

# ***Improving the warehouse network at Apollo Vredestein***

*Bachelor Thesis Industrial Engineering & Management*

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## Preface

This document is the report on the bachelor's assignment I did for my study Industrial Engineering & Management. The assignment was done at Apollo Vredestein. During my time at the company, I have learned a lot of valuable things, both on and off subject. I would like to thank Frits and Wim of Apollo Vredestein for making me feel welcome at the company and guiding me through the assignment.

Furthermore, I would like to thank Eduardo Lalla for his supervising role. His patience really helped me in understanding the situation, as well as forcing me to thoroughly think things through. I would also like to thank Martijn Mes for his useful feedback on the bachelor's thesis. Finally, I would like to thank the support team of Aimms for allowing me to use their software off-campus.

I hope you enjoy reading my thesis.

Wouter Ensink

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# Management summary

## Introduction and context

Apollo Vredestein is a major player in the global tyre industry. Their European Distribution Centre is located in Enschede and consists of a central warehouse connected to a production hall. Since this warehouse does not have sufficient storage capacity for all stock, the company owns three additional warehouses in close proximity. This leads to a situation where stock is divided over the several warehouse locations. Since the central warehouse is the preferred location for all in- and outbound operations, stock often has to be moved back and forth the warehouse network. These movements are called relocations. I am asked to research this situation of internal flows for their Passenger Car Tyres, and to reduce these internal flows in complexity.

The scope is defined so that it fits under the responsibilities of the problem holder and company supervisor. As a result, only the logistics of the internal flows are analysed for improvements. Issues that fall beyond the responsibility of the company supervisor are identified and acknowledged in Chapter 6.

## Solution approach

The complexity of internal flows PCT is defined as a combination of the size of the flows and the unpredictability. In order to reduce these aspects, a general strategy for stock relocations has to be developed. The situation is described in a mathematical model, which can then be optimized to find a general strategy. The analytical solving of the model is done in Aimms 4.68, which proves to be efficient. However, since the company does not have access to this software package, a heuristic approach was developed in order to find solutions. This heuristic was then implemented in a 'relocation tool', designed for daily use of planning relocations.

## Results

The formulation of the situation as an adapted assignment problem allowed for finding an optimal solution the relocation assignment problem through analytical solving. The heuristic approach is able to find solutions that are very close to optimal (<0.1%) in sufficiently low computational times. The resulting tool is currently used by the warehouse staff, to identify products suitable for relocations.

## Recommendations

I would recommend the company to implement the relocation tool in the decision process around relocations. Additionally, the tool can be used to test cases such as increasing the capacity for relocation by temporarily renting an extra transport truck during busy periods. Hopefully the implementation of the relocation tool will reduce the workload of the warehouse staff, to work on the underlying problems. The solutions to these problems, in descending order of effectivity, are identified in this thesis as:

1. Decreasing the inventory size
2. Increasing the capacity of the central warehouse
3. Redesigning the warehouse network
4. Improving the storage assignment policy

I recommend the company to conduct further research in these directions, as solving the underlying problems will most likely result in large reductions in the complexity of internal PCT flows.

## List of acronyms

HU	Handling Unit
SKU	Stock Keeping Unit
PCT	Passenger Car Tyre
CTT	Container Terminal Twente
KPI	Key Performance Indicator
WMS	Warehouse Manager Indicator
FIFO	First In First Out



# Chapter 1: Introduction and context

This chapter describes the context of the assignment presented by the company. It involves finding the core problem and the definition of the research methodology and scope.

## 1.1 Introduction to the company

Apollo Vredestein is a major player in the global tyre industry. While the mother company, Apollo, is based in India, Apollo Vredestein has their headquarters in The Netherlands. The office is based in Amsterdam while all operations are performed in Enschede. This includes the warehousing and distribution of over 5 million tyres per year. These products are either produced in the facility in Enschede (operating 24/7 for 50 weeks per year), or enter the supply chain either via ship or truck. The finished goods enter the warehouse network in the central warehouse, adjacent to the production hall, where they are either stored on site or prepared for transport to one of the additional warehouses the company owns. Since the total in-house warehouse capacity is insufficient during inventory peaks, the company also rents multiple 12-foot containers at Container Terminal Twente (CTT), a trip of 8 km by truck away from the central warehouse.

The central warehouse is also the main location for outbound operations i.e., a large part of order picking and truck loading is done from the central warehouse. The finished goods are then distributed from the central warehouse to any of the smaller warehouses through Europe or directly to the customer.

## 1.2 Assignment description

The supply chain of Apollo Vredestein has been under a lot of pressure the last years. The demand during peaks is higher than the total warehouse capacity, so the company is forced to produce on a make-to-stock basis. As a result, the average inventory is very large and the company has been struggling to store and operate it. The production line produces about 130.000 tyres per week. These finished goods enter the central warehouse in a dedicated area and need to be moved and stored before the next production batch arrives. Pausing the production line is extremely expensive and therefore not an option. Additionally, Apollo Vredestein carries out a one-day lead time policy (i.e., the sales department promises customers that any ordered products will arrive within 24 hours in order to gain competitive advantage). As a result, products often have to be transported to the central warehouse in narrow timeframes.

These factors put a lot of stress on both the inbound and outbound operations in the central warehouse. Over the years, the continuous pressure has led to a situation where the internal flows of finished goods are large and complex. The products often follow multiple movements before the final transport to the customers. Considering the fact that internal flows occupy both the limited labour and transport capacity, the situation in the supply chain is expensive and inefficient. Therefore the company presented the following assignment:

### *Reduce the complexity of the internal flows of Passenger Car Tyres*

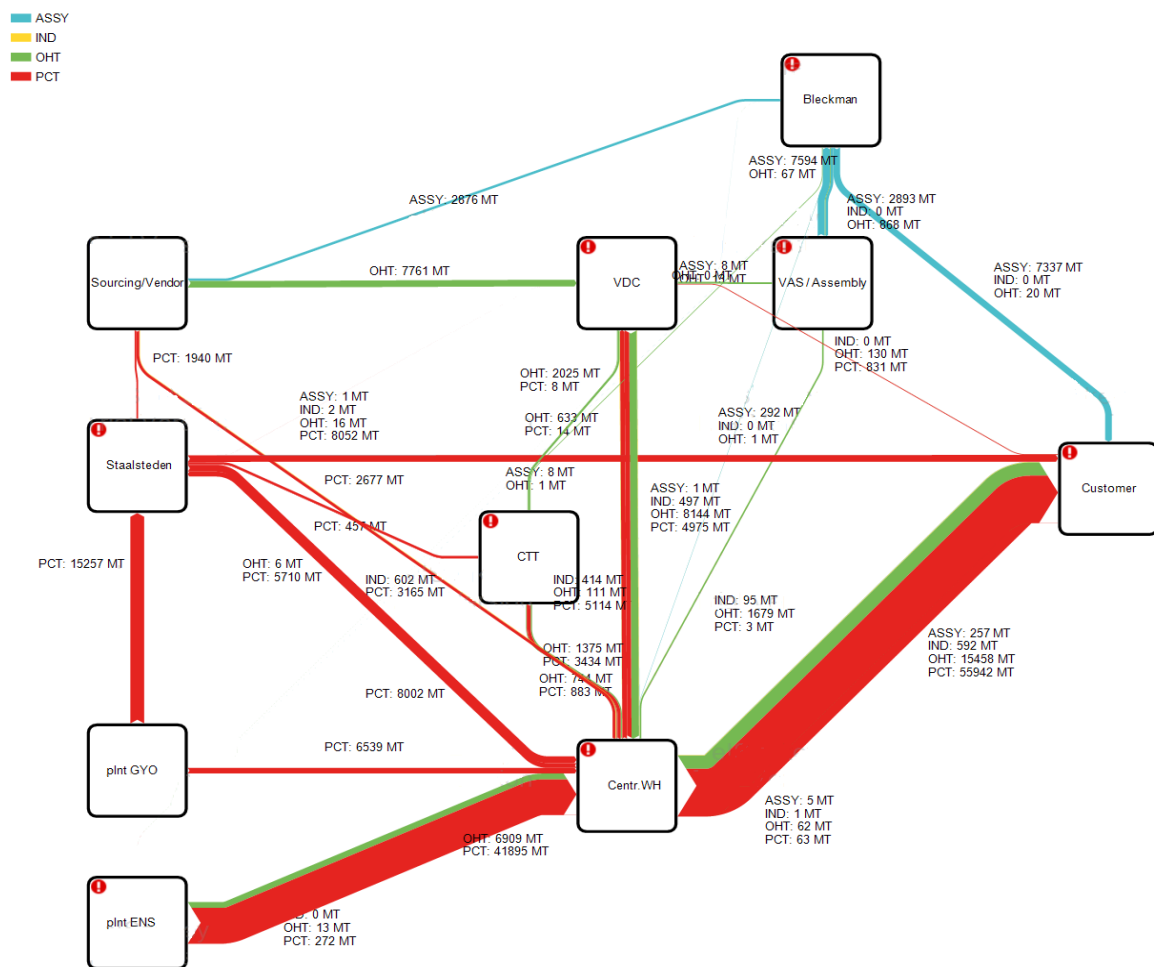
Passenger Car Tyres (PCT) are the bulk of Apollo Vredestein's sales volume. The flows are called complex for two reasons. First, the amount of internal movements (i.e., movements that occur within the company's supply chain) a single PCT can follow is large. Ideally, finished goods are stored upon entering a warehouse. Then, after some time, they are order-picked and transported to the customer. The situation at Apollo Vredestein is often very different than this ideal scenario, partly due to the reasons explained above. Second, these movements are initiated manually, which causes them to be unpredictable. For each internal movement, either the Inventory Manager or one of the

Warehouse Managers selects a new location for an amount of PCT stock. There is no general approach for this process. Thus, the complexity of the internal flows of PCT stock in this context concerns both the sheer amount of movements and the unpredictability of timing and destination of the movements.

Figure 1.1 is a visualisation of the complexity and size of the flows in the current situation. The flows of PCT are presented in red. The relevant nodes for PCT are the central warehouse (Centr. WH), the production facilities in Enschede (plnt ENS), Hungary (plnt GYO) and sources (Sourcing/Vendor). VDC and Staalsteden are additional warehouses owned by the company. CTT represents the rented ship containers.

**Figure 1.1: Flowchart of the warehouse network at Apollo Vredestein**

**As Is Scenario**



Almost all PCT products enter the system from the production facilities in Enschede and Hungary. All PCT produced in Enschede are first stored (temporarily) in the central warehouse. The PCT from Hungary and external sources are divided over Staalsteden and the central warehouse. What follows is a web of flows relocating PCT stock from and to VDC, CTT and the central warehouse, caused by the capacity deficiencies. These movements add no value to the products, while requiring a large amount of resources. In the words of the company’s Supply Chain CEO: “We are burning money”.

### 1.3 Problem identification

According to Heerkens & Van Winden, the action problem presented by a company is often a result of several underlying problems (Heerkens & Van Winden, 2012, p.44). Since completely solving one problem is more effective than almost solving more problems, it is crucial to select the right core problem. Since resources (e.g. time, money) are always finite, it is advised to follow a methodological approach when selecting the core problem. First, a list of all problems should be constructed. Formulating these problems in a problem cluster can help identify causal relations between problems to eventually arrive at the core problem (Heerkens & Van Winden, 2012, p.46).

The following problems were identified through exchanges with the supply chain CEO, the Manager European Distribution Centre, and the Logistics Engineer, also, observations in the warehouses were considered.

1. The internal flows of PCT are too complex
2. The amount of internal movements of PCT stock is too high
3. The path of storage locations of PCT stock is unpredictable
4. The central warehouse has insufficient capacity
5. Large inventory due to make-to-stock policy
6. Stock is relocated to generate short-term storage capacity
7. Relocation of stock is initiated per individual case
8. There is no general strategy for stock relocation

Figure 1.2: Problem cluster of the situation at Apollo Vredestein

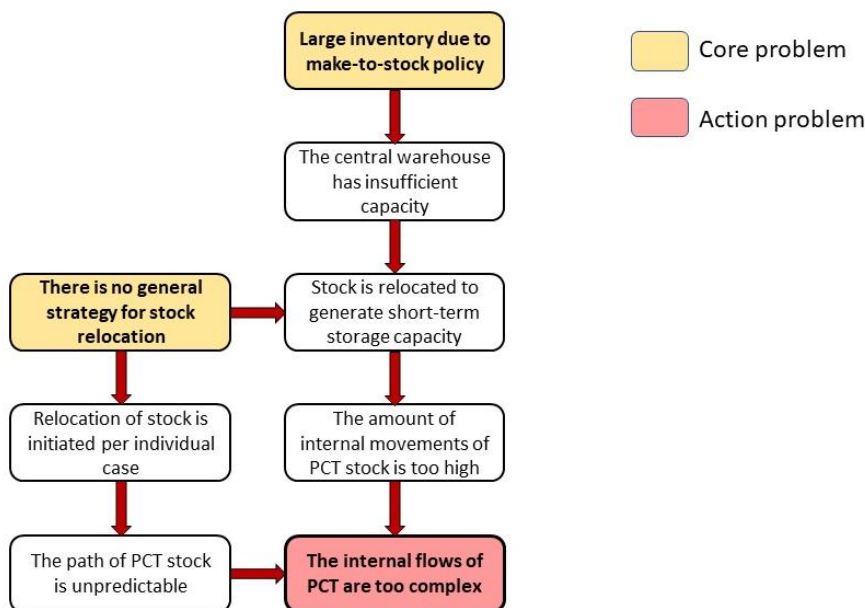


Figure 2.1 presents the causal relations between the problems. The core problem is the problem that has no further causes and that can be influenced (Heerkens & Van Winden, 2012, p.48). Hence, there are two possible core problems. The first core problem is the large inventory size due to the make-to-stock policy. The inventory size has multiple underlying factors, such as a large product range and the horizon over which orders are planned. It is also important to note the physical nature of the products: each PCT weights around 9 kg and its volume is about 0.30 cubic metres. Since the problem holder for this project is the Manager European Distribution Centre and the scope is ten weeks, the complexity and multi-disciplinary nature of this problem falls beyond the scope of this bachelor's

assignment. As a result, the lack of a general strategy for stock relocation is selected as the core problem for this project.

In the current situation, all stock storage and retrieval is determined by an algorithm in the Warehouse Management System (WMS) the company applies. Based on characteristics such as product origin, packaging, size and brand, the WMS applies a strategy established by the supply chain staff to determine the optimal stock location. However, the efficient approach of the WMS is often disturbed when stock relocation is executed to generate space, as explained before. These relocations are assessed per individual case and then manually edited into the WMS by the Warehouse Manager. The relocations are then added to a 'bucket' of tasks. Warehouse employees complete these tasks parallel to the regular operations (i.e., order picking and replenishing). As a result, relocation tasks often linger for a few days during busy periods.

Since all relocations are currently assessed individually, there is no overarching approach. Relocations are unpredictable and not optimised through a mathematical or heuristic approach. Developing a general strategy for stock relocations will therefore result in a reduction of internal flows, as well as a more predictable set of paths for PCT stock.

#### 1.4 KPI, norm and reality

As described in the problem identification phase, solving the core problem (i.e. there is no general strategy for relocations) will most likely contribute to a situation with less complex internal flows. However, the magnitude of desired change and outcome are not described; improvement in general is too vague. A description of the discrepancy between norm and reality is required. In order to do so, a variable should be connected to the core problem. The operationalisation of this variable should be addressed by selecting indicators for measurement of the variable (Heerkens & Van Winden, 2012, p.52).

The variable connected to the core problem is the amount of internal movements. The measurement of this variable is specified through two Key Performance Indicators (KPI), as explained in the next subsections.

##### 1.4.1 KPI 1: Average pallet movements per kg PCT

Since the total amount of stock (inbound and outbound) and the internal transport capacity are constant, a reduction of the amount of movements will inevitably mean that the internal flows are more efficient.

There are several types of movements a pallet PCT can follow in the Apollo Vredestein's warehouse network. The most important and necessary movements are PutAway and Retrieval. These are also respectively the first and last movement a pallet can encounter. PutAway is the action of placing an inbound product in a storage location. Retrieval consists of order-picking and replenishment. Any solution to the core problem, i.e. a strategy for stock relocations, could never eliminate either PutAway or Retrieval movements. As a result, PutAway and Retrieval movements are not included in the term 'pallet movements'.

Any movements that occur between PutAway and Retrieval are relocations. These movements are of no added value and are contributors to the complexity of the internal flows. Conclusively, the amount of pallet movements is the sum of movements between warehouses and movements within warehouses per pallet.

#### 1.4.2 KPI 2: Average pallet movement cost per kg PCT

The second variable involves the costs that accompany the pallet movements. This variable ensures that the obtained solution to the core problem actually reduces the complexity of internal flows in a profitable way. The total costs is composed of handling and transport costs. Handling and transport costs per kg PCT are known and consist of (reach) truck driver wage, fuel and the cost of using the truck.

#### 1.4.3 Norm and reality

The company has no clear values for both variables, so they must be derived from historical data provided by the WMS. Furthermore, a value for the norm of average pallet movements is hard to predict, since a single pallet of PCT can easily follow four movements (e.g., from the initial storage location to a area for temporary storage, from the temporary storage to the docks of the desired warehouse, from the docks of the desired warehouse to the new storage location) when relocated once. Therefore a reasonable norm for Indicator 1 is a reduction of average pallet movements of 20%.

Regarding Indicator 2, the cost should be minimalised. Since the goal is to reduce the amount of movements instead of reducing the cost, this value of this variable should at least not increase with the obtained solution.

**Table 1.1: Norm and reality per KPI**

<b>KPI description</b>	<b>Norm</b>	<b>Reality</b>
Average pallet movements $X$ per kg PCT	The average pallet movements $X$ decrease with a least 20%.	Stock relocations happen non-stop during the day. Pallets PCT can easily spend time in three different warehouses.
Average pallet movement cost $C$ per kg PCT	The cost $C$ of moving pallet loads PCT in stock relocations should at least not increase with any solution	Some relocations are more expensive than others, due to distance and dock capacities. However, all pallet movement cost $C$ is a waste of resources.

### 1.5 Problem solving approach

The second phase of the MPSM involves the problem solving approach. This chapter describes the objective of the project and the stakeholders involved. A plan of approach to solving the core problem is constructed. The phases of this plan, each connected to a research question, will be described and motivated. Finally, the scope of the project is defined.

#### 1.5.1 Project objective

The objective of this project is to solve the company's action problem, i.e. reducing the complexity of the internal PCT flows, by constructing a solution to the core problem in a business research. As explained in Section 1.3, the core problem is the lack of a general strategy for PCT stock relocations. Consequently, the main deliverable for this project is a strategy for stock relocations of PCT.

#### 1.5.2 Stakeholders

The stakeholders that are directly connected to this project are the company coach and problem holder, Frits Eijkelenkamp (Manager European Distribution Centre), and Wim Bolk (Logistics Engineer). They will provide access to the required data and facilitate this project. Furthermore, they

are the recipients of the final recommendation this project offers the company. They should be consulted in important decisions and considerations regarding the direction of the solution.

Indirectly connected to this project are the Inventory Manager and Warehouse Managers currently engaged with the operational side of stock relocations. Their opinions and views should be gauged, as they will likely have useful practical knowledge.

### *1.5.3 Plan of approach*

The creators of the MPSM advise to formulate the requirements for the plan of approach based on what there is to do, what there is to choose and what there is to know in the project (Heerkens & Van Winden, 2012, p. 60).

The most important actions required are: constructing a model of the current situation, collecting all data for the model, formulating a strategy based on the knowledge found in the model and presenting the findings in the form of recommendations to the company.

The following potential choices are important: which methodology will be used to model the situation, the choice of optimisation technique and selecting the proper test method for the strategy.

The knowledge required to solve the core problem involves the following topics:

- The current process of storing PCT stock
- The current process for relocating PCT stock
- Mathematical models that fit the company's situation
- The limitations and validity of those models
- The optimisation of the applied model
- The evaluation of the solution
- The implementation of the solution in the company's supply chain

Combining these knowledge problems, actions and choices, a plan of approach can be constructed. Each phase is connected to a research question and a deliverable. A motivation for the research questions and the knowledge problems they intend to solve are provided.

#### **Phase 1: Analysis**

1. *What is the current situation of PCT stock relocations in Apollo Vredestein's supply chain?*
  - a. *How are relocations of PCT stock currently processed?*
  - b. *What are the values of X and C in the current situation of PCT stock relocations?*

The first phase of the plan of approach is an in-depth analysis of the current situation at Apollo Vredestein. The goal is to obtain all relevant information regarding the warehouse network of the company in order to assess the context, possible solutions and constraints of the situation. Furthermore, an exact value for the variables described in Section 1.4 in the current situation should be determined in this phase. The deliverable, a written report of the as-is PCT flows and all influencing factors, serves two purposes. First, the information forms a foundation for the second phase. Second, it provides the company with insight about the complexity of the PCT flows.

#### **Phase 2: Constructing a model based on theory**

2. *How can Operations Research be used to address stock relocations in warehouses?*
  - a. *What models from the theory are relatable to the situation of PCT stock relocation?*
  - b. *How can the situation of PCT stock relocations be represented in a mathematical model?*

The second phase aims to process the knowledge found in the first phase into a mathematical model representing the PCT flows. This mathematical representation is the deliverable for Phase 2. In order to formulate the model, relevant literature will have to be assessed. The model used will be based on models constructed in literature considering comparable situations, adapted to the case of this project.

### **Phase 3: Formulating a solution based on model optimisation**

3. *What strategy for stock relocations can be devised for the case of Apollo Vredestein?*
  - a. *What is the solution that is obtained from optimizing the model?*
  - b. *How can this solution be implemented at Apollo Vredestein as a strategy for relocations?*

The third phase of the plan of approach considers the solution of the model. The strategy based on the results of the optimisation is the deliverable linked to this phase. The findings from Phase 2, the literature review, will be combined with the data found in the analysis. The resulting solution should be tailored to the company's situation and within the constraints described in Phase 1.

### **Phase 4: Evaluation**

4. *How can the obtained strategy be implemented in the decision process around stock relocations effectively?*

The fourth phase considers the evaluation of the selected strategy. Due to the high pressure on Apollo Vredestein's supply chain, it is not likely that the strategy can be tested in the scope of this project, since it will most likely require a reshuffle of stock and alter the layout of the central warehouse. Instead, the obtained strategy will have to be tested in a simulation. The deliverable for this phase is an analysis of the strategy's performance.

### **Phase 5: Recommendations and conclusions**

5. *Which improvements for the company are recommended to make?*

The fifth and final phase of the problem approach describes the recommended improvements for the company. These recommendations are changes the company has to make in the warehousing of the PCT products in order to solve the action problem. The deliverable for Phase 5 is a report of recommended improvements.

## **1.6 Scope and limitations**

Due to the narrow timeframe (i.e., ten weeks), the research will be limited to the problems involving the logistics of the European Distribution Centre. The inventory management will not be addressed, since the policy for determining inventory levels has recently been reviewed. Furthermore, only solutions suitable for deployment on an operational level will be addressed.

As a result, this research can be seen as treating symptoms (rather than causes) of a set of larger problems. However, I believe that, given the scope of the research assignment, this approach is the most likely to solve the most urgent operational problem (i.e., the scheduling and execution of stock relocations). This will hopefully reduce the daily time and effort spent on stock relocations by the Manager European Distribution Centre and the Logistics Manager, so that they can focus on the underlying problems.

# Chapter 2: Analysis of context

This chapter of the research covers an in-depth analysis of the current situation of PCT stock relocations at Apollo Vredestein. This analysis is of both a qualitative and quantitative nature, supported by the following research questions.

- 1a) *How are relocations of PCT stock currently processed?*
- 1b) *What are the values for the average pallet movements  $X$  and the accompanying cost  $C$  per PCT?*

Research question 1a concerns the current storage policies, the PCT flows and the processes currently involved with PCT stock relocations. Research question 1b concerns the indicators  $X$  and  $C$ , which are the average amount of pallet movements per kg PCT and the average pallet movement cost per kg PCT respectively. Table 2.1 describes the structure of Chapter 2.

**Table 2.1: Structure of Chapter 2**

1a)	2.1	Passenger Car Tyres
	2.2	Warehouses
	2.3	Current storage location assignment policy
	2.4	Storage flows
	2.5	Stock relocation
1b)	2.6	Key Performance Indicators
	2.7	Conclusion

## 2.1 Passenger Car Tyres

Apollo Vredestein produces a large number of tyres for all types of vehicles, including but not limited to: passenger car tyres, industrial tyres, bike tyres and agricultural tyres. As described in Section 1.2. this project considers only the Passenger Car Tyres (PCT). The majority of PCT Apollo Vredestein handles is produced in the production facility in Enschede. The remaining PCT are produced in the production facility in Gyongyos, Hungary or outsourced. The distribution of PCT over the production facilities is described in Table 2.2.

**Table 2.2: Expected distribution of PCT per source per year**

Source	Quantity PCT	Percentage PCT
Production ENS	4,819,934	61.81%
Production GYO	2,487,665	31.90%
Sourcing	490,612	6.29%
<b>Total</b>	<b>7,798,211</b>	

PCT are stored on stackable pallets. The exact amount of PCT per pallet depends on the size of the product and averages around 18. On average, a PCT weights 8.9 kg. The maximum amount of pallets that can be stacked is either 4 or 5, depending on the specific warehouse height. Apollo Vredestein currently has 1,145 PCT SKU's in their assortment.



## 2.2 Warehouses

The warehousing activities of Apollo Vredestein’s Personal Car Tyres (PCT) take place in four main locations: the central warehouse, VDC, Staalsteden and CTT. Each warehouse has its own functionalities and characteristics. Table 2.3 provides an overview of the warehouses, ranked descending in age.

**Table 2.3: Overview of warehouse characteristics**

Location #	Function	Capacity (m <sup>2</sup> )	Capacity (bins)	Capacity (pallets)	Distance to location 1 (km)
1	Central warehouse	22,463	1,250	25,000	0
2	Warehouse	9,113	750	11,950	0.1
3	Warehouse	21,500	1,323	22,815	3.5
4	Overflow containers	35,000	N/A	N/A	12.5

### 2.2.1 Location 1: Central Warehouse

The central warehouse is the hotspot of Apollo Vredestein’s warehouse network. The warehouse is the default location for all PCT order-picking and shipping. All outbound products from production enter the supply chain via this warehouse, as well as 48.8% of PCT from sources i.e., production Hungary and India, see Appendix A2.1. Furthermore, 85% of all PCT are shipped from the central warehouse to the customer, see Appendix A2.2.

In order to deal with these large flows, the warehouse is largely dedicated to PCT products. The layout of the central warehouse is depicted in Appendix A2.3. The storage locations closest to the docks are dedicated to order-picking activities. Small quantities of in-demand SKU’s are stored here for efficient order-picking. The remainder of PCT dedicated locations are reserved for bulk storage.

Over the years, the central warehouse has been expanded to its limit. When the inventory size exceeded the central warehouse capacity, the company was forced to rent additional capacity at VDC, located a mere 100 metres away.

### 2.2.2 Location 2: VDC

The VDC is mainly used as bulk storage, for both PCT and Agricultural Tyres (ACT), and the storage of blocked and/or obsolete products, as depicted in Appendix A2.4. The storage locations at the VDC are regarded as ‘overflow’ locations i.e., extra capacity for temporary storage. In most cases, PCT stored in the VDC are moved back to the central warehouse for shipping at some point in time. Order-picking in and shipping from the VDC is undesirable, but not impossible.

### 2.2.3 Location 3: Staalsteden

The third location, Staalsteden, is a large warehouse located about 3,5 km away from Location 1. In contrast to the other locations, Staalsteden is dedicated for PCT storage. In an earlier attempt to reduce the amount of flows at location 1, about half of the storage locations at Staalsteden were dedicated to a specific portion of PCT products, i.e. those of the Apollo brand. The dedicated area is divided into a detail pick (forward) and bulk (reserve) area for Apollo PCT, as depicted in Appendix A2.5.

Apollo PCT produced in the facility in Enschede (adjacent to Location 1) are stored temporarily in the area reserved for internal transport in the central warehouse, before being shipped to Staalsteden. PCT of the Apollo brand that enter the system through sources (production India or Hungary), are shipped directly to Staalsteden. The remaining storage locations at Staalsteden are used for the bulk

storage of non-Apollo, i.e. Vredestein brand, overflow PCT, which follow the same flow as PCT stored in Location 2.

#### *2.2.4 Location 4: CTT*

The fourth and final location is the Container Terminal Twente (CTT), which was added to Apollo Vredestein's warehouse network when the combined capacity of locations 1-3 proved insufficient. The containers, rented from an external party, are used for bulk storage of overflow PCT and ACT. The amount of containers Apollo Vredestein rents varies heavily through the year, see Appendix A2.6. The maximum number of containers occupied simultaneously for PCT in the period between 04-05-2017 and 04-11-2018 is 468, which corresponds to roughly 552,431 PCT or 4,357.4 Metric Tonnes of stock.

The logistics of CTT are handled by the owner of the location. Therefore, Apollo Vredestein's Supply Chain staff is not occupied with planning and logistics of the containers. However, Apollo Vredestein does pay a daily rent per container, as well as a container handling fee.

### *2.3 Current storage location assignment policy*

The storage policy is the set of priority rules a company applies to solve the storage-retrieval problem. According to de Koster et al. (2007), two main decisions within this problem can be identified:

1. Layout design and dimensioning of the storage system
2. Assigning products to storage locations

The first decision involves the determination of number of blocks, aisle dimensions and ratio of picking and storage areas. These decisions have large consequences and are, therefore, often decided on a tactical level. In the scope of this assignment, the dimensioning of blocks and aisles are constant.

The second decision considers the allocation of stock over storage locations on an operational level. Apollo Vredestein currently applies a storage policy in the form of priority rules in the WMS in order to assign products (per pallet) to storage locations. Each SKU in the company's assortment is assigned to a product group. Then, a preferred storage location is determined for that group. When an amount of a SKU enters the system, the storage location assignment algorithm, explained in Section 2.3.3, assigns the products to a storage bin within the preferred storage location. PCT are always placed in storage areas within a location, regardless of product group. Allocating products to pick areas is considered a replenishment operation.

#### *2.3.1 Product groups*

Each SKU is assigned to a product group based on two characteristics: product type and origin. There are three types of PCT, namely: Apollo brand, Vredestein brand and spike tyres. PCT originate either from the production facilities in Enschede and Gyongyos, or from external sources.

Spike tyres are regular PCT that are 'spiked' in the production facility in Enschede. Although the original product may come from each of the sources, the finished product i.e., the spiked tyre, will always enter the system from production Enschede. As a result, there are 7 combinations of product type and origin, depicted in Table 2.4.

**Table 2.4: Product groups for PCT**

Product group	Type	Origin
1A	Apollo brand	Enschede (NL)
1B	Apollo brand	Gyongyos (HU)
1C	Apollo brand	Worldwide
2A	Vredestein brand	Enschede (NL)
2B	Vredestein brand	Gyongyos (NL)
2C	Vredestein brand	Worldwide
3A	Spike tyres	Enschede

### 2.3.2 Preferred locations

The set and order of locations in which the WMS will search for a storage bin is based on the product's group. The preferred locations per product group are explained in Table 2.5.

**Table 2.5: Preferred locations per product group**

IF Product group = ""	Then Preferred location = ""
1A	Staalsteden
1B	Staalsteden
1C	Staalsteden
2A	Central Warehouse, then VDC
2B	Receiving location, then Central warehouse, then VDC
2C	Receiving location, then Central warehouse, then VDC
3A	VDC, then Central Warehouse

Vredestein brand tyres that are not produced in Enschede are ideally stored close to where they are received. For example, a truck filled with, amongst other products, Vredestein PCT from Gyongyos can be scheduled to a dock at Staalsteden (Location 3). The preferred storage location for these products is then the bulk storage area in Staalsteden. If there are no feasible locations available, the next preferred location is the central warehouse.

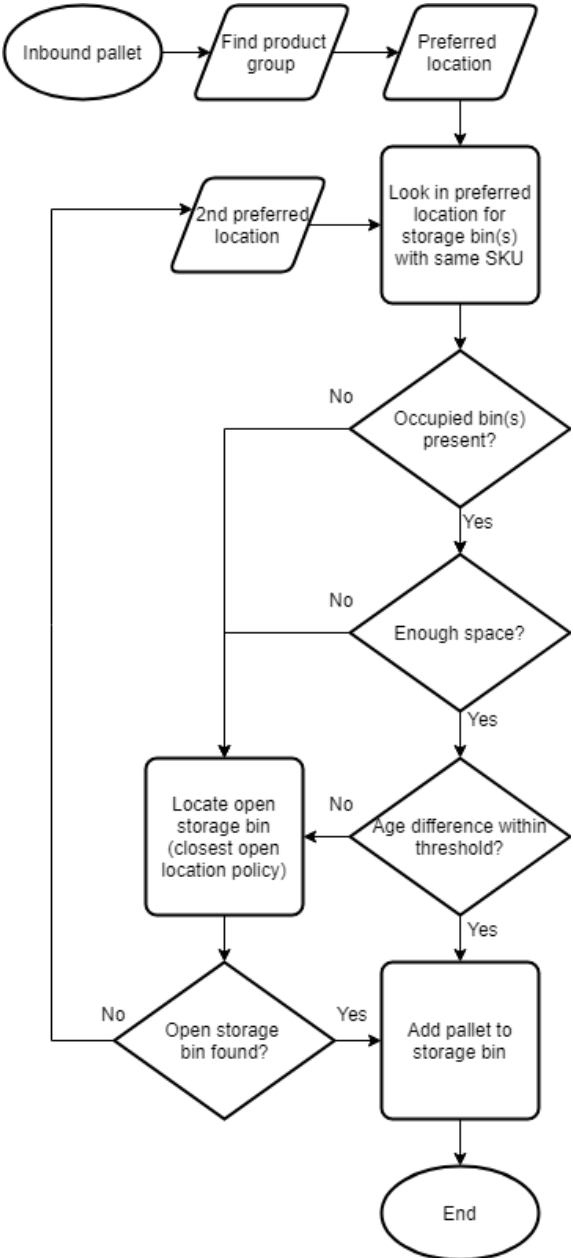
### 2.3.3 Storage location assignment policy

The last step in Apollo Vredestein's storage policy is an algorithm that assigns the pallets of PCT stock to a storage bin within the preferred location. Each storage bin may only contain pallets of one SKU. The algorithm favours adding products to already occupied locations with the same SKU over assigning new locations. If the algorithm finds multiple available locations with the same SKU, it will choose the locations with the highest utilization (current amount of stock / storage location capacity). Apollo Vredestein applies a form of a First In First Out (FIFO) policy, i.e., with regards to order picking, the oldest product is prioritized over newer batches. Since the company follows a FIFO policy, not all products of the same SKU can be stored in one bin. Instead, a threshold is determined for each SKU, which describes the maximum allowed difference in production weeks of the oldest and the newest product.

If there are no feasible occupied storage bins for a given product in its preferred storage location, the algorithm attempts to find an open storage bin. This bin is found using a policy that can be explained as a closest open location policy, in which the algorithm 'walks' past all storage bins in the preferred location and selects the first open bin it encounters. If there are no open storage bins, as well as no

feasible occupied bins, the algorithm repeats the same process in the second preferred location. Figure 2.1 is a visualisation of the logic the algorithm applies.

Figure 2.1: Logic flowchart of Apollo Vredestein’s storage location assignment algorithm



2.4 Storage flows

Regarding PCT, there are many paths a product can follow, see Appendix A2.7. PCT can enter the system through three different sources, spend an unknown amount of time in one or more of the warehousing locations, in order to eventually be shipped to a customer. This section divides the PCT flows in three parts: In- and outbound quantities, putaway flows and overflow.

### 2.4.1 In- and outbound quantities

PCT can enter the system in either the central warehouse or Staalsteden, depending on their provenance. Table 2.6 shows the expected distribution of inbound PCT for the period of 04-05-2017 – 04-11-2018.

**Table 2.6: Quantities of inbound PCT**

<b>From</b>	<b>To</b>	<b>Product category</b>	<b>Metric Tonnes per year</b>
Plant Enschede	Central warehouse	PCT	41,894.7
Plant Gyongyos	Staalsteden	PCT	15,257.2
Plant Gyongyos	Central warehouse	PCT	6,538.8
Sourcing/Vendor	Central warehouse	PCT	3,165.2
Sourcing/Vendor	Staalsteden	PCT	1,940.0
			<b>68,795.9</b>

PCT from the plant in Gyongyos or other sources are shipped to Staalsteden if they transport large quantities of Apollo brand tyres.

After receiving the PCT, they are stored in a location that is determined by the storage policy, see Section 2.3. Once sold, the products are order-picked (guided by a retrieval policy) and prepared for shipment. Ideally, all outbound flows are handled through the central warehouse. However, if large portions of stock on the orders for a truck are stored in either VDC or Staalsteden, the Inventory Manager may decide to do the order-picking and shipment there.

Table 2.7 shows the distribution of pick locations per PCT. This is the location in which a unit of PCT is removed from the HU used for bulk storage and added to a new order-related HU. The majority, i.e. 86.3% of PCT stock is picked from the central warehouse. About half of the PCT picked in Staalsteden was cross-docked and subsequently shipped in the central warehouse, see Appendix A2.8. This movement concerns PCT of the Apollo brand, as explained in Section 2.2.3.

**Table 2.7: Quantities of outbound PCT**

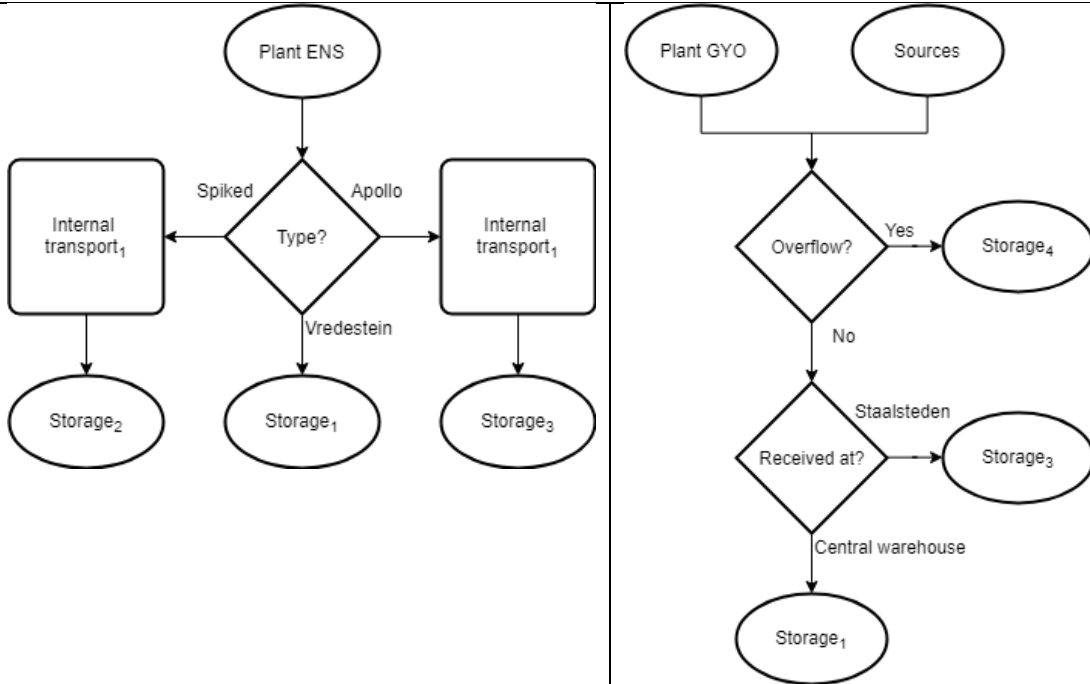
<b>Dispatch location</b>	<b>To</b>	<b>Product category</b>	<b>MT per year</b>
Central warehouse	Customer	PCT	55,941.5
Staalsteden	Customer	PCT	8,052.0
VDC	Customer	PCT	831.0
			<b>64,824.5</b>

### 2.4.2 Putaway flows

The storage flows for PCT involve the putaway operations for all inbound PCT, described in Section 2.3. However, this storage policy is just a set of priority rules. In practise, some of these rules are never triggered, since the conditions are always prevented. An example is the priority rule for Vredestein brand PCT from Gyongyos, which states that the central warehouse should be selected as storage location if the receiving location is full. In reality, a truck from Gyongyos is always scheduled for transport to a warehouse with enough open locations. If there is not enough room in any of the warehouses, the inventory manager reroutes the truck directly to the overflow at CTT.

Figure 2.2 represents the storage flows of PCT. The locations refer to areas within a certain warehouses that is given in subscript e.g., storage<sub>3</sub> refers to the bulk storage PCT area in the Staalsteden.

Figure 2.2: Storage flows of PCT at Apollo Vredestein



### 2.4.3 Overflow

The overflow for PCT consists of the bulk storage areas at VDC, Staalsteden and the containers at CTT. Stock moves to overflow areas are primarily caused by high space utilization in the central warehouse. Whenever the amount of free locations in the central warehouse approaches a point where there is no room for the inbound PCT from production, the inventory manager initiates a stock relocation to an overflow area. This process is explained in Section 2.5.

As already mentioned in Section 2.4.2, truckloads from the production facility in Gyongyos can be redirected to the overflow. In practise, about 68% of all containers filled at CTT were redirected from Gyongyos, as shown in Appendix A2.9. When PCT leaves the overflow at CTT, it is almost always shipped to the central warehouse, see Appendix A2.10, where the stock is cross-docked to the docks for outbound transport.

## 2.5 Stock relocations

There are two necessary operations for all PCT in Apollo Vredestein's warehousing process: putaway and retrieval. Putaway involves the initial storage operation and retrieval consists of either order picking or replenishment (i.e., from bulk storage to detail pick areas). Stock relocations are pallet movements that are not part of putaway or retrieval operations. Each relocation movement in Apollo Vredestein's warehouses is initiated manually, i.e., an employee edits the location of a product in the WMS. This section describes the current situation of stock relocations. In order to do so, the relocation drivers, the relocation options and the decisions involved with stock relocations are explained.

### 2.5.1 Relocation drivers

Stock relocations are a short-term solution for a constant problem: the lack of storage capacity of the warehouse system and the central warehouse in particular. This problem can be divided in four subproblems and corresponding objectives.

#### Driver 1: Generate enough space for inbound PCT from production

The most important reason for initiating stock relocations is the required space in the central warehouse for inbound PCT from the Enschede production facility. The facility operates 24 hours a

day, 7 days a week and produces about 130,000 tyres each week. Each batch of tyres has to be stored in one of the warehouses, to free up the buffer area for the next batch. Pausing the production line because the buffer area is full is extremely costly and should be avoided at all cost.

#### *Driver 2: Generate enough space for inbound PCT from external sources*

The central warehouse is also the main storage location for inbound PCT (Vredestein brand) from external sources, i.e. the production site in Gyongyos as well as sources from India. Once the trucks have docked at the central warehouse, the cargo needs to be unloaded and stored.

#### *Driver 3: Pick orders in time*

The first two drivers referred to inbound processes. On the other side, an important reason for initiating stock relocations is to make sure that the outbound processes can be executed properly. More specifically, each day the right products need to be present in the right warehouses, in order to be able to pick all orders for that day. It is important to note that the central warehouse is the preferred location for outbound transport and that there are more SKU's in Apollo Vredestein's PCT product range than there are storage bin locations in the central warehouse.

#### *Driver 4: Follow 'soft FIFO' policy*

While Passenger Car Tyres typically have a shelf life of 5 to 10 years, some of Apollo Vredestein's customers want the newest tyres they can deliver. In order to make sure that the difference in production week between the newest and oldest stock of some SKU is within reasonable limits, Apollo Vredestein employs a 'soft FIFO' policy, see Section 2.3.3. Therefore, the fourth relocation driver is to make sure that the difference in production weeks for all SKUs does not exceed the threshold<sup>1</sup>.

### *2.5.2 Relocation options*

The Inventory Manager has four types of actions at his disposal in order to treat the abovementioned drivers. All of these tools can be used within 24 hours and are employed for both inbound and outbound relocation drivers. The different actions can be, and usually are used in combination with each other.

#### *Option 1: Stock moves between warehouses*

The first relocation option is to move pallets of PCT stock from one warehouse to another. The most common example of this option is a relocation of one truckload PCT from the central warehouse to the bulk storage at the VDC, for the sake of achieving the first two drivers. Stock moves between warehouses are also performed in order to reach the third and fourth driver, in which case pallets of PCT stock are transported from the VDC and Staalsteden to the central warehouse.

Both movements use the same internal transport capacity (trucks and docks). The Inventory Manager tries to schedule these movements in a way that the trucks never travel without cargo.

#### *Option 2: Stock moves within warehouses*

The second option is moving pallets of PCT stock from one storage bin to another in the same warehouse. Usually this means that the pallets PCT in two separate storage bins with the same SKU, both not completely full, are joined in one storage bin. The freed location can then be used to store pallets of some other SKU. This is undesirable, since the manual interruption disarranges the logic from the storage policy. Furthermore, stock moves within a warehouse can lead to some issues with the soft FIFO policy.

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<sup>1</sup> The threshold for most PCT SKUs is 12 weeks. Some specialty PCT have a threshold of 1 week, which enforces a weekly FIFO policy.

Stock moves within a warehouse are a large problem in the central warehouse, where the in- and out-bound pressure is high. For example, in the period of 01-10-2017 to 30-09-2018, 62410 pallets of PCT stock were moved within the central warehouse. This averages on about 171 pallets a day and is 97.6% of all movements of this type, see Appendix A2.11.

#### *Option 3: Overflow capacity at Container Terminal Twente*

The Inventory Manager can also decide to use the overflow capacity at the CTT. If the overflow container capacity is used for the first two drivers, a ship container is ordered from CTT and filled with PCT and transported back to the CTT. The maximum amount of SKUs in a container is one i.e., all products in the container need to be identical. As a result, the capacity at the CTT is useful for storage of large batches (about 1.000 PCT per container, depending on the dimensions of the particular SKU). The reverse movement i.e., collecting the stock from the CTT, is driven by the third and fourth objective. On some occasions, Apollo Vredestein's Sales Department sells whole container loads at a discounted price to customers.

#### *Option 4: Order picking in different warehouses*

The fourth and last option is only relevant for orders with relatively few SKUs. While all orders are preferably picked in and shipped from the central warehouse, the Inventory Manager may decide to handle some orders from other warehouses. For example, a customer orders a full truckload PCT consisting of only three SKUs. The Inventory Manager will then check if enough stock of these SKUs is present in either the VDC or Staalsteden. If this is the case and the soft FIFO policy allows it, the truck can be loaded in the warehouse where the stock is present.

#### *2.5.3 Relocation decisions*

The Inventory Manager schedules the stock relocations each day for the next 24 hours. The goal is to meet all four drivers in the best way possible, using a combination of the four options for stock relocations. In order to do so, the Inventory Manager receives the 'Stock mix report'. This is an up-to-date overview of quantities of old and new stock present in the different storage locations per SKU. Furthermore, the amount of products that need to be order picked are summarized per SKU. This quantity is based on all orders that are cleared by the Sales Department, i.e. with enough stock present in the system and delivery dates within a week.

In order to meet the first and second objective, the Inventory Manager determines the storage bin utilization for the central warehouse. When the bin utilization approaches a limit, stock relocations are initiated to generate storage capacity at the central warehouse. The 'Stock mix report' is used to find SKUs with large quantities of stock and a low amount of orders. These products can then be relocated to either the VDC, Staalsteden or CTT, or a combination of these locations, based on the quantity of products that need to be relocated. Furthermore, stock moves within warehouses are manually initiated when the amount of open storage bins in the central warehouse falls below 20. There is no mathematical optimisation involved with the decisions regarding these stock moves.

With regards to the third and fourth objective, the Inventory Manager calculates the difference between the amount of stock present in the central warehouse and the VDC combined and the amount of products that need to be picked per SKU. This difference is sorted so that the largest deficiency is on top. Subsequently, for all SKUs with stock deficiencies in the central warehouse, relocations are composed to meet these deficiencies. This process is not optimised as well.



## 2.6 Key Performance Indicators

Sections 2.7 and 2.8 provide a quantitative analysis of the current situation of PCT stock relocations at Apollo Vredestein. It aims to answer research question 1b by finding the current values for the Key Performance Indicators (KPI) *X* and *C*:

*X*: The average amount of pallet movements per product PCT

*C*: The average cost of pallet movements per product PCT

The term 'pallet movements' describes all movement done in pallet loads only, i.e. the putaway and all relocations. Order picking and/or replenishment movements are not taken into account, in order to reduce size and complexity of the data.

The calculation of indicators *X* and *C* were done based on historic WMS data from the period of 01-10-2017 to 30-09-2018. All putaway, relocation, reshuffle and overflow CTT movements in that timeframe were collected and analysed in an Excel file. The rows, as depicted in Appendix A2.12, correspond to order lines, the columns provide information on the locations, type and SKU of the pallet move.

### 2.6.1 KPI: *X* – average pallet movements per product PCT

The first step in the calculation of indicator *X* was to distinguish all movement types. In order to avoid unnecessary complexity, movement types with less than 50 products PCT per year were discarded. This resulted in ignoring 0.013% of all putaway moves. For relocation, reshuffle and overflow CTT, no moves were discarded.

Secondly, the total amount of moves, as well as the total amount of PCT shipped per movement type was calculated. Subsequently, the amount of handling actions involved per movement type were determined. For example, during the period of 01-10-2017 to 30-09-2018, 525,526 pallets of PCT were moved from 'PWB' to 'PVD'. The location 'PWB' corresponds to the bulk PCT storage locations in the central warehouse, the location 'PVD' belongs to the docks at VDC. While a move from PWB to PVD is documented as one operation, the pallet is in fact handled four times: first the pallet is picked by a reach truck and delivered to the docks at the central warehouse, where it is loaded into a transport truck, transported by said truck and then unloaded at the docks of VDC.

In order to correctly calculate the average amount of pallet movements per product, weights were connected to the movement types, see Appendix A2.13. A pallet move carried out by a reach truck is counted as one move. Pallets moved by a transport truck are multiplied with a factor three. A crane move is also counted as one move. As a result, the total amount of pallet moves in a year is 20,048,651. See Appendix A2.13 for the calculation of the total amount of pallet moves.

Since indicator *X* describes the average amount of pallet movements per PCT, the total amount of PCT handled over the period of one year is required. The pallet movements involve putaway and storage moves (and no retrieval), so the total amount of PCT handled over the period of one year is described by the total amount of inbound PCT. As a result, the total amount of PCT handled between 01-10-2017 and 30-09-2018 was 6,867,394, see Appendix A2.14. This leads to the following value for *X*:

$$X = \frac{\text{Total pallet moves}}{\text{Total PCT handled}} = \frac{20,048,651}{6,867,394} = 2.919$$

### 2.6.2 KPI: C – average pallet movement cost per product PCT

In the calculation of indicator X, all movements over the period of one year were categorized. The result is a list of 51 types of pallet movements and the quantities of PCT that followed that movement path in a year. For each of these types of pallet movement, the cost was calculated based on the required resources and time spent, and the wages of different types of personnel. Furthermore, CTT employs standard rates for transport to and from CTT and crane handling.

These costs were calculated per metric tonnes and then multiplied by the amount of metric tonnes shipped through the movement types per year, see appendix A2.15. The result is a total pallet movement cost of € 1.205.959,03. This leads to the following value for C:

$$C = \frac{\text{Total cost of pallet moves}}{\text{Total PCT handled}} = \frac{€1,205,959.03}{6,857,394} = €0.176$$

## 2.6 Conclusion

This chapter analysed the current situation of stock relocations at Apollo Vredestein, based on the following research questions:

- 1a) *How are relocations of PCT stock currently processed?*
- 1b) *What are the values for the average pallet movements X and the accompanying cost C per PCT?*

In order to provide context for research question 1a, the products, locations and policies were described in Sections 2.1-2.3. The resulting flows are depicted in Section 2.4. The fifth section, Stock Relocations, is a structured overview of the decision process for relocations. It should be evident that there is a lot of room for improvement there, since the situation is too complex for effective manual calculation. In addition to the large size of the solution set, there is a delicate trade-off to be made regarding the first two and the second two relocation objectives.

The second part of this chapter consists of a quantitative analysis of the situation. Two indicators, X and C, were determined based on historical data from 01-10-2017 to 30-09-2018. The resulting values for X and C are:

$$\begin{array}{ll} X = 2.919 & \text{Average pallet movements per PCT} \\ C = €0.176 & \text{Average pallet movement cost per PCT} \end{array}$$

## Chapter 3: Literature review

This chapter involves the process of modelling the situation of relocations at Apollo Vredestein based on knowledge collected from the literature, in order to be able to derive a scientifically valid solution. The research question addressed in this chapter are:

- 2) Which methods from Operations Research can be used to address stock relocations in warehouses?

The structure of this chapter is described in Table 3.1.

**Table 3.1: Structure of Chapter 3**

3.1	Warehouse management
3.2	Storage assignment problems
3.3	Relocation problems
3.4	Conclusion

### 3.1 Warehouse management

Warehouses are an important part of supply chains, fulfilling two main functions: (1) temporary storage and protection of finished goods and (2) facilitating value adding operations e.g., sorting orders and packaging goods, as described by Heragu, Du, Mantel & Schuur (2005). In order to perform these functions, a typical warehouse consists of several functional areas, corresponding to certain activities. Van den Berg and Zijm (1999) divide the activities over four typical functional areas, as depicted in Table 3.2.

**Table 3.2: Functional areas in a typical warehouse**

Functional area	Activity
Receiving docks	<ul style="list-style-type: none"><li>• Receive products</li><li>• Verify quantity and quality</li><li>• Prepare for transportation</li><li>• If necessary: change Handling Unit (HU) e.g., pallets, cartons</li></ul>
Storage area	<ul style="list-style-type: none"><li>• Store received loads in the assigned storage locations</li></ul>
Order picking area	<ul style="list-style-type: none"><li>• Retrieve requested products</li><li>• Transport picked products to shipping area</li></ul>
Shipping area	<ul style="list-style-type: none"><li>• Sort picked products per order (sometimes done in picking process)</li><li>• Load orders in the assigned transport trucks</li></ul>

Heragu *et al.* (2005) describe an additional warehousing activity in modern warehouses: cross-docking. Cross-docking refers to the process of shipping received loads directly to the shipping area, with the possibility of storing them temporarily in a designated cross-docking area. It is often used by companies to decrease the inventory levels. The cross-dock area in a warehouse is typically used as a buffer location in distribution centres (De Koster *et al.*, 2007).

There are a large number of decisions to be made in warehouse management, on different levels of planning horizons. On a strategic level, the optimal amount of warehouses and their locations have to be determined. Van der Berg and Zijm (1999) classify the most important tactical warehouse management problems and provide the accompanying decisions in example models. De Koster *et al.* (2007) describe common warehouse management problems on both tactical and operational levels in their literature review on the design and control of the order picking process in a warehouse. These problems are outlined in Table 3.3.

**Table 3.3: Overview of common planning problems in warehouse management**

<b>Problem</b>	<b>Level</b>	<b>Objective</b>	<b>Decisions</b>
Storage location assignment	Operational	Minimize total travel time and maximize space utilization.	1. Choose a policy for assigning products to storage locations
Order batching	Operational	Minimize travel time for order picking	1. Assigning orders to order batches
Order routing	Operational	Minimize travel time for order picking	1. Decide optimal route for a set of orders
Layout design	Tactical	Minimize total handling cost	1. Design functional areas 2. Aisle configuration (e.g., aisle sizes, number of blocks)
Zoning	Tactical	Minimize travel time or order throughput time	1. Number of zones (each zone is assigned to one order picker).
Storage assignment: Forward-reserve allocation	Tactical	Minimize total picking + replenishing efforts (i.e., labour or cost)	1. Assign products to either bulk storage or picking areas

The stock relocations in the situation at Apollo Vredestein involve the process of assigning some stock to a new storage location. Therefore, the literature on storage assignment problems (both tactical and operational) is the most likely to contain relevant knowledge for this research.

### 3.2 Storage assignment problems

The Storage Location Assignment Problem (SLAP) is a common problem in warehouse management (De Koster *et al*, 2007). It aims at finding the optimal policy for allocating inventory to storage locations (or slots) in a fixed warehouse setting<sup>2</sup>. The performance of the applied policy is typically measured using two indicators: (1) the total space required for storing all products and (2) the total material handling cost (i.e., total cost of storing and retrieving the product). In a fixed warehouse setting, these indicators are often referred to as (1) the space utilization and (2) the total travel time of both storage and retrieval operations.

Storage location assignment policies can be classified into three categories: randomized, dedicated and combined. A dedicated storage policy assigns each product permanently to a specific slot (or slots if the stock is larger than the slot capacity) based on a characteristic, ideally minimizing the total travel time for storage and retrieval operations. Randomized storage policy assigns each product to a random slot, maximizing the space utilization at the cost of increased travel times. A combined policy is a dedicated storage location assignment policy that uses some random factor to improve the space utilization of the policy.

Battista *et al.* (2013) show that applying a dedicated storage policy provides the upper bound of required slots for a unit-load warehouse, while a randomized storage policy provides the lower bound.

<sup>2</sup> Warehouse characteristics such as storage capacity, functional area sizes, product range, material handling costs and demand patterns are predetermined.

Since randomized storage policies, and therefore all combined storage policies, require a continuous track record of which products are assigned to which slots, most of the research on SLAP considers warehouses with an Automated Storage Retrieval System (AS/RS) i.e., storage and retrieval operations are performed by a crane or robot. However, due to the sophisticated state of modern warehouse systems and innovations such as of Radio Frequency Identification (RFID) tags, the complex policies derived from research on AS/RS can easily be implied in non-automated warehouses. Hausman *et al.* (1976) describe the fact that in unit-load warehouse, a randomized storage policy resembles the closest-open-location rule often used in practise, in the sense that both policies maximize space utilization.

Furthermore, Hausman *et al.* (1976) describe the possibilities for improvement by applying a turnover-based rather than a randomized assignment policy, by assigning the products with the highest turnover to the locations closest to the In/Out (I/O) point. This is closely related with ABC analysis of inventory, where products are divided in three groups based on their contribution to total turnover. The authors show that the improvement possibilities (i.e., reduction in travel times) increases as the skewness<sup>3</sup> of the inventory distribution increases. Since it is unrealistic to assume that the turnover of each pallet of each product is known and/or constant over time, a class-based turnover assignment policy is proposed. Storage locations are partitioned into classes based on travel times with regard to the I/O point. Products are then assigned to a class of storage locations based on their turnover (e.g., the products with the highest turnovers are assigned to the class with the lowest travel time). The assignment of products to a specific location within the class of storage locations is randomized. Results show that applying the class-based turnover assignment policy yields significant<sup>4</sup> improvements over randomized storage assignment. De Koster *et al.* (2007) describe the research done on the optimal partitioning strategy in class-based storage policies. While most research is done on an AS/RS environment, Petersen and Aase (2004) show in a simulation study that class-based storage policy outperforms randomized storage policy in low-level non-automated warehouses.

The SLAP is concerned with assigning the products optimally to storage locations in a fixed warehouse setting. Although it is often solved as an individual problem, the performance of a storage location assignment policy is closely related to the performances of policies applied in other warehouse aspects (e.g., order-picking, forward-reserve allocation, layout design). Heragu *et al.* (2005) discuss the lack of a joint solution for warehouse management problems and propose an approach for the finding the optimal functional area sizes and production allocation, while minimizing total material handling cost. In order to do so, they first determine all possible flows (i.e., the plausible paths through the functional areas) in the warehouse. Additionally, the corresponding costs to the flows are defined. Then, the assignment of products to flows and the resulting flow capacities are optimized in a mixed-integer linear programming problem.

### 3.3 Relocation problems

The abovementioned problems all describe a warehouse that applies a permanent storage assignment policy. While such a static environment may not be realistic for businesses with highly fluctuating demand patterns and peaks in inventory levels, not much has been written on the subject of less permanent storage assignment. Chen, Langevin and Riopel (2010) address the case of a warehouse that applies dynamic storage (i.e., products are allowed to be relocated) to reduce the S/R machine travel times during peak periods. They define a relocation as the action of moving one

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<sup>3</sup> A skewness of 20%/60% refers to a distribution where the top 20% of all products contribute to 60% of total turnover.

<sup>4</sup> Up to 62.5% improvement for highly skewed (20%/90%) inventory distributions and three classes.

product from its original storage location to a new one. Under the assumption that all storage and retrieval requests are known for each period, the authors formulate the problem as an integer linear programming model that minimizes the total relocation time. The binary decision variables represent the assignment of a product to one of the several relocation options. An efficient two step heuristic is proposed by first determining which items need to be relocated and subsequently determining the optimal destination of relocation for those items. A metaheuristic method called *tabu search* is applied to find a solution with a minimal gap in reasonable computation times.

Quintanilla *et al.* (2015) define the relocation problem as an assignment problem in which the items to be relocated as well as the destinations of the relocation are determined. They propose a heuristic for optimizing space utilisation by performing relocations. However, they assume a warehouse setting with multiproduct (i.e., a storage location can contain multiple SKU), which is unrealistic for most businesses. Furthermore, their model disregards all material handling costs, including the cost of performing the relocations.

Pazour and Carlo (2015) stress the fact that most SLAP policies are based on some item demand characteristics, which may vary over time. As a result, SLAP policies should be updated regularly to account for shifting demand profiles. The authors define the process of changing from an initial SLAP policy to a new policy as reshuffling. Subsequently, they consider an AS/RS warehouse where the new SLAP policy is known under the assumption of a dedicated storage policy. As a result, all relocation moves are given. The mathematical model, which minimizes total loaded and unloaded travel time of the S/R machine, is a special case of the asymmetric travelling salesman problem.

### 3.4 Conclusion

This chapter aimed at solving the following research question:

- 2) *Which methods from Operations Research can be used to address stock relocations in warehouses?*

The chapter consists of a literature review on stock relocations and the development of a model for optimizing stock. Section 3.1 showed that, within the field of warehouse management, the literature on storage assignment problems was mostly likely to contain relevant knowledge. This knowledge was summarized in Section 3.2. Furthermore, several papers on different approaches to relocations problems were addressed in Section 3.3.

## Chapter 4: Solution approach

This chapter consists of the application of a mathematical model to the case of Apollo Vredestein, in order to obtain a solution. It aims to answer the following research questions:

- 3) *What strategy for stock relocations can be devised for the case of Apollo Vredestein?*
  - a) *How can the situation of PCT stock relocations be represented in a mathematical model?*
  - b) *What is the solution obtained from solving the mathematical model?*

Research question 3a involves formulating the case of Apollo Vredestein as a mathematical model, in order to be able to find an optimal relocation assignment policy. Research question 3b explores the process of finding solutions of such a model. The structure of Chapter 4 is explained in Table 4.1.

**Table 4.1: Structure of Chapter 4**

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3a)	4.1	Simplifications and assumptions for modelling relocations
	4.2	The relocation assignment model
3b)	4.3	Example of a solution for the relocation assignment model
	4.4	Solving the model analytically in Aimms
	4.5	A heuristic approach
	4.6	Conclusion

### 4.1 Simplifications and assumptions for modelling relocations

The warehouse network of Apollo Vredestein functions quite differently than most warehouses discussed in the literature. Some simplifications and generalizations are required. The warehouses are unit-load and all storage bins<sup>5</sup> are single-product (i.e., a bin can only contain products of one SKU). Daily records of PCT stock per bin is unavailable. Since almost all relocations revolve around the central warehouse, this location will be the point of view of the model for relocations. In order to keep the model as simple as possible, the central warehouse will be the only place where order-picking is allowed. The other warehouses (e.g., VDC, Staalsteden and CTT) are addressed as bulk capacity, with optimal space utilization<sup>6</sup>.

Furthermore, only the relocation movements of the types ‘stock moves between warehouses’ and ‘overflow at CTT’ are modelled, see Section 2.5.2. In order to be able to address ‘stock moves within warehouses’, a highly detailed discrete-event simulation of (at least) the central warehouse is required. This is not feasible nor is it desirable for achieving a scientific valid solution. Additionally, it is not possible to include relocations of both directions (i.e., relocations away and towards the central warehouse) since they are dependent of each other, despite the fact that different objectives are followed. Instead, the model will describe the optimal relocations away from the central warehouse, such that enough space is created for the inbound products from the production facility (relocations drivers 1 & 2, see Section 2.5.1). Relocation drivers 3 & 4 will be included in the model’s constraints.

The model considers the situation of a warehouse network, where all warehouses are single-product and unit-load. The network has a central warehouse, which facilitates all in- and out-bound processes. Inbound products from the production facility adjacent are initially stored in the central warehouse. The other warehouses use a randomized storage policy that maximizes the space utilization. Furthermore, the warehouse network facilitates a supply chain that produces make-to-

---

<sup>5</sup> Storage locations will be referred to as storage bins from now on

<sup>6</sup> See Sections 2.3.3 and 3.2

stock and therefore has a large amount of inventory. The central warehouse has insufficient capacity to store stock of all SKUs and orders are only known within a short timespan (e.g., one week). As a result, some of the stock has to be relocated from the central warehouse to one of the other warehouses, in order to free up warehouse capacity for inbound products from the production facility.

Products are relocated per pallet, so the stock should be expressed in amount of pallets.

$$\text{Amount of pallets in inventory} = \left\lceil \frac{\text{amount of products in inventory}}{\text{amount of products per pallet}} \right\rceil$$

This implicitly assumes that the total pallet utilisation (i.e., fraction of pallet capacity used) is maximized through the entire warehouse network.

The relocation flows are defined as the possible set of warehouses a product can be stored in. All products have to shipped from the central warehouse. In the situation of Apollo Vredestein, four relocations flows are defined. These flows are described in Table 3.4. The locations refer to the locations explained in Section 2.2.

**Table 4.2: Flows for PCT relocations**

Flow	Initial location		Relocated to		Final location
1.	Central Warehouse	→	Central Warehouse	→	Central Warehouse
2.	Central Warehouse	→	VDC	→	Central Warehouse
3.	Central Warehouse	→	Staalsteden	→	Central Warehouse
4.	Central Warehouse	→	CTT	→	Central Warehouse

The model requires input data from the daily ‘StockMix report’, the monthly ‘Inventory Quality’ and the amount of pallet capacity that needs to be made available in the central warehouse, estimated by the warehouse manager on a daily basis. The expected Duration of Stay (DOS) is calculated based on the current stock level and the average daily demand forecasts. Handling cost and storage cost are known for all flows. It is assumed that once a product is assigned to a relocation flow, it will spend the full expected DOS at the relocation destination. For example, if product X with a DOS of 19 days is assigned to flow 2, the storage cost is calculated based on the storage cost of the VDC.

As a result, the model assumes the following:

- The amount of requested pallet capacity at the central warehouse is known
- Bin utilization at VDC, Staalsteden and CTT optimal
- Relocation costs are known
- Each relocated product has to be transported back (in a replenishing move) to the central warehouse eventually
- Replenishing<sup>7</sup> is optimal and does not influence the relocation capacity
- The newest products are relocated, while the oldest products are selected for replenishing, thus applying FIFO
- Demand is constant over the planning horizon

<sup>7</sup> Shipping products back to the central warehouse for order-picking



## 4.2 The relocation assignment problem

The relocation assignment model considers the problem of assigning products to relocation flows. It considers a situation of a company with  $n$  SKUs and  $m$  warehouses. The first warehouse location ( $j=1$ ) is the central warehouse, from which all in- and outbound operations are performed. For a variety of possible reasons (e.g., the central warehouse inventory is so large that inbound processes are in danger of being shut down) the warehouse manager might need to relocate a certain amount  $D$  of pallets from the central warehouse to another location. In such a case, the relocation assignment model finds the products (and stock levels) that are most suitable and assigns this stock to a flow to one of the warehouses. It does so by finding the solution that has the minimum total handling and storage costs. The model is further specialized for the case of Apollo Vredestein, but can easily be modified to fit other cases. The model is described in Section 4.2.1, the constraints are further explained in Section 4.2.2.

### 4.2.1 The relocation assignment model

The following description is used to formulate the model.

#### Input parameters:

$i$	Product index, $i = 1, 2, \dots, n$ ,
$j$	Location index, $j = 1, 2, \dots, m$ ,
$Q_{ij}$	Amount of stock (pallets) of product $i$ in flow $j$ ,
$q_i$	Cycle stock (pallets) of product $i$ ,
$N_i$	Inventory norm (pallets) of product $i$ ,
$L_i$	Production lead time (days) of product $i$ ,
$D$	Amount of requested available capacity (pallets) at the central warehouse,
$\lambda_i$	Amount of ordered pallets of product $i$ ,
$T_i$	Expected average Duration Of Stay (DOS) of the stock of product $i$ in days,
$TC_j$	Total capacity of relocation destination $j$ ,
$RC_j$	Relocation capacity of flow $j$ ,
$H_j$	Handling cost of relocation one pallet in flow $j$ ,
$S_j$	Cost of storing one pallet one day in flow $j$ ,
$CC$	Capacity of a container (pallets),
$\alpha_i$	Excess stock (pallets) of product $i$ with $\alpha_i = \max\{Q_{i1} - N_i, 0\}$ ,
$\beta_i$	Amount of pallets of product $i$ available for relocation with $\beta_i = \max\{Q_{i1} - \lambda_i, 0\}$ ,

#### Decision variable:

$X_{ij}$	Amount of pallets of product $i$ to assign to flow $j$
$c_i$	Amount of containers to fill with product $i$

#### Model 1:

$$\min Z = \sum_{j=1}^m \sum_{i=1}^n X_{ij} H_j + \sum_{j=1}^m \sum_{i=1}^n X_{ij} S_j T_i \quad (1)$$

s.t.

$$\sum_{j=1}^m X_{ij} = Q_{i1} \quad \forall i \quad (2)$$

$$\sum_{i=1}^n \sum_{j=2}^m X_{ij} \geq D \quad (3)$$

$$\sum_{j=2}^m X_{ij} \leq \min \{\alpha_i, \beta_i\} \quad \forall i \quad (4)$$

$$\sum_{i=1}^n X_{ij} + \sum_{i=1}^n Q_{ij} \leq TC_j \quad \text{for } j > 1 \quad (5)$$

$$\sum_{i=1}^n X_{ij} \leq RC_j \quad \text{for } j > 1 \quad (6)$$

$$X_{i4} = c_i * CC \quad \forall i \quad (7)$$

$$X_{ij} \in \mathbb{Z} \quad \forall i, j \quad (8)$$

$$c_i \in \mathbb{Z} \quad \forall i \quad (9)$$

Input parameters  $\lambda_i$ ,  $Q_{ij}$ , and  $i(1 \text{ to } n)$  can be obtained from the 'StockMix report' Apollo Vredestein currently uses to make decisions for stock relocation. The values for  $q_i$ ,  $N_i$  and  $L_i$  can be obtained from the 'Inventory Norms' file Apollo Vredestein uses for inventory planning. Parameters  $H_j$ ,  $S_j$ ,  $TC_j$ ,  $RC_j$  and  $CC$  should be available to a warehouse manager. The value for input parameter  $D$  should be given by the warehouse manager, based on the expected in and outbound volumes. The value of  $T_i$  can either be calculated as an average based on historical data, or obtained through demand forecasting. In the second case,  $T_i$  is determined by multiplying the days of stock (based on cycle stock in days calculations) with the production lead time:

$$T_i = \frac{\sum_{j=1}^m Q_{ij} L_i}{2q_i} \quad \forall i \quad (10)$$

This approach for calculating  $T_i$  automatically updates the expected DOS with the forecasted demand pattern, since the value for  $q_i$  is calculated monthly. Note that, according to the abovementioned definition of  $T_i$ , the relocation assignment model calculates the total handling and storage cost based on an expected duration of stay, which will most likely result in high numbers.

#### 4.2.2 Explanation of the constraints

The model assigns each pallet of each product to one of the flows (i.e., either stay in the central warehouse or relocate to one of the other warehouses). The objective function (1) minimizes the total cost of both handling the stock in the relocation move and storing the stock during the expected DOS. The handling cost of the relocation is assumed to be constant regardless of the direction. Note that the handling cost for flow 1 will be 0. The storage cost per pallet is determined based on a daily price per pallet multiplied with the expected DOS. This daily price does not necessarily have to be the actual rent. The central warehouse will carry a premium, since the pallet capacity there is much more valuable than the other warehouses.

Constraint (2) ensures that all products in the central warehouse are assigned to one of the flows. Constraint (3) makes sure that at least the required amount of open capacity at the central warehouse is achieved. Constraint (4) ensures that no relocation is made such that the remaining stock in the central warehouse is either lower than the inventory norm or the short term orders. This constraint might result in no feasible solutions. If that is the case, it can be relaxed. Constraints (5) and (6) describe the capacity for each relocation (i.e., transport trucks and drivers available) and total storage capacity of each warehouse. Constraint (7) ensures that only full container loads are assigned to flow 4, since Apollo Vredestein highly prefers filling containers with stock of one SKU. Constraints (8) and (9) force the decision variables to be positive.

### 4.3 Example of a solution for the relocation assignment model

In order to explain the model in an understandable way, an illustrative example is provided. Consider a situation of a company that has two warehouses: a central warehouse that facilitates receiving, order-picking and shipping and a container warehouse for bulk storage. The warehouse has 5 SKUs in stock, stored in the two warehouses. The values for the input parameters for the model described in Appendix A3.1.

Solving the model analytically with the software package: Aimms 4.68 leads to the solution depicted in Figure 3.1, with a solving time of 0.02 seconds.

Figure 4.1: In and output values of the illustrative example model

Input				Output																																																							
<table border="1"> <thead> <tr> <th rowspan="2"></th> <th colspan="2">Stock</th> <th rowspan="2"></th> </tr> <tr> <th>Central Warehouse</th> <th>Container Storage</th> </tr> </thead> <tbody> <tr> <td>sku1</td> <td>8.0</td> <td>15.0</td> <td></td> </tr> <tr> <td>sku2</td> <td>6.0</td> <td></td> <td></td> </tr> <tr> <td>sku3</td> <td>12.0</td> <td>20.0</td> <td></td> </tr> <tr> <td>sku4</td> <td>18.0</td> <td>14.0</td> <td></td> </tr> <tr> <td>sku5</td> <td>40.0</td> <td>18.0</td> <td></td> </tr> </tbody> </table>					Stock			Central Warehouse	Container Storage	sku1	8.0	15.0		sku2	6.0			sku3	12.0	20.0		sku4	18.0	14.0		sku5	40.0	18.0		<table border="1"> <thead> <tr> <th rowspan="2"></th> <th colspan="2">Relocation</th> <th rowspan="2"></th> </tr> <tr> <th>Central Warehouse</th> <th>Container Storage</th> </tr> </thead> <tbody> <tr> <td>sku1</td> <td>8.0</td> <td></td> <td></td> </tr> <tr> <td>sku2</td> <td>6.0</td> <td></td> <td></td> </tr> <tr> <td>sku3</td> <td>10.0</td> <td>2.0</td> <td></td> </tr> <tr> <td>sku4</td> <td>18.0</td> <td></td> <td></td> </tr> <tr> <td>sku5</td> <td>25.0</td> <td>15.0</td> <td></td> </tr> </tbody> </table>					Relocation			Central Warehouse	Container Storage	sku1	8.0			sku2	6.0			sku3	10.0	2.0		sku4	18.0			sku5	25.0	15.0	
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<table border="1"> <thead> <tr> <th rowspan="2"></th> <th>Alpha</th> <th>Beta</th> <th>DOS</th> </tr> </thead> <tbody> <tr> <td>sku1</td> <td></td> <td>4.0</td> <td>21.6</td> </tr> <tr> <td>sku2</td> <td></td> <td></td> <td>11.3</td> </tr> <tr> <td>sku3</td> <td>2.0</td> <td>4.0</td> <td>72.0</td> </tr> <tr> <td>sku4</td> <td>3.0</td> <td>18.0</td> <td>20.0</td> </tr> <tr> <td>sku5</td> <td>15.0</td> <td>28.0</td> <td>47.5</td> </tr> </tbody> </table>					Alpha	Beta	DOS	sku1		4.0	21.6	sku2			11.3	sku3	2.0	4.0	72.0	sku4	3.0	18.0	20.0	sku5	15.0	28.0	47.5	<table border="1"> <thead> <tr> <th rowspan="2"></th> <th colspan="2">NewStock</th> <th rowspan="2"></th> </tr> <tr> <th>Central Warehouse</th> <th>Container Storage</th> </tr> </thead> <tbody> <tr> <td>sku1</td> <td>8.0</td> <td>15.0</td> <td></td> </tr> <tr> <td>sku2</td> <td>6.0</td> <td></td> <td></td> </tr> <tr> <td>sku3</td> <td>10.0</td> <td>22.0</td> <td></td> </tr> <tr> <td>sku4</td> <td>18.0</td> <td>14.0</td> <td></td> </tr> <tr> <td>sku5</td> <td>25.0</td> <td>33.0</td> <td></td> </tr> </tbody> </table>					NewStock			Central Warehouse	Container Storage	sku1	8.0	15.0		sku2	6.0			sku3	10.0	22.0		sku4	18.0	14.0		sku5	25.0	33.0			
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The model is presented with a value for the required capacity at the central warehouse  $D = 14$ . The solution found by Aimms is the set of relocations with the optimal total relocation cost, for which at least 14 pallets are relocated. The total relocation cost of €3681 consists of the sum of the handling cost involved with the relocations and the total cost of storing all products for the expected DOS.

### 4.4 Solving the model analytically in Aimms

In order to be able to formulate a strategy for the situation of stock relocations at Apollo Vredestein, the model has to be solved for the case of the company. The input data (i.e., StockMix report and Inventory norms) was collected for the day of 08-07-2019. The calculation of the handling and storage cost are explained in Appendix A4.1 and A4.2. In total, 857 SKU and their characteristics were evaluated in the model.

The software package Aimms 4.68 is able to solve the relocation model for the case of Apollo at 08-07-2019 in reasonable computation times i.e., less than a second. The high value for the total relocation cost can be explained by the fact that some products have a very high expected DOS (i.e., over 1000 days). Figure 4.1 shows the in- and out-put for the scenario of Apollo Vredestein at 08-07-2019. The TotalRelocationCost of €201,185.00 refers to the cost of storing and handling all products in stock over their entire expected DOS.

Figure 4.2: Input and output of the Aimms model

Input			
	StorageCost	HandlingCost	MinRelocSize
Central Warehouse	0.086		
Container Storage	0.111	15.3	45.0
VDC	0.068	4.8	
Staalsteden	0.062	4.3	
	TotalCapacity	SumOfStock	RelocationCapacity
Central Warehouse	25000	16150	
Container Storage	500000	19145	720
VDC	11950	6947	400
Staalsteden	22615	12736	240
RequiredCapacity			= 700
Output			
	TotalRelocations		
Central Warehouse	15420		
Container Storage	90		
VDC	400		
Staalsteden	240		
TotalRelocationCost			= 201185

```

Math.Program      : OptimalRelocations
# Constraints     : 5561
# Variables      : 6818 (3389 integer)
# Nonzeros       : 22618
Model Type       : MIP
Direction        : minimize

SOLVER           : CPLEX 12.9
Phase            : Postsolving
Iterations       : 355
Nodes            : 0 (Left: 1)
Best LP Bound    : 201185.3259 (Gap: 0.00%)
Best Solution    : 201185.3259 (Post: 201185.3259)
Solving Time    : 0.05 sec (Peak Mem: 0.2 Mb)
Program Status   : Optimal
Solver Status    : Normal completion

Total Time       : 0.00 sec
Memory Used      : 154.4 Mb
Memory Free      : 10151.2 Mb
    
```

Since Apollo Vredestein does not have access to the software used for solving the relocation assignment model, an alternative solution approach has to be determined. For this reason, a heuristic algorithm is determined to approach the optimal solution of the relocation assignment model.

#### 4.5 A heuristic approach

The heuristic approach to finding the optimal relocations consists of two parts: (1) finding the products suitable for relocation and (2) finding the best relocation flows for these products. In order to keep the algorithm as simple as possible, only the stock that is available for relocation (i.e., the minimum of  $\{\alpha_i, \beta_i\}$ ) is analysed. This level of stock available for relocation per product will be referred to as  $R_i$ . The proposed heuristic ranks the stock based on a value for  $Y_i$  and assigns the highest ranking stock first to the least expensive relocation flow. The heuristic is described below. The steps are explained in Section 4.5.1.

*Heuristic algorithm:*

*Step 1.* Define  $R_i = \min \{\alpha_i, \beta_i\} \quad \forall i$ .

*Step 2.* Check whether a feasible solution exists. If  $\sum_{i=1}^n R_i \geq D$  and  $\sum_{j=2}^m RC_j \geq D$ , the optimization is feasible, else no feasible solution exists.

*Step 3.* Define  $Y_i = R_i T_i \quad \forall i$  and  $Z_j = R_i * (H_j + S_j T_i)$  as the cost of relocation stock  $R_i$  to flow  $j$ . Order  $Y_i$  in nonincreasing order, such that the highest value is first.

*Step 4.* For the first value of  $Y_i$ , calculate  $Z_j$  for  $j = \{2, \dots, m\}$  and let  $j = j^*$  occur for the smallest value of  $Z_j$  for which

$$\sum_{i=1}^n X_{ij} + R_i \leq RC_j \quad (11)$$

$$\sum_{i=1}^n (X_{ij} + Q_{ij}) \leq TC_j \quad (12)$$

If  $j^* = m$  then  $X_{im} = c_i * CC$ .

*Step 5.* Set  $X_{ij^*} = R_i$  and  $X_{i1} = Q_{i1} - R_i$ .

*Step 6.* If  $\sum_{i=1}^n \sum_{j=2}^m X_{ij} \geq D$  go to *Step 7*. Else, move to the next value of  $Y_i$  and go back to *Step 4*.

*Step 7.* Set  $X_{i1} = Q_{i1} \quad (\forall i | \sum_{j=2}^m X_{ij} = 0)$ .

#### 4.5.1 Explanation of heuristic steps

The heuristic algorithm first determines the maximum amount of stock available for relocations per product in *Step 1*. In the second step, it checks the feasibility of the situation, with regards to the requested amount of pallet capacity  $D$ . The third step orders the products based on the value of  $Y_i$  (i.e., the stock available for relocations multiplied with the expected DOS). Then, in the fourth and fifth step, the optimal feasible relocation flow is determined for the product with the highest value of  $Y_i$ . Equation 11 ensures that the selected stock is only assigned to flow  $j$  if the capacity for relocation to the corresponding location is not exceeded. Equation 12 does the same with regards to the total warehouse capacity. Note that the product with the highest value of  $Y_i$  has the highest potential cost savings, due to the high expected DOS. After confirming this relocation, the algorithm goes back to step 4, or terminates if the required amount of pallet capacity is met. Step 7 sets the relocation flow for all products that were not assessed in step 4-7 to the central warehouse.

The ordering variable  $Y_i$  is assumed to select the right products to relocate based on the definition of  $Y_i = R_i T_i$ . The effects of defining  $Y_i$  as  $Y_i = R_i$  and  $Y_i = T_i$  are analysed in Section 4.3. Furthermore, the abovementioned heuristic only considers the relocations for the products with the highest value of  $Y_i$ . This is not an issue for relocation flows 2 and 3, where the storage cost is lower than the central warehouse. However, for the fourth relocation flow, it might be better to store products with a shorter DOS in the containers. In order to cope with this shortcoming of the proposed heuristic, a *local search sampling* method can be included between step 6 and 7.

#### 4.5.2 Illustrative example of the heuristic approach

Consider the illustrative example presented in Section 4.3. A step by step representation of the heuristic approach is given below.

*Step 1:* Define  $R_i = \min \{\alpha_i, \beta_i\} \quad \forall i$ .

$i$	$R_i$
1	0
2	0
3	2
4	3
5	15

*Step 2:* Check whether a feasible solution exists. If  $\sum_{i=1}^n R_i \geq D$  and  $\sum_{j=2}^m RC_j \geq D$ , the optimization is feasible, else no feasible solution exists.

The required capacity  $D$  in the example given in Section 4.3 was 14 pallets.

$$\sum_{i=1}^5 R_i = 24 \geq D$$

$$\sum_{j=2}^2 RC_j = 20 \geq D$$

*Step 3:* Define  $Y_i = R_i T_i \quad \forall i$  and  $Z_j = R_i * (H_j + S_j T_i)$  as the cost of relocation stock  $R_i$  to flow  $j$ . Order  $Y_i$  in nonincreasing order, such that the highest value is first.

$i$	$Y_i$
5	712.5
3	144.0
1	0
4	60.0
2	0

*Step 4:* For the first value of  $Y_i$ , calculate  $Z_j$  for  $j = \{2, \dots, m\}$  and let  $j = j^*$  occur for the smallest value of  $Z_j$  for which  $\sum_{i=1}^n X_{ij} + R_i \leq RC_j$  and  $\sum_{i=1}^n (X_{ij} + Q_{ij}) \leq TC_j$ . If  $j^* = m$  then  $X_{im} = c_i * CC$ .

$Z_2 = 15 * (4 + 1 * 47,5) = 772,5$ , note that in this example  $CC = 1$ .

*Step 5:* Set  $X_{ij^*} = R_i$  and  $X_{i1} = Q_{i1} - R_i$

$X_{51} = 15, X_{52} = 25$

*Step 6:* If  $\sum_{i=1}^n \sum_{j=2}^m X_{ij} \geq D$  go to *Step 7*. Else, move to the next value of  $Y_i$  and go back to *Step 4*.

$\sum_{i=1}^n \sum_{j=2}^m X_{ij} = 15 \geq D$ , go to *Step 7*.

*Step 7:* Set  $X_{i1} = Q_{i1}$  ( $\forall i | \sum_{j=2}^m X_{ij} = 0$ ).

$i$	$X_{i1}$	$X_{i2}$
1	8	0
2	6	0
3	12	0
4	18	0
5	25	15

The result is an Objective Function Value of €3689,81. Note that the solution obtained by the heuristic approach is about 9 euros more expensive. This can be explained by the fact that the heuristic stops calculating relocations once the value for  $D$  is met, while the Aimms model finds the best solution for which at least  $D$  pallets are moved.

#### 4.5.3 Simulated annealing

The heuristic algorithm orders all products based on a characteristic  $Y_i$ . Products with a high value of  $Y_i$  are good candidates for relocation to the cheaper warehouses (i.e., VDC and Staalsteden, location 2 and 3 respectively). However, these products are not necessarily the most suitable for temporary storage at the CTT. A simulated annealing algorithm, originally described by Kirkpatrick *et al.* (1983) is used in order to improve the solution as constructed by the heuristic.

First, the solution and its neighbourhood structure have to be determined. Let  $\pi$  be the set of proposed relocations, with  $\pi = \{X_{ij}, \dots, X_{nm}\}$ . Not all of these relocations are relevant for the simulated annealing algorithm, since it only the assignment of stock to the CTT. Define two sets  $U$  and  $V$ , where  $U$  is the set of products assigned for relocation to CTT and  $V$  is the set of products with enough stock available to fill one container. As a result,  $U$  is the set of products  $i$  for which  $X_{i4} \geq CC$  and  $V$  is the set of products  $i$  for which  $R_i - X_{i2} - X_{i3} \geq CC$ <sup>8</sup>. The objective function of the initial solution ( $S_0$ ) is the total cost of relocating all products  $i \in U \cup V$ , with  $Z_i = \sum_{j=1}^4 X_{ij} * (H_j + T_i * S_j)$  and is referred to as  $G(S_0) = \sum_{i \in (U \cup V)} Z_i$ . In the first iteration of the simulated annealing algorithm, the initial solution is taken as the current solution:  $S_{cur} = S_0, G(S_{cur}) = G(S_0)$ . The neighbourhood of this solution is obtained through a swap operator:

1. Find products  $u \in U$  and  $v \in V$  and perform SWAP( $u, v$ ) by being  $u' = v$  and  $v' = u$
2. The neighbour solution  $S_{nb}$  consists of the union of sets  $U$  and  $V$ , including the swapped elements

<sup>8</sup> All products  $i$  in set  $V$  have enough available stock in the central warehouse to enable a relocation to the CTT.

3. The objective function of the neighbour solution is referred to as  $G(S_{nb}) = \sum_{i \in (U \cup V)} Z_i$ , which is the total relocation cost of all  $i \in U \cup V$ , after performing  $\text{SWAP}(u, v)$ .

The temperature factor is  $c_{stop} \leq c \leq c_{start}$  with  $c_{start} = 10.000$  and  $c_{stop} = 0.01$ . The Markov chain length is  $k = 1$  and  $\alpha = 0.995$ . These values are further described and improved in Section 4.2.3. The probability of accepting a solution with a worse objective value is defined as  $P_{cur,nb} = e^{-\frac{G(S_{cur}) - G(S_{nb})}{c}}$ . Given these facts, the simulated annealing algorithm is as follows:

*Simulated annealing algorithm:*

- Step 1.* Set  $U = \{i | X_{i4} \geq CC\}$  and  $V = \{i | R_i - X_{i2} - X_{i3} \geq CC\}$ .
- Step 2.* Set initial solution  $S_0$  and  $G(S_0)$ .
- Step 3.* Current solution  $S_{cur} = S_0$ ,  $G(S_{cur}) = G(S_0)$ ,  $c = c_{start}$ .
- Step 4.* Select a candidate solution  $S_{nb}$  from the neighbourhood of  $S_{cur}$  by swapping randomly selected elements  $u \in U$  and  $v \in V$ . Calculate  $G(S_{nb})$ .
- Step 5.* If  $G(S_0) < G(S_{nb}) \leq G(S_{cur})$ , set  $S_{cur} = S_{nb}$  and go to *Step 6*.  
If  $G(S_{nb}) \leq G(S_0)$ , set  $S_0 = S_{cur} = S_{nb}$  and go to *Step 6*.  
If  $G(S_{nb}) > G(S_{cur})$ , generate a random number  $p$  from a  $U(0,1)$ - distribution.  
If  $p \leq P_{cur,nb}$ , set  $S_{cur} = S_{nb}$  and go to *Step 6*.
- Step 6.*  $c = c * \alpha$
- Step 7.* If  $c \leq c_{stop}$  go to *Step 8*, otherwise go to *Step 4*.
- Step 8.* Final solution is  $S_0$  with objective value function  $G(S_0)$

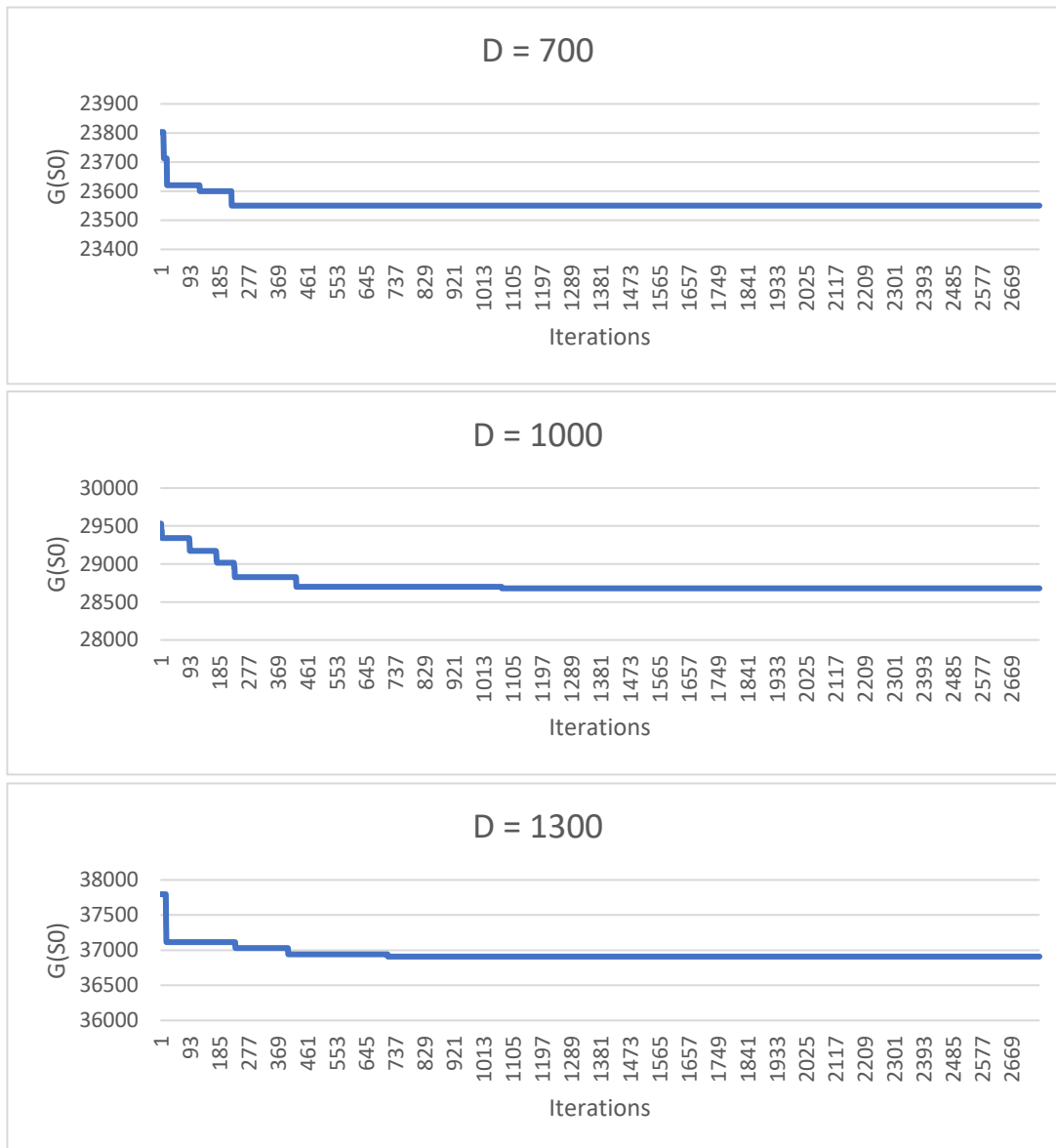
#### 4.5.3 Parameter tuning

Using the parameter values described in Section 4.2.2, the simulated annealing algorithm will perform 2757 iterations (i.e., until  $c_{stop}$  is reached). However, it is quite possible that the optimal solution is obtained in an earlier phase of the simulated annealing algorithm. In order to verify this, the performance of the algorithm was measured for three cases (i.e.,  $D = 700$ ,  $D = 1000$ ,  $D = 1300$ ). The results are presented in Figure 4.2.

The value for  $G(S_0)$  reaches the final value rather quick, as can be seen from Figure 4.2. For the case of  $D = 700$ ,  $G(S_0)$  stops decreasing after the 224<sup>th</sup> iteration. The case for  $D = 1000$  stabilizes after the 1071<sup>th</sup> iteration and the final case needs 713 iterations. Based on these results, the value for  $\alpha$  can be decreased, so that the simulated annealing algorithm performs 1200 iterations. This results in

$$\alpha = \sqrt[1500]{\frac{c_{stop}}{c_{start}}} = 0.9908.$$

Figure 4.3: Parameter tuning



#### 4.6 Conclusion

This chapter analysed the following research questions:

- 3) *What strategy for stock relocations can be devised for the case of Apollo Vredestein?*
  - a) *How can the situation of PCT stock relocations be represented in a mathematical model?*
  - b) *What is the solution obtained from solving the mathematical model?*

Section 4.1 explored the simplifications and assumptions necessary to model the situation of stock relocation at Apollo Vredestein in an effective manner. As a result, a mathematical model is presented in Section 4.2. The process of finding the solution to the model is described in an example, as shown in Section 4.3. The software package Aimms 4.68 is capable of solving the model analytically for the case of Apollo Vredestein. However, since the company does not have access to this software package, a heuristic approach is developed. This approach is explained in Section 4.5.



## Chapter 5: Numerical experiments

This chapter involves testing the approaches to finding a solution to the relocation assignment problem as described in Chapter 4. The approaches will be evaluated through numerical experiments. The following research questions will be addressed.

- 4) *How do the heuristic approaches perform with regards to finding a solution for the relocation assignment problem?*
- 5) *How can the heuristic be implemented as a strategy for relocations?*

The structure of Chapter 5 is described in Table 5.1.

**Table 5.1: Structure of Chapter 5**

4)	5.1	Numerical experiments
	5.2	Discussion
5)	5.3	Implementation of the strategy for stock relocations
	5.4	Insights
	5.5	Measuring the improvement of implementing the strategy

### 5.1 Numerical experiments

The numerical experiments consist of two parts. First, measurements are taken to determine the best performing heuristic approach. Second, a larger sample of data sets is used to validate the performance of the chosen heuristic, combined with an extensive testing of the complementing simulated annealing algorithm. The objective function value (OFV) is measured, together with the gap(%) and CPU time (seconds). All measurements are performed on a HP Elitebook, with an Intel Core i5 8<sup>th</sup> gen processor operating at 1.60 GHz.

#### 5.1.1 Experiments on the heuristic alternatives.

As mentioned in Section 4.5, the value of  $Y_i$  is one of the experimental factors. Heuristic\_v1 refers to the version of the algorithm that uses  $Y_i = R_i T_i$ , Heuristic\_v2 uses  $Y_i = T_i$  and Heuristic\_v3 uses  $Y_i = R_i$ . The results of the numerical experiments on the performances of the heuristics are presented in Table 5.2. All algorithms were programmed in and calculated by Microsoft Excel VBA. Three datasets of days at Apollo Vredestein were used to test the performance of the alternative versions of the heuristics. For each of these cases, three values for the required amount of pallets to be relocated ( $D$ ) are given, so that the performance of the heuristics can be measured consistently.

Table 5.2: Results of experiments on the heuristics

scenario approach	03-07-2019			10-07-2019			17-07-2019		
	D=700	D=1000	D=1300	D=700	D=1000	D=1300	D=700	D=1000	D=1300
<b>Aimms 4.68</b> <b>CPLEX 12.9</b> <b>Solver</b>									
CPU time (s)	0.06	0.05	0.05	0.08	0.05	0.06	0.08	0.06	0.05
OFV(€)	227704	232259	237778	229031	233558	239020	221621	226226	232146
Gap(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Heuristic_v1</b>									
CPU time (s)	0.38	0.36	0.36	0.38	0.39	0.39	0.39	0.37	0.38
OFV(€)	231318	237594	242684	230574	238465	244997	223356	231389	238003
Gap(%)	1.59	2.30	2.06	0.67	2.10	2.50	0.78	2.28	2.52
<b>+Simulated annealing</b>									
CPU time (s)	0.58	0.58	0.58	0.59	0.61	0.63	0.61	0.58	0.58
OFV(€)	230275	234498	238240	229847	235144	239734	222461	227872	232992
Gap(%)	1.13	0.96	0.19	0.36	0.68	0.30	0.38	0.73	0.36
<b>Heuristic_v2</b>									
CPU time (s)	0.36	0.36	0.36	0.39	0.37	0.38	0.38	0.37	0.39
OFV(€)	228602	235234	242954	229981	236497	244221	222676	229242	236989
Gap(%)	0.39	1.28	2.18	0.41	1.26	2.18	0.48	1.33	2.09
<b>+Simulated annealing</b>									
CPU time (s)	0.56	0.58	0.55	0.62	0.59	0.60	0.58	0.60	0.61
OFV(€)	227818	232389	237948	229179	233683	239148	221834	226368	232292
Gap(%)	0.05	0.06	0.07	0.06	0.05	0.05	0.10	0.06	0.06
<b>Heuristic_v3</b>									
CPU time (s)	0.37	0.34	0.36	0.39	0.38	0.38	0.38	0.37	0.38
OFV(€)	239434	245333	250913	234889	242293	246867	226256	233324	240699
Gap(%)	5.15	5.63	5.52	2.56	3.74	3.28	2.09	3.14	3.68
<b>+Simulated annealing</b>									
CPU time (s)	0.57	0.55	0.56	0.60	0.59	0.60	0.59	0.60	0.58
OFV(€)	237244	241361	246148	234153	239473	243648	225480	230954	237150
Gap(%)	4.19	3.92	3.52	2.24	2.53	1.94	1.74	2.09	2.16

### 5.3.2 The best performing heuristic

Table 5.2 shows that Heuristic\_v2 combined with simulated annealing is the best performing heuristic. The average observed gap for this approach was 0.06%. Note that Heuristic\_v2 exclusively uses the expected DOS to rank the products suitable for relocation. which appears to be the most effective option. This can be explained by the fact that some products have very high expected DOS values (i.e.. > 1 year). Relocating these products to the warehouses with the lowest daily storage cost can reduce the total cost significantly. Heuristic\_v2 assigns the products with the highest DOS first,

while Heuristic\_v1 and Heuristic\_v3 prioritize other products. The combination of Heuristic\_v2 and the simulated annealing algorithm will from now on be referred to as the ‘relocation assignment algorithm’.

### 5.3.3 Experiments on the performance of the relocation assignment algorithm

The performance of the relocation assignment algorithm is tested in a new set of numerical experiments. The algorithm is applied to fifteen cases from Apollo Vredestein, consisting of data from five subsequent months. First, the case is solved in Aimms, providing an optimal lower bound for the objective function value. Then, the heuristic (i.e., the relocation assignment algorithm without the addition of the simulated annealing algorithm) is applied, in order to obtain an initial solution. The performance of the simulated annealing algorithm is tested by running it ten times for all instances. The minimum, average and maximum values for the OFV are stored, together with the average gap and running time. The results are described in Table 5.3 and further explained in Section 5.3.4.

**Table 5.3: Results of the experiments on the performance of the relocation assignment algorithm**

Instance			Aimms model			Heuristic			Simulated annealing				
Date	Utilization	SKUs	OFV(€)	Gap(%)	T(s)	OFV(€)	Gap(%)	T(s)	Min(€)	Avg(€)	Max(€)	Gap(%)	T(s)
1/3/19	71.1%	903											
	D = 700		244185	0.00	0.16	245006	0.33	0.20	244248	244248	244248	0.03	0.22
	D = 1000		249219	0.00	0.09	251642	0.97	0.10	249282	249282	249282	0.02	0.13
	D = 1300		256952	0.00	0.16	259212	0.88	0.11	257024	257026	257028	0.03	0.14
1/4/19	65.1%	841											
	D = 700		219606	0.00	0.13	220474	0.40	0.09	219738	219738	219738	0.06	0.13
	D = 1000		225457	0.00	0.09	227090	0.72	0.09	225572	225572	225574	0.05	0.13
	D = 1300		233191	0.00	0.14	234834	0.70	0.10	233316	233318	233320	0.05	0.15
1/5/19	74.8%	880											
	D = 700		246208	0.00	0.13	247157	0.39	0.17	246309	246309	246309	0.04	0.25
	D = 1000		250682	0.00	0.09	253763	1.22	0.10	250745	250745	250745	0.03	0.19
	D = 1300		256089	0.00	0.19	261507	2.11	0.11	256155	256155	256155	0.03	0.15
1/6/19	80.1%	893											
	D = 700		187498	0.00	0.17	188411	0.49	0.10	187639	187639	187639	0.08	0.15
	D = 1000		192059	0.00	0.09	194987	1.52	0.10	192101	192101	192101	0.02	0.16
	D = 1300		197421	0.00	0.14	201859	2.25	0.10	197465	197465	197465	0.02	0.14
1/7/19	73.8%	920											
	D = 700		200173	0.00	0.13	200986	0.41	0.11	200212	200212	200212	0.02	0.15
	D = 1000		204658	0.00	0.08	207578	1.43	0.11	204722	204722	204722	0.03	0.20
	D = 1300		210053	0.00	0.67	214454	2.10	0.11	210164	210164	210164	0.05	0.22

### 5.3.4 Elaboration on the performance of the relocation assignment algorithm

As can be seen from Table 5.3, the relocation assignment algorithm is able to find a solution that is very close to the optimal OFV (i.e., the gap is below 0.1%) in a consistent manner. Furthermore, the simulated annealing algorithm finds this close-to-optimal solution almost every time it is applied. The exception is the case of 1/4/19 for D = 1000 and D = 1300, in which some of the obtained solutions deviate at most €4.- from the best found solutions. A possible explanation for this fact is that for this particular case multiple global minima exist which have an OFV very close to each other. If this is the case, the simulated annealing algorithm would not be able to find the global optimum after a certain amount of iterations.

## 5.2 Discussion

The purpose of the numerical experiments was to find an alternative approach to finding a solution for the relocation assignment problem. This alternative approach should be easily accessible for Apollo Vredestein, the objective function value (i.e., total relocation cost) of the solution should be close to the optimal solution and the process of finding the solution should not take significant time. The current approach for determining relocations can take up to an hour, so a computational time of less than a second is already a huge improvement. The results of the numerical experiments, as depicted in Tables 5.2 and 5.3, show that these objectives are easily met.

The calculations of the heuristic, done in Section 5.1.1 in Microsoft Excel VBA take 0.36 seconds on average. The addition of a simulated annealing algorithm, as described in Section 5.2.1, result in an extra computation time of 0.20 seconds on average. The average total computation time of 0.59 seconds is considered to be a good result by the company, since the heuristic has to be performed for operational means, at most once every hour. The calculations of the relocation assignment algorithm are a bit less time-consuming. The results described in Table 5.3 show that both the computational times for the heuristic as well as the simulated annealing algorithm are about 0.10 seconds lower. This difference in computation times can most likely be addressed to the state of the computer. The experiments were conducted with about a month time in between, so it is likely that the computational power of the computer was different for both experiments due to for example memory usage.

## 5.3 Implementation of the strategy for stock relocations

The goal of solving the relocation assignment model was to find a strategy for stock relocations at Apollo Vredestein, which in turn would reduce the complexity of the internal PCT flows, see Section 1.3. As shown in the numerical experiments, the logic behind that strategy should be based on the relocation assignment algorithm. Since all input data for the model, and therefore also for the heuristic is available to the warehouse manager, an automated excel program can be created and used to solve the relocation assignment problem. This program, from now on referred to as 'relocation tool', can be implemented in the daily process of planning the stock relocations. The relocation tool should be robust while easy to access.

The relocation tool was constructed using a combination of scripts in Microsoft VBA and Excel data queries. The input data is automatically generated by queries, given that the required data sheets are in the correct input directory. An example of the input data sheet is described in Appendix A4.3. The required amount of pallet capacity  $D$  is determined in a control sheet. The trigger for the relocation assignment algorithm is a button on this sheet. The result of the algorithm is an output sheet consisting of the products and the amount of stock to be relocated, such that  $D$  pallet capacity is generated at the central warehouse at minimum cost.

The relocation tool can be implemented in the decision process regarding stock relocations by enabling the inventory planner to use the tool. Currently, stock relocations are planned based on the information in the 'StockMix report' and some undefined priority rules, as explained in Section 2.5.3. The inventory planner can incorporate the relocation tool in the daily process of stock relocation decisions. The output of the tool should be treated as an advice and needs to be adjusted according to the actual distribution of stock over the bins. For example, if the relocation tool advices to relocate 40 pallets of some product  $i$  while the stock of product  $i$  is divided in bins of 35 pallets, it is more efficient to relocate 35 pallets, since the final goal is to generate free bins. If used correctly, the tool will enable the inventory planner to find stock of inactive and overstocked products, without having to manually check the stock levels of all SKU.

## 5.4 Insights

The heuristic, as used in the relocation tool, is able to solve the relocation assignment problem for Apollo Vredestein within a fraction of a second. This is already an improvement on the current situation, in which the inventory manager spends about half an hour a day sorting the data in order to be able to find suitable products for relocation. Even more so, the approach to finding those products is more sophisticated than the current approach. Whereas the inventory manager currently only has the stock levels per product per warehouse and his common sense to his disposal, the relocation tool combines several information sources, as described in Section 4.2.1, taking the company's inventory control and demand forecasting in consideration.

As a result, the relocation tool, and therefore the heuristic, consistently finds leftover stock that has been removed from the official product range. These batches of PCT, sometimes as large as a thousand products, linger in the central warehouse, consuming much needed warehouse capacity. Since, the inventory manager would previously search for the SKU with the largest stock minus short-term orders, these middle sized batches would stay under the radar.

Additionally, the relocation tool selects, given the current cost parameters, products for relocation to CTT with an expected DOS that lies around a 100 days. This is quite different than the current policy, where the products with the longest expected DOS are selected for relocation to CTT.

## 5.5 Measuring the improvements of implementing the strategy

Measuring the effects of implementing the strategy by using the relocation tool on a daily basis is unfortunately not feasible in available timespan. Since the products selected for relocation often have very high expected DOS (> 1 year), it is not possible to measure the improvements within reasonable limits. Additionally, comparing the decisions made by the relocation tool to decisions made by the inventory manager on the basis of historical data provides no valid results. This is largely because of the many variables that have to be taken into account. For example, during relatively busy periods, it might take a week after making the decision to relocate some stock before the relocation is actually performed.

Fortunately, the company chose to implement the relocation tool, since the underlying logic and assumptions are reasonable. This allows for the validation of the results of the relocation tool, which can be used for finetuning. One way of doing this is comparing the amount of relocations over a period of time (e.g., 3 months) to that same period of time in the previous year. Since the demand and inventory levels follow seasonal patterns, this allows the company to see whether the implementation of the relocation tool results in less movements. Another way of validating the strategy is tracking the relocations as advised by the tool and performed by the warehouse staff. The paths of the relocated products can be compared to the predicted paths (and expected DOS in particular) in order to test the consistency of the tool.

# Chapter 6: Conclusions and recommendations

This chapter consists of an evaluation of the strategy for stock relocation developed in Chapter 4 and the final recommendations for the company. It aims to answer the following research question:

6) Which improvements for the company are recommended to make?

In order to do so, the outcome of this research will be evaluated with regards to the core problem, the solution approach and the relocation tool. Furthermore, the recommendations regarding the implementation of the relocation tool, as well as recommendations for further improvements are made. The structure of this chapter is explained in Table 6.1.

Table 6.1: Structure of Chapter 6

6.1	The core problem
6.2	Assumptions in the solution approach
6.3	Recommendations regarding the relocation tool
6.4	Further improvements
6.5	Conclusion

## 6.1 The core problem

The core problem of Apollo Vredestein, as determined in Section 1.3, was the lack of a general strategy for stock relocations. As a result, the internal flows of PCT within the network of warehouses was complex due to the sheer size and unpredictability of the flows. PCT stock was relocated on a daily basis by a variety of employees, for multiple reasons. The decisions regarding which stock to relocate and the relocation destination were more often than not motivated by gut feeling.

The strategy for stock relocations, obtained in Chapter 4, provides Apollo Vredestein with a standardized approach to relocations. The relocations proposed by the relocation assignment will result in fewer internal flows, since the algorithm is more likely to select the most suitable stock for relocations. In this case, the most suitable stock for relocations is the stock that is the least likely to be ordered within a short horizon. While the current decision process involves gut feeling, the relocation assignment algorithm combines the actual stock levels with the forecasted demand.

While a reduction of internal flows is desirable, the improvement in predictability of stock relocations is perhaps a bigger benefit to the company. Using the relocation assignment algorithm, stock relocations can now be scheduled in advance, disburdening a large part of the daily tasks of the inventory manager. Furthermore, the warehouse manager can evaluate the effect of short term improvements during busy periods e.g., renting an extra transport truck for internal transport, more effectively.

## 6.2 Assumptions in the solution approach

The chosen solution approach (i.e., formulating the relocation problem in a mathematical model) proved to be beneficial. However, it is important to address some assumptions made in the model, as they are also implicit assumptions of the relocation assignment algorithm. The first assumption is the fact that PCT is only stored and moved in pallet quantities. This is a reasonable assumption, since stock is always relocated in whole pallet quantities.

The assumption that space utilization at the warehouses is optimal however can lead to some problems. The model considers warehouses with a capacity of an  $x$  amount of pallets, while in reality the warehouses have a capacity of an  $y$  amount of bins, each with a bin capacity. Of course the total

capacity in pallets remains the same, but since bins can only contain one SKU it is in fact different. One possible troublesome scenario could be that the stock of some SKU is divided over three bins. The algorithm could now select half of the stock of that SKU for relocation, thus leaving one bin half empty. Whether this is a problem depends on whether that particular SKU is currently in production, the differences in production weeks and the stock levels at the other warehouses. In any case it is necessary that an experienced employee monitors the relocations.

Additionally, the model assumes that replenishment are optimal, i.e., relocating products back from some warehouse to the central warehouse can be done most efficiently. This assumption allows for modelling the situation as a set of flows which a product can follow, all starting and ending at the central warehouse. While the inventory manager might do his job well, mistakes in scheduling the replenishing moves are inevitable. This could lead to some problems (in particular with relation to the 24 hours policy, see Section 1.3 and Section 2.5.1) if the relocation assignment algorithm is followed strictly. In this case, only the bare minimum amount of stock of each SKU would be present in the central warehouse. A possible solution for this problem is to increase the inventory norm for each SKU by some margin, thus increasing the safety stock.

The model also assumes that the soft FIFO policy is followed by selecting the oldest products for replenishing (and implicitly, selecting the newest products for relocation). The impact of this assumption depends on the effectiveness of the storage location assignment policy (see Section 2.3.3).

Finally, the model assumes the demand to be constant over the planning horizon. This assumption is of course not very likely, but it is the best available approximation.

### 6.3 Recommendations regarding the relocation tool

The strategy for stock relocations was implemented in a robust Excel tool named 'relocation tool', as described in Section 5.3. While Excel might not seem like the most suitable software for such a tool, it was selected because it is used by all employees involved with the decisions regarding stock relocations. The tool requires up-to-date versions of the 'Stockmix report' and 'the Inventory quality' document. Due to this fact, the tool is susceptible for human errors. I would recommend the company to implement the logic of the relocation assignment algorithm in their warehouse management system, in order to be able to prevent human error in a more effective way.

The tool is best used for two occasions. First, the tool can be used on a daily basis to find the most suitable stock for relocation. This saves time for the inventory manager, while aiding in reducing the complexity of the internal flows. Second, the tool can be used to evaluate the effectiveness of interventions, for example during busy periods or long term solutions such as increasing the warehouse capacity of one or more warehouses.

### 6.4 Further improvements

The solution developed in this research addresses a problem in Apollo Vredestein's warehouse network that is caused by multiple underlying factors. As a result, implementing the relocation assignment algorithm can be seen as treating the symptoms rather than the cause. Even though the stakeholders are well aware of these underlying factors, I think it is wise to state them, since treating these problems will likely result in much greater results (at the cost of higher investments). These problems were observed during the research and fall beyond the scope of this project. In decreasing order of magnitude, these solutions are:

5. Decreasing the inventory size
6. Increasing the capacity of the central warehouse
7. Redesigning the warehouse network
8. Improving the storage assignment policy

With regards to the first problem, decreasing the inventory size will inevitably result in less complex internal flows, as well as an overall reduction of logistic cost. The stock level at Apollo Vredestein exceeded the internal capacity in 46% of time in the period of 02-01-2017 to 07-01-2019.

Additionally, at some observation points, the total inventory was 2.7 times the inventory norm. This can be explained by the fact that, at that some observation point, there was more stock reserved for orders than the total inventory norm (40% actual stock is reserved for orders). The European Supply Chain CEO is aware of these problems. These observations were deliberately left out of the research, since they fall well beyond the scope of the project.

The second option is to increase the capacity of the central warehouse. This would be a costly procedure, since the warehouse is technically at maximum capacity. One solution would be to connect the central warehouse to the VDC, resulting in one larger warehouse. The stakeholders are aware of this scenario. I would recommend further research to this option, in order to gain a factual overview of cost and benefits of such a solution.

The third option involves changing the parameters of the warehouse network in a way that the constraints are better aligned. This would require at least: more reliable information on production planning, a complete reshuffling of about 7,200 Metric Tonnes of stock and a project team with a lot of time and expertise.

The fourth option consists of adapting the approach of the relocation assignment algorithm in the storage assignment policy. In other words, consulting the information on demand forecasting in the process of finding the best storage location for all stock. This would result in less relocations, since products are more likely to be in the desired location. However, a major downside of this approach would be the fact that the demand forecasts change monthly, resulting in monthly reshuffles of stock.

## 6.5 Conclusion

This chapter aimed to answer the following research question:

- 6) *Which improvements for the company are recommended to make?*

Section 6.1 shows that the result of this project is indeed an effective and implementable strategy in the decision process around stock relocations. However, as Section 6.2 states, there are some underlying assumptions that need to be addressed. As a result, the relocation assignment algorithm should not be interpreted as an optimal solution, but instead occupy an advisory role. The monitoring eye of the inventory manager will in my opinion always be necessary in a situation as complex as the warehouse network of Apollo Vredestein.

Section 6.3 describes the intended daily use of the relocation tool and explains its additional function as a tool for evaluating interventions. Section 6.4 describes further topics of research the company could look in to, in order to effectively increase the performance of their warehouse network.



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