0.0000	1
2	4,652.477	4,837.537	4,735.190	1,720,652.477	1,720,837.537	1,720,735.190	11	0	0.7349	0.0000	10
3	4,427.972	4,576.072	4,505.727	4,528,427.972	4,528,576.072	4,528,505.727	29	0	0.5567	0.0000	14
4	6,989.482	7,070.790	7,043.433	3,282,989.482	3,283,070.790	3,283,043.433	21	0	0.7456	0.0000	45
5	1,543.180	1,550.276	1,548.857	469,543.180	469,550.276	469,548.857	3	0	0.6526	0.0000	0
6	8.936	9.843	9.481	910,008.936	910,009.843	910,009.481	0	5 (20ft)	0.0000	0.7087	0
7	7,529.117	8,258.093	7,904.987	4,570,529.117	4,571,258.093	4,570,904.987	6	31 (45ftw)	0.5507	0.9223	2
8	1,397.555	1,403.655	1,399.682	781,397.555	16,403.655	16,399.682	5	0	0.2934	0.0000	13
9	4,038.660	4,094.701	4,063.880	1,876,038.660	1,876,094.701	1,876,063.880	12	0	0.8567	0.0000	3
10	197.075	229.600	219.580	1,638,197.075	1,638,229.600	1,638,219.580	2	6	0.5231	0.6528	0
11	3,097.346	3,183.716	3,148.131	5,242,097.346	5,242,183.716	5,242,148.131	28	1 (40ft). 3(40ftw)	0.5774	0.3942	30
12	41.098	47.925	44.308	468,041.098	468,047.925	468,044.308	3	0	0.5671	0.0000	33
13	62.123	65.289	63.996	1,404,062.123	1,404,065.289	1,404,063.996	0	2 (20ft). 5 (40ft)	0.0000	0.4264	0
14	529.134	542.180	532.552	1,040,529.134	1,040,542.180	1,040,532.552	0	5 (40ft)	0.0000	0.8546	0
15	1,766.553	1,862.162	1,804.557	1,249,766.553	1,249,862.162	1,249,804.557	8	0	0.7177	0.0000	0
Total	36,653.512	38,104.643	37,397.165	29,650,653.512	28,887,104.643	28,886,397.165	131	58	0.6345	0.7739	151

Table 34: Results experiment 6 setting 2 - maximum 6 weeks transportation in advance

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	465.121	465.471	465.191	468,465.121	468,465.471	468,465.191	3	0	0.5242	0.0000	1
2	5,230.673	5,382.679	5,273.299	1,721,230.673	1,721,382.679	1,721,273.299	11	0	0.7349	0.0000	10
3	8,175.554	8,313.296	8,250.827	3,596,175.554	3,596,313.296	3,596,250.827	23	0	0.7009	0.0000	26
4	8,471.313	8,507.413	8,488.312	3,128,471.313	3,128,507.413	3,128,488.312	20	0	0.7815	0.0000	55
5	1,773.537	1,774.628	1,774.410	469,773.537	469,774.628	469,774.410	3	0	0.6526	0.0000	0
6	18.961	51.291	25.921	910,018.961	910,051.291	910,025.921	0	5 (20ft)	0.0000	0.7087	0
7	3,846.870	4,167.104	4,048.354	4,566,846.870	4,567,167.104	4,567,048.354	6	31 (45ftw)	0.5507	0.9223	2
8	1,447.146	1,452.040	1,448.909	781,447.146	781,452.040	781,448.909	5	0	0.2934	0.0000	13
9	4,302.531	4,936.166	4,645.295	1,876,302.531	1,876,936.166	1,876,645.295	12	0	0.8567	0.0000	3
10	163.675	178.400	168.400	1,638,163.675	1,638,178.400	1,638,168.400	2	6 (40ftw)	0.5231	0.6528	0
11	4,142.381	4,302.430	4,242.285	4,866,142.381	4,866,302.430	4,866,242.285	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	37.473	54.850	43.802	468,037.473	468,054.850	468,043.802	3	0	0.5671	0.0000	22
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	593.735	607.958	600.823	1,040,593.735	1,040,607.958	1,040,600.823	0	5(40ft)	0.0000	0.8546	0
15	1,401.012	1,426.909	1,413.640	1,249,401.012	1,249,426.909	1,249,413.640	8	0	0.7177	0.0000	0
Total	40,085.153	41,635.806	40,904.639	27,769,085.153	27,770,635.806	27,769,904.639	123	55	0.6752	0.8180	212

Table 35: Results experiment 6 setting 3 - maximum 10 weeks transportation in advance

Scenario	Min. penalty	Max. penalty	Avg. penalty	Min. objective	Max. objective	Avg. objective	Number trucks	Number containers	Truck utilisation	Container utilisation	UI
1	394.739	423.964	407.729	468,394.739	468,423.964	468,407.729	3	0	0.5242	0.0000	1
2	5,726.446	5,870.414	5,804.508	1,721,726.446	1,721,870.414	1,721,804.508	11	0	0.7349	0.0000	10
3	8,541.676	8,830.301	8,698.246	3,596,541.676	3,596,830.301	3,596,698.246	23	0	0.7009	0.0000	26
4	10,065.282	10,128.094	10,103.237	3,130,065.282	3,130,128.094	3,130,103.237	20	0	0.7815	0.0000	55
5	1,588.015	1,713.792	1,661.454	469,588.015	469,713.792	469,661.454	3	0	0.6526	0.0000	0.0000
6	19.587	51.291	26.297	910,019.587	910,051.291	910,026.297	0	5 (20ft)	0.0000	0.7087	0.0000
7	2,643.736	2,772.498	2,704.725	4,565,643.736	4,565,772.498	4,565,704.725	6	31 (45ftw)	0.5507	0.9223	2
8	2,381.212	2,414.463	2,395.639	626,381.212	626,414.463	626,395.639	4	0	0.3634	0.0000	32.0000
9	5,550.219	6,020.668	5,771.309	1,877,550.219	1,878,020.668	1,877,771.309	12	0	0.8567	0.0000	3
10	115.050	117.800	116.930	1,638,115.050	1,638,117.800	1,638,116.930	2	6 (40ftw)	0.5231	0.6528	0
11	4,370.203	4,467.226	4,427.836	4,866,370.203	4,866,467.226	4,866,427.836	27	1 (40ft). 2 (40ftw)	0.5978	0.5313	39
12	1,646.738	1,665.310	1,655.690	313,646.738	313,665.310	313,655.690	2	0	0.8264	0.0000	39
13	15.171	15.171	15.171	988,015.171	988,015.171	988,015.171	0	2 (20ft). 3 (40ft)	0.0000	0.6148	41
14	585.147	613.401	603.763	1,040,585.147	1,040,613.401	1,040,603.763	0	5 (40ft)	0.0000	0.8546	0
15	2,886.458	3,062.183	2,984.024	1,094,886.458	1,095,062.183	1,094,984.024	7	0	0.8106	0.0000	9
Total	46,529.679	48,166.576	47,376.559	27,307,529.679	27,309,166.576	27,308,376.559	120	55	0.6910	0.8180	257