Storage assignment of (semi-)finished products in an environment with multiple plants, warehouses, and production lines

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Delft University of Technology

Faculties of Civil Engineering and Geosciences | Technology, Policy and Management |
Mechanical, Maritime and Materials Engineering
Master of Science in Transport, Infrastructure & Logistics

TIL5060 Graduation project

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by

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Preface

This thesis is the final product for my degree on Master of Science in Transport, Infrastructure, and Logistics at the Delft University of Technology. The research is conducted in cooperation with Delft University of Technology and Tata Steel IJmuiden. It addresses the storage assignment of steel products in the context of the Tata Steel manufacturing site with many facilities. The multidisciplinary nature of this thesis resulted in the most challenging and interesting research I have ever worked on during my studies. Even though I had difficulties during the thesis process, I am looking back at a wonderful and mostly learning journey of my life.

In full honesty, I could not achieve this outcome without support from some people. First, I want to express a great gratitude to my thesis committee members, each of whom has provided patient advice, guidance, and flexibility throughout the research process. I remember the day I randomly approached Jafar Rezaei before he was going home. Although I had merely a topic or research approach, he directly agreed on to be part of my thesis with the words: "Yes, I want to supervise you. I think the topic is interesting, you are interesting, and I am interesting." You were so positive in all the meetings about my work that encouraged me to further improve it. Much thanks for helping me during the scoping and research approach of my project. I would like to express my gratitude towards Yousef Maknoon, without you I could never present this report. You helped me with endless hours during the modelling phase of my study, thank you for being so flexible with all the meetings and times you spend on me. Both Jafar and Yousef made me laugh during the meetings, whenever I think about your jokes I always smile. Next, I would like to thank Wouter Beelaerts van Blokland for providing me useful insights from a lean perspective, and finding the time to supervise me, even though you have so many other students. I would especially want to thank my final committee member Michiel van Randwijk from Tata Steel for giving me the opportunity to conduct this research at an incredible manufacturing site. Thank you for helping me all those (late) hours at the company, and providing me such useful feedback. All the flexibility you gave me showed that you trusted me and my capabilities.

I want to thank my mum for cooking me all those delicious meals during lunch and dinner. I could not reach this day if it was not for you and dad. Thanks to my friends from TIL for advising, studying, eating, complaining, and laughing together. Without our daily thesis days I would never enjoy it so much. I also want to express my gratitude to my colleague Irene for your unlimited moral support in all the conversations we had during the daily walks. Last but most important, I want to particularly thank my partner for all the daily support and endless love you gave me. You listened to my everlasting thesis talks, you were there during the sleepless nights, you were there when I needed a break and do something fun, you were there whenever I needed you. I am writing the gratitude to you with tears in my eyes, while I am in the library in Delft. This is how much I appreciate what you did for me until today and how much you mean to me.

Mehwish Ahmed
Delft, January 2019

Summary

Many manufacturing systems consist of a number of factories, storage locations, production lines, and an enormous amount of different products. The performance of manufacturers is highly determined by the warehousing in the production process, particularly with the storage allocation. Thus, the topic of this study is the assignment of (semi-)finished products to storage locations. The research is conducted in Tata Steel IJmuiden, which has a complicated production process with many facilities. A wide variety of steel items are produced in this manufacturing site.

The problem considers a fully connected network with two factories as suppliers, five demand locations (out of two end-users and three plants), and two service facilities located in between. Each supplier, demand or service point has a dedicated input and/or output warehouse. The warehouses differ in characteristics. The type of product that could be stored is dependent on the ability of warehouses to store products with storage conditions. The capacity is of importance in this particular system, as there are capacity limits compared to the amount of inventory. There are also five product characteristics that should be taken into account. First of all, the production route determines the supplier and demand. As the production is a pull system, the destination is known a priori. The second feature consists of the need of a service treatment. The third element, the storage conditions, has two requirements: 1) dry storage, where products should be stored in a closed warehouse, and 2) the rest time of the products. The fourth feature is the priority or due date of the product. The final characteristic is the SKU type, which indicates the importance of the SKU type specified with the ABC classification and the repeating pattern of the demand.

On the one hand the supplying plants are continuously producing, and on the other hand the warehouses have capacity limits. Furthermore, current assignment incorporates some randomness and neglects relevant product features. It considers the fixed product characteristics production route, need of service, and storage conditions, but it disregards the relevant due dates and SKU types. All of these aspects result in re-assignments of products and thus additional handling with an increased risk of damages. This study evaluates existing assignment rules, and develops and tests new assignment policies considering the aforementioned product features to provide products-oriented storage assignment decisions. The model aims to reduce the extra handling by synchronising the storage allocation and the demand. Two additional objectives are the storage time and due date met. Even though these aspects are synchronised together, there still might be extra handling due to the high stock levels and capacity limits of the storage locations.

The scientific contribution is the integrated approach of different literature fields and methodologies. Current research focused on warehousing of small products in a single warehouse. The products are categorised in this study using the ABC classification to provide specific service levels for the various SKU types. Synchronising the storage allocation with the demand, and the involvement of a complicated network are important aspects of the routing problems. The synchronisation could also be related to cross-dock problems with the aim of reducing double handling. Although, cross-dock problems limit the temporary storage to 24 hours and do not incorporate capacity limitations on the warehouses. The integrated modelling approach consists of simulation solved with assignment policies, the ABC analysis, and the implementation of multi-criteria decision-making (MCDM) using the best-worst method. MCDM is the decision-making between

several alternatives considering multiple criteria. The combination of the engineering method in which the rules are implemented, and where the rules are constructed through decision-makers, provides a useful approach.

The results of this study consist of three parts: the current situation, the assignment policies, and the disruptions. The current state results indicated the great share of high priority products in the system. In addition, it described the overall low performance on the objectives, especially considering the high priority products. The reason for this output is that the higher the priority, the shorter the delivery time windows, and the lower the performance or service level. Moreover, the sensitivity analysis on the colours confirmed that slightly increasing the high priority products significantly affect the outcomes. If there are more critical products in the system with a low service level, the overall performance decreases. Therefore, it is difficult to achieve higher service levels for high priorities. Next to aiming for an overall improvement of the assignment, the focus lies on particularly intent to achieve higher performances on the prioritised goods. Some assignment policies are retrieved from literature, while others are implemented using multiple product features by applying MCDM. Besides, each policy is run for different sets of production and demand.

The findings indicate that the random allocation has the lowest performance, and the current state the second lowest, because of the randomness in the rules. The closest open location from destination has a high performance on the storage time and due date met, but lower on the number of handling. Furthermore, the results are stable over the runs where very high performances cannot be achieved. It also appears that this storage policy leads to an unstable system in case of high inventory levels. The other policies incorporate the product features, the production route with the colour and/or SKU type. The outcomes show that the highest overall performances, and on the important products, are achieved when incorporating both the colour and SKU type. However, as the results of MCDM showed the relatively low importance of SKU type compared to production route and colour, the model neglecting the SKU type has only a bit lower performance. Assigning the products based on due dates in the system, and eventually the SKU type have promising outcomes. Another interesting point is that in case of high stock levels, the model considering all the characteristics has more extra handling, although, the highest improvements are achieved on storage time and due date. The robustness of this policy is also tested with disruptions in the production, where certain days the production is partly or completely down. When incorporating this policy with disruptions, the outcomes suggest that the performance of the overall system even increases, which shows that storage assignment decisions with product features are promising.

The main rule is to allocate the goods with a short delivery time window directly to the destination. Class A should have a slightly higher importance to be assigned to the destination than the C-product. Particularly the combination of a high priority and class A should always be allocated to the destination. The ratio of the capacity at the destination and the amount of stock for this destination determines which product with specific features should be stored at the destination or an intermediate hall. If the destination is full, a high priority product should remain at the supplier until there is place at the destination. Goods with a wide delivery window should be assigned to an intermediate warehouse except when there is always capacity at the destination.

There are some limitations of this study, which provides future research avenues. Storage assignment is associated with picking. While the pick-up in this research had to be fixed, it highly affects the findings. A combination of optimal assignment and pick-up rules will provide better results as these influence each other. Another limitation and potential future research is to incorporate the availability of resources (e.g. train and crane). The model considers a "continuous" flow: when a product is produced or requested, it can be directly moved. In reality, equipment's are required to perform the movements. These should be incorporated using resources with capacities and time. Another future research direction is to incorporate re-assignments to other warehouses. A new module should be added with rules to provide a possibility for relocation.

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List of Abbreviations

AS/RS	Automated Storage and Retrieval System
BC	Base Case
CD	Closest open location from destination
CO	Closest open location from origin
DES	Discrete Event Simulation
FIFO	First In, First Out
IRP	Inventory Routing Problem
P-D	Production-Distribution
POP	Plateau or Pallet with legs
PR	Production Route
PRC	Production Route and Colour
PRCST	Production Route, Colour and SKU type
PRP	Production Routing Problem
PRST	Production Route and SKU type
R	Random
SCC	Service Centre
SKU	Stock Keeping Unit
WIP	Work-In-Process

1
Introduction

1.1 Background

The increasing competitiveness of the market oblige manufacturing facilities to optimise their operations. The manufacturing production environment has moved towards numerous markets served globally (Shah and Ierapetritou, 2012). Most of the manufacturing systems are very large and complex, incorporating a number of plants and warehouses, and producing an enormous number of distinctive products (Sethi et al., 2002). A major element in the performance of manufacturing is warehouse operation planning. High costs in warehouse management are caused mostly by too much inventory, incorrect inventory mix, inventory placed in non-optimal locations in the warehouse, and inefficient picking (Sarudin and Shuib, 2015). Order picking can be divided into four disciplines: zoning policies, routing policies, order batching, and storage location assignment (Fontana and Nepomuceno, 2017). According to Van Den Berg (1999) & Rouwenhorst et al. (2000), the efficiency of warehouse operations is highly dependent on the storage allocation. Therefore, the allocation of (semi-)finished goods to storage locations forms the topic for this study.

Many factors affect the performance and efficiency of storage assignment. Some of these factors include the demand pattern of each product, product characteristics, size and layout of the warehouse, the picking method, and the material handling system (Petersen, 1999; Chan and Chan, 2011). Most of these factors are accounted for in this research. Several demand patterns are examined, as these influence the performance. The storage assignment decisions incorporate numerous relevant product features. Manufacturing facilities have many warehouses, which is taken into account here. The material handling system is of importance due to the damages that can occur from handling. Thus, the aim of this study is to reduce the amount of handling.

The research is conducted in the steel manufacturer Tata Steel IJmuiden in the Netherlands. Steel is an important raw material for automotive, construction, household appliances, and many other consumer goods (Denton et al., 2003; Zarandi and Ahmadpour, 2009). On the one hand, steel industries need to be more cost-efficient and produce high quality of steel, and on the other hand these businesses should reduce tardiness (Mohanty, 2004). Companies need to differentiate from competitors based on customer service. The main attribute for this purpose is the order-fulfilment time (Denton et al., 2003). Steel production is a pull system with an integrated manufacturing process (Denton and Gupta, 2004), consisting of raw material procurement, semi-finished product supply (e.g. hot metal), finished product making, and material distribution at different stages within the production process (Chen et al., 2012). It is a few-to-many industry, which refers to the use of a few raw materials to produce a huge variety of end products. Thus, the product differentiation increases as further the progress in the chain (Denton et al., 2003).

1.2 Problem description

The system consists of three aspects: production, storage and outbound (see figure 1.1). On a single site of 750 hectares, there are multiple plants and warehouses spread over the area. This study considers two production facilities as suppliers, and five demand locations out of which two are end-users and three are factories. Therefore, the outbound can be divided into two aspects: 1) semi-finished goods going to the next processing plant in the production line, or 2) finished goods ready for export to the customer. Moreover, there are two service plants where certain products get a service treatment in between these supplier and demand points.

After production processes in the plants, products need to be stored. There are multiple warehouses among two production stages. Every supplier point or a demand location has a dedicated input or output storage hall. These warehouses can also function as intermediate warehouses for other products. Each warehouse has its own characteristics: capacity, type of product that can be stored, and the dedication to a facility. Furthermore, there are an enormous amount of different steel products for various customers within the production chain. These products can follow different routes in the chain. The product features that need to be considered are the production route (e.g. supplier and demand point) as the destination is known a priori, the need of a service, storage conditions, due dates, and the product type. The characteristics of the storage locations and the storage conditions of the products need to be matched.

As there are various supplier and demand locations, warehouses, production lines, and products, storage assignment decisions are involved to allocate the products to the storage locations. Currently, there are many re-assignments resulting in double handling. Since the major cost component of these large products is the handling, also because of the resulting damages, the transportation is out of scope. The reasoning for this decision is that in Tata Steel, and other steel manufacturers, the inbound transportation is relatively cheap, as it is performed by train. Moreover, the distances are quite short since the facilities are located on a single site. The production sites are continuously producing, while the warehouses have capacity limits. Thus, the stock levels prevent the storage of all the products at the destinations leading to additional handling. The current assignment approach considers the available storage capacities of the warehouses and the production route of the product. However, the performance is relatively low, as the assignment decisions disregard mostly the product features, such as the due dates (or priority). This priority indicates the urgency of further production or the delivery to the customer.

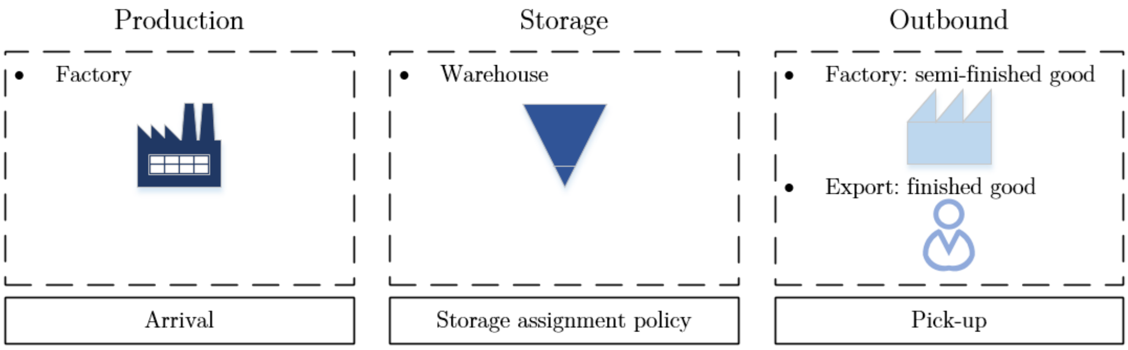

Figure 1.1: System elements

1.3 Scientific and practical relevance

1.3.1 Scientific relevance

There are four different streams of literature: storage assignment, ABC inventory classification, routing problems, and cross-docking. The literature review in the field of storage assignment indicated that the studies on storage assignment mostly consider the warehousing of small products in a single warehouse. In addition, most of the existing research is in the context of automated systems (De Koster et al., 2007). Moreover, the comparison of numerous policies in previous research is limited. The ABC classification is often used to reduce the number of unique products and determine service levels per class (Torabi et al., 2012), which makes the ABC assignment a useful approach in this system. The conducted analysis in the field of routing problems showed the application on outbound distribution, while in some industries the inbound is important. Most of the literature on cross-dock focus on terminal cross-docking (Ross and Jayaraman, 2008). Many papers restrict the temporary storage to 24 hours (Stephan and Boysen, 2011). Furthermore, the capacity of storage has not been taken into account while in practice the storage capacity is often limited (Ladier and Alpan, 2016). Finally, most problems are tackled with optimisation.

This research is an integrated approach of these four components. The characteristics of the system under study (see section 1.2) require the integration of several disciplines to form the theoretical perspective. The storage assignment is applied on assignment policies considering large products. These policies form the set of rules to assign products to storage locations. The ABC-classification is performed to decrease the number of distinctive products arriving from the suppliers and provide higher service levels for important classes of goods. The routing problems emphasise the importance of synchronising several aspects, in this case the storage allocation with the demand, which can be the end-users or the factories. This synchronisation is also related to the cross-docking problems with inbound (supply) and outbound (demand) doors, direct transfer or temporary storage, and the objective of minimising double handling.

This study contributes to the academic research as follows. The warehousing problem occurs in a manual picking environment of large products. The storage policies are evaluated where multiple warehouses are incorporated. The capacities of the warehouses are taken into account in a simulation model. The aim of the model is to reduce the number of handling by synchronising the storage allocation and the demand. The network is the inbound distribution of a manufacturer instead of the common outbound distribution. The traditional ABC-method is applied in the storage assignment decisions, as also recommended by Li et al. (2016) in future research. Furthermore, cross-docking is combined with traditional warehousing with no limitation on the storage time. The combination of these concepts forms the theoretical perspective of this research. This integration also holds for the research approach. As mentioned earlier, a simulation model is constructed, and the ABC classification is performed. In addition, several storage policies are tested in the model, which can be referred to as heuristics. Next to testing existing policies from the storage assignment literature, heuristics are designed by implementing the method multi-criteria decision-making with the Best-Worst method (see chapter 4 for further information).

1.3.2 Practical relevance

Tata Steel IJmuiden is facing a problem in aligning inventory and production. More products are being produced than the storage capacities of the destinations. The warehouses and plants are dispersed over the site, and as a result, (semi-)finished goods are multiple times being moved. Since the problem is complex, the expectation is that by performing this research, knowledge will be gained to tackle the problem. This study will be the first step within the department to evaluate a system where Work-In-Process (WIP) inventory is product-oriented stored. Furthermore, others like distribution centres, steel manufacturers, other manufacturing industries, and supply chains face a similar problem. Warehousing and inventory are two relevant activities that affect the performance (Muppani and Adil, 2008b). The inventory of raw materials, intermediates, and finished products needs precise planning and scheduling. Synchronising demand and supply by aligning inventory and production with end-user demand is a challenge companies are facing all around the world. In this context, the industry will be favoured by transferring the theoretical knowledge to practical applications that fit their operations. Research results need to be communicated to the industry to have an effect on practice of warehouse operations (Gu et al., 2007).

1.4 Research objective and research question

The objective of this research is to evaluate existing storage policies from literature on this particular system, and develop and evaluate new assignment policies where product features are taken into account. The main performance indicator is the number of handling. The other two performance measures are the average storage time and the due date met. The handling costs form a higher cost component than the transportation cost and a risk for damages. Thus, the transportation costs are not taken into account. The idea is to develop different rules for the products dependent on for instance the priority in due dates and the type. Distinctive service levels will be provided for the goods, which are determined by these features. Following this objective, the main research question that will answer the objective is:

How should the various (semi-)finished goods among multiple locations (plants or end-users) in the production chain be allocated to the warehouses such that the number of handling are taken into account?

The research question can be divided into the following sub-questions:

1. What are the characteristics of the system?
2. How can the current state of assignment be measured?
3. How to categorise the (semi-)finished products into classes?
4. Which set(s) of assignment policies should be applied on warehousing?
5. How to translate the outcomes of the study to simple rules?
6. What recommendations can be made regarding the actions?

1.5 Research outline

Figure 1.2 shows the outline of the study. This figure presents the chapters and the relevant concepts. The corresponding sub-questions discussed in the chapters are also stated.

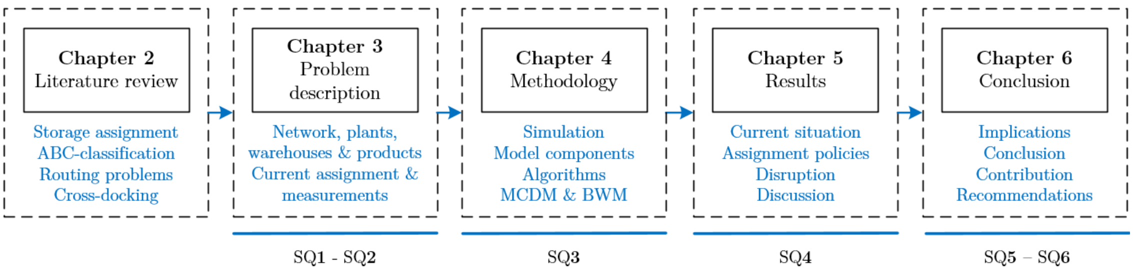

Figure 1.2: Research outline

2
Literature review

The warehousing problem in this study has multiple inbound and outbound locations, where the inbound are the plants and the outbound either factories or the end-users. It consists of several warehouses dispersed over an area with specific characteristics, such as the capacity or the dedication to a facility. In addition, there are many different products with certain features that need to be taken into account, for instance the storage conditions or the due date. The aim is to synchronise the storage allocation to these warehouses with the demand, considering the various features of the warehouses and the products. This main goal is expressed in three sub-objectives: reduction of double handling and average storage time, and meeting a higher due date. It should be noted that even though the storage allocation and the demand are synchronised, there still might be double handling because of the capacity limitations of the warehouses.

There are four different streams of literature related to the problem: storage assignment, ABC inventory classification, routing problems, and cross-docking. The problem of this research can be classified as storage assignment decisions for large products. Since there are many different goods involved, the system follows an ABC assignment in order to provide specific service levels for the classes. The routing problems cover the fact that the storage allocation and the demand should be synchronised. The cross-dock problems incorporate the synchronisation as well with the objective of reducing double handling, but with some differences. The remaining of this chapter discusses these fields of literature in sequential order, after which the final section presents the conclusion.

2.1 Storage assignment

Warehouses form an important aspect within the logistics system. A warehouse is used to buffer or store products between several points in the chain, such as raw materials, semi-finished goods, and finished products (De Koster et al., 2007). In literature, three types of warehouses are distinguished: distribution-, production-, and contract warehouses (van den Berg and Zijm, 1999). The functionality of the warehouses within this research is production and distribution. There are four decision problems in warehouse management: lay-out design, picking policies, storage assignment policies, and routing methods (Chan and Chan, 2011). The warehousing problems could be divided in with or without capacity limits. Particularly in decision problems with capacity limits, the storage assignment policies provide an efficient way of locating products in a warehouse to improve space utilisation and increase order picking performance, although it received less attention

(Gagliardi et al., 2007). Also the review on manufacturing by Esmaeilian et al. (2016) revealed that the published work on warehouse systems between 1990 and 2015 is only approximately 2%.

Warehousing problems either consider small products or large products. The current state of literature mostly considers warehousing problems for small goods such as in Macro and Salmi (2002), Gagliardi et al. (2007), Muppani and Adil (2008b), and Chan and Chan (2011). The small parts are often stored in batches using carton boxes that are put on shelves, or several boxes grouped on pallets and then stored on racks. These products are easier to handle due to the light weight, the standardised unit of loading (e.g. box or pallet), and as a consequence the ability to handle more products at a time. The warehousing problems with big parts are neglected in literature and also different from the small products. When the inventory consists of large products, the inventory costs, transportation costs, and handling costs are higher. Especially the handling costs are important, since it is difficult to handle as it is heavier, only one product at a time step can be handled, and the resulting damages that can occur from handling. The purpose of the storage assignment is to lower these handling costs.

Table 2.1 shows the existing storage assignment policies in literature (De Koster et al., 2007; Guerriero et al., 2013; Ong and Joseph, 2014). The implementation of class-based storage involves the number of classes, product assignments to classes, and storage locations for each class (Muppani and Adil, 2008a). Class-based storage provides an in-between policy that has benefits of both random and dedicated storage (Gu et al., 2007). There are two groups of class-based storage, namely dedicated purposes and ABC classification (Chan and Chan, 2011). The ABC-method is mostly used for forming classes in warehouse management research (Ashayeri et al., 2002; Choy et al., 2013; Mirabelli et al., 2015; Li et al., 2016). Similar to these studies, the ABC-classification will be used to form the classes (see section 2.2).

Table 2.1: Storage location assignment policies

Policy	**Explanation**	**(Dis)advantage**
Random	Assignment of products to random available warehouses	+ high space utilisation - high travel distance
Closest open location	First empty location	+/- Space full around depot and occupied further away
Dedicated	Reserving a storage location for a specific product	+ fast-moving items close to Pick-up/ Drop-off point (P/D) - more storage space
Full-turnover	Distribution over storage area according to turnover	- variation of demand and product assortment
Class-based	Forming and distributing classes to storage space	+ fast-moving items stored closely + flexibility and low storage space

From the conducted literature analysis on storage assignment, the papers also have some other assumptions that are different in this research. Most of the literature considers warehousing problems of small parts, while here the large products are considered with the main objective of reducing the number of handling instead of generally minimising the travel distance (Petersen et al., 2004; Chan and Chan, 2011). Furthermore, the storage assignment is fairly limited to within a single warehouse, while this study considers multiple warehouses. The review papers on storage assignment, Gu et al. (2007), De Koster et al. (2007), Gu et al. (2010), and Ong and Joseph (2014), concluded that studies combine multiple aspects of warehouse management, for example storage assignment with picking. This study does incorporate picking, although it is fixed (see section 4.4). Additionally, most studies focus on comparison of two policies, while for this case several assignment policies will be compared. Finally, Fontana and Nepomuceno (2017) identified two order-picking systems: the picker-to-parts system, where humans are employed for order picking, and the parts-to-picker system, which is an automated storage and retrieval system

(AS/RS). Most research of class-based storage is in the context of AS/RS (Petersen et al., 2004; De Koster et al., 2007), though Tata Steel operates with the manual order picking environment.

2.2 ABC inventory classification

The warehousing problem in this study and the corresponding assignment policies incorporate the ABC-classification. It is worldwide used by firms in inventory control (Torabi et al., 2012). The reason for applying ABC is that the range of different Stock Keeping Units (SKUs) is too large to implement specific inventory control methods for SKUs (Teunter et al., 2010). The ABC classification is applied in this research because of these benefits of reducing SKU types and therefore making the inventory more controllable. The technique is based on the Pareto principle. This rule implies that around 20% of the inventory has the most importance and accounts for approximately 80% of the total value of the inventory, and most of the products have little importance (Rezaei and Salimi, 2015). The three classes in the ABC inventory classification are as follows (Chu et al., 2008; Tinelli et al., 2011):

- **Class A** (high value items): around 15-20% of the goods account for 75-80% of the total inventory value.
- **Class B** (medium value items): 30-40% of the items account for approximately 15% of the total inventory value.
- **Class C** (low value items): 40-50% of the goods account for around 5-10% of the total inventory value.

The number of classes can be extended, although, the amount of groups is generally limited to maximum six classes (Silver et al., 1998). Several criterion exist in the literature for classification of products to groups. The most common criterion is the demand or annual consumption (Tinelli et al., 2011; Teunter et al., 2010). The use of one criterion to classify the products is referred to the traditional ABC method. Number of authors consider multiple criteria since there are many other criteria affecting the classification, such as Chu et al. (2008) and Nallusamy et al. (2017).

After forming classes and allocating SKUs to the classes, the service level per class needs to be decided on to control the inventory. The idea is to optimise the level of attention on the different classes (Rezaei and Salimi, 2015). Research of Teunter et al. (2010) have shown that the standard approach is to fix the service levels per group. There has been discussion in the literature regarding the focus on the classes. Ramanathan (2006) suggests to control and monitor class A. Moreover, according to Tinelli et al. (2011), class A items should be allocated near the entry, while class C should be allocated to positions with higher distances. On the other hand, some authors argue that correct treatment of C products can result in the main cost reductions (Viswanathan and Bhatnagar, 2005; Teunter et al., 2010; Van Kampen et al., 2012).

When comparing this study to the current state of research, some similarities and differences can be identified. The ABC-classification is performed to reduce the types of inventory, and provide specific inventory control methods per class. This research also uses the dominant traditional ABC method by forming three classes based on the annual consumption. The perspective of the authors Ramanathan (2006) and Tinelli et al. (2011) are shared to have a higher service level for class A in comparison to the other classes. The use of multiple criteria to put the products into classes is not taken into account in this study. Another difference that is quite important, is the fact that normally the ABC analyses in storage assignment decisions is applied on the class-based policy only. In this research, the ABC-classification is used to reduce the enormous amount of various SKUs to a couple of classes for all the storage assignment policies.

2.3 Routing problems

Manufacturing industries or typical supply chains consist of sequential activities of production, storage, and distribution. Every activity is planned using decisions from their preceding activities (Adulyasak et al., 2015). Within this context, the coordination among the engaged elements is crucial. The interest in the integration of production, transportation, warehousing, and inventory management is growing, as it significantly affects the overall performance of the chain (Fahimnia et al., 2008; Archetti et al., 2014). The problems that are coordinating several of the aforementioned elements are the routing problems, for instance the Inventory Routing Problem (IRP) or the Production Routing Problem (PRP). The PRP optimises production, inventory, distribution and routing decisions (Adulyasak et al., 2015).

The case in this research is different. This study does not consider the transportation or the inventory costs. The reason for comparing this research to the routing problems is the fact that the production and the scheduling need to be synchronised together to achieve a better performance. This problem synchronises the storage allocation coming from several production facilities with the demand, which is either a production facility or the end-user. However, even though these are synchronised, double handling could still occur because of the capacity limitations. The involved network is comparable to the production-distribution (P-D) model (see figure 2.1). There are some slightly variations of the P-D model compared to this study, which are: 1) there is one production line per plant, each of them are dedicated to a type of product at a time, but every machine can produce a different type of product after adjusting the specifications in the system, 2) both semi-finished and finished products are moved, and 3) the end-users are formed by a plant or a customer. Fahimnia et al. (2013) addressed the need for real-world problems on P-D planning and optimisation. Most of the existing research use analytical models (Adulyasak et al., 2015). However, according to Fahimnia et al. (2008), simulation proved to be a powerful modelling and performance evaluation tool for complex real-world problems. This study will apply simulation. Several versions exist of these problems. Table 2.2 presents the criteria for classification (Andersson et al., 2010). The features of this study are underlined in the table, except for fleet composition and fleet size, as these are not incorporated.

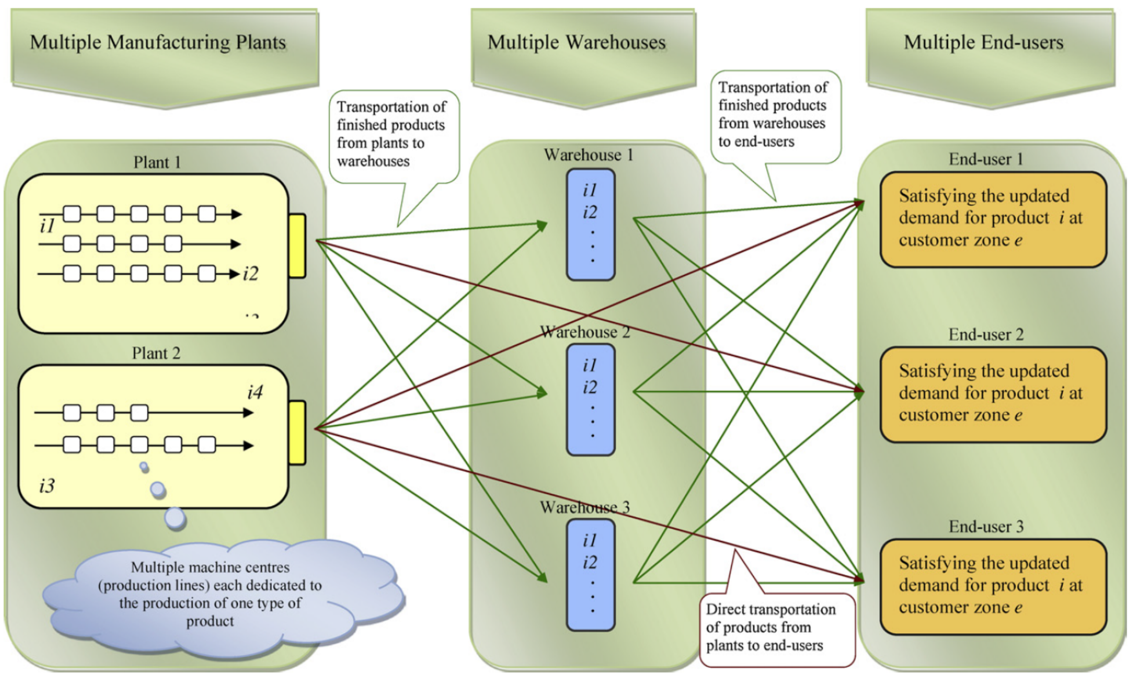

Figure 2.1: Complex P-D model (Fahimnia et al., 2013)

Table 2.2: Criteria for routing problems classification

Criteria		**Possibilities**	
Time horizon	Finite	<u>Infinite</u>	
Demand	<u>Stochastic</u>	Deterministic	
Structure	One-to-many	Many-to-one	<u>Many-to-many</u>
Routing	<u>Direct</u>	<u>Multiple</u>	Continuous
Inventory	Lost sales	Back-order	<u>Non-negative</u>
Fleet composition	Homogeneous	Heterogeneous	
Fleet size	Single	Multiple	Unconstrained

There are some differences between this study and the routing problems. Routing problems consider the coordination of production, transportation, and inventory. This research synchronises different elements, namely the storage assignment from factories with the demand, which is a factory or the end-user. Thus, the transportation movements and resulting costs are out of the scope. The papers on the routing problems focus mostly on the outbound distribution of products, while the inbound logistics is important in some industries, like in the steel industry. Simulation is performed instead of analytical models that are dominant in literature.

2.4 Cross-docking

Cross-docking has been adopted in manufacturing systems. It is beneficial since it favours on-time delivery and low handling costs (Thapa et al., 2011). The process of cross-docking starts with trucks assigned to the inbound doors. The products have two possible routes: directly to the outbound door or temporary storage, which results in double handling. Every movement of a good involves three aspects: pick-up, transfer and drop-off (Maknoon et al., 2016). The amount of products in need of double handling should be minimised. Thus, the decision if a product is directly moved to the outbound door or to temporary storage should be taken explicitly (Maknoon et al., 2017). The same holds for the problem in this research. The inbound doors can be considered as the supplying factories, and the outbound doors as the demand. The direct movement is the direct shipment of the product from supply to demand, and the temporary storage is the storage of goods in other warehouses. The assignment to warehouses other than the destination results in extra handling. Some other performance measures identified in the review by Ladier and Alpan (2016) that are also applicable to this research, are the total product stay time and the number of touches. The number of touches consists of three classes: one-touch, two-touch (or single stage), and multiple touch (or two stage), see figure 2.2 (Van Belle et al., 2012). When relating it to this study, one-touch is the direct shipment from supplier to demand. Single-stage can be seen as storing in one warehouse in between. Two-stage holds in case of two intermediate warehouses, which is not taken into account in this study.

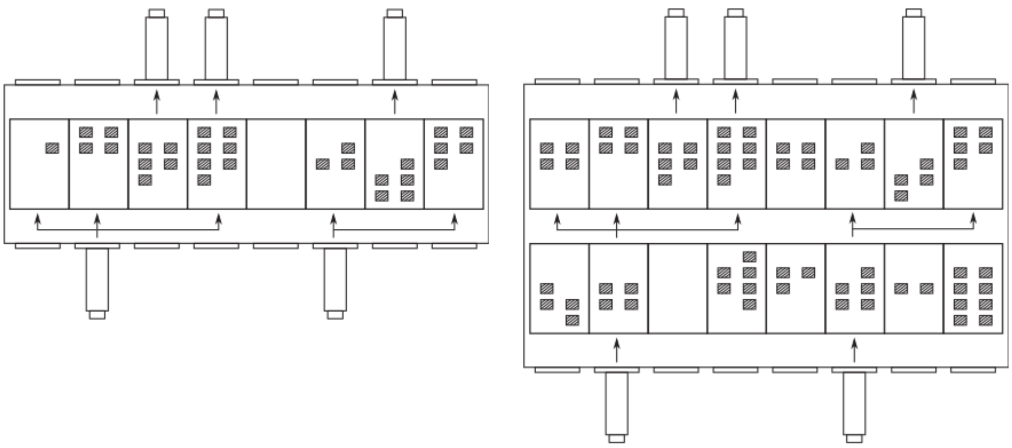

Figure 2.2: Single-stage versus two-stage cross-dock (Van Belle et al., 2012)

Synchronising the storage allocation with the demand is similar to the routing problems, but also to the cross-dock problems. The difference in this research and cross-dock problems is that in the later case, everything has to leave the doors and storage areas of the cross dock facility at the end of the planning horizon. Furthermore, there is no specific location dedicated to a specific product. Therefore, the double handling situation in this study is also more complicated as there are multiple direct shipments. In order to classify this research problem, the review papers of cross-docking provided several criteria (Boysen and Fliedner, 2010; Van Belle et al., 2012; Ladier and Alpan, 2016). Table 2.3 presents these classification criteria. The position of this research problem is underlined apart from the shape, since the shape of the network of this study cannot be captured with one of the possibilities. Ladier and Alpan (2016) divides the papers on strategic, tactical and operational. This study is operational as it considers the scheduling of the products.

Table 2.3: Criteria for cross-dock classification

Criteria	**Possibilities**			
Shape	I	L	T	H
Number of dock doors	6	<u>7</u>	8+	
Internal transportation	<u>Manually</u>	Automated	Combination	
Service mode	<u>Exclusive</u>	Mixed	Combination	
Pre-emption	Yes	<u>No</u>		
Arrival pattern	Concentrated	<u>Scattered</u>		
Departure time	<u>No restrictions</u>	Inbound	Outbound	Both
Product interchangeability	<u>Pre-distribution</u>	Post-distribution		
Temporary storage	<u>Yes</u>	No		

Compared to the papers on cross-docking, some other dissimilarities can also be identified with this study. There are three types of cross-docking: manufacturing cross-dock, distribution cross-dock, and terminal cross-dock (Ross and Jayaraman, 2008). Most of the authors focus on terminal cross-docking, while this research is an example of manufacturing cross-docking. The operating system of cross-docks can be classified into two groups: automated and manual (Maknoon et al., 2014). Especially in manual systems, the handling of products is costly and labour intensive (Bartholdi III and Gue, 2000). In this study, double handling should be avoided because of the costs but also the resulting damages that can occur from handling. Also, many papers mention the restriction of temporary storage to 24 hours, otherwise it is traditional warehousing (Stephan and Boysen, 2011; Vasiljevic et al., 2013). However, Apte and Viswanathan (2000) indicate that many organisations use a combination of cross-docking and warehousing to combine the benefits of both, likewise within this research. Moreover, in practice often the storage capacity is limited. Nevertheless, many studies do not take this aspect into account (Ladier and Alpan, 2016), while here there are capacity limits. The literature reviews of cross-docking by Boysen and Fliedner (2010) & Ladier and Alpan (2016), pointed out that cross-docking problems are mostly tackled with optimisation and less with simulation. This study applies simulation as a modelling tool.

2.5 Conclusion literature review

The four disciplines in the literature analysis are storage assignment, ABC inventory classification, routing problems, and cross-docking. The combination of the concepts forms the theoretical perspective of this research. To the knowledge of the author, these fields of literature have not been previously combined. This chapter covered the position of this work in relation to the previous studies in each of the streams. The warehousing problem is regarding large products with multiple warehouses, which are neglected in literature. The main objective is to reduce the number of handling, as the handling is a major cost component for large products in comparison to the transportation. Assignment rules are partly retrieved from the storage assignment studies. The involvement of numerous distinctive SKUs requires the need of an ABC assignment. The routing problems showed that synchronising of the components, in this case the storage allocation and the demand, are important. Furthermore, similar to P-D problems, this system covers a network of plants, warehouses, and end-users. Synchronisation is relevant in cross-dock problems as well, although this system is slightly distinctive. In cross-docking, all the products have to leave the cross-dock system at the end of the planning horizon and there is no dedication to the inbound or outbound doors. Figure 2.3 presents an overview of the similarities and differences of each field in comparison with this study, which are identified in the previous sections. In this figure, the similarities are indicated in blue (the middle) and the differences in black (the sides).

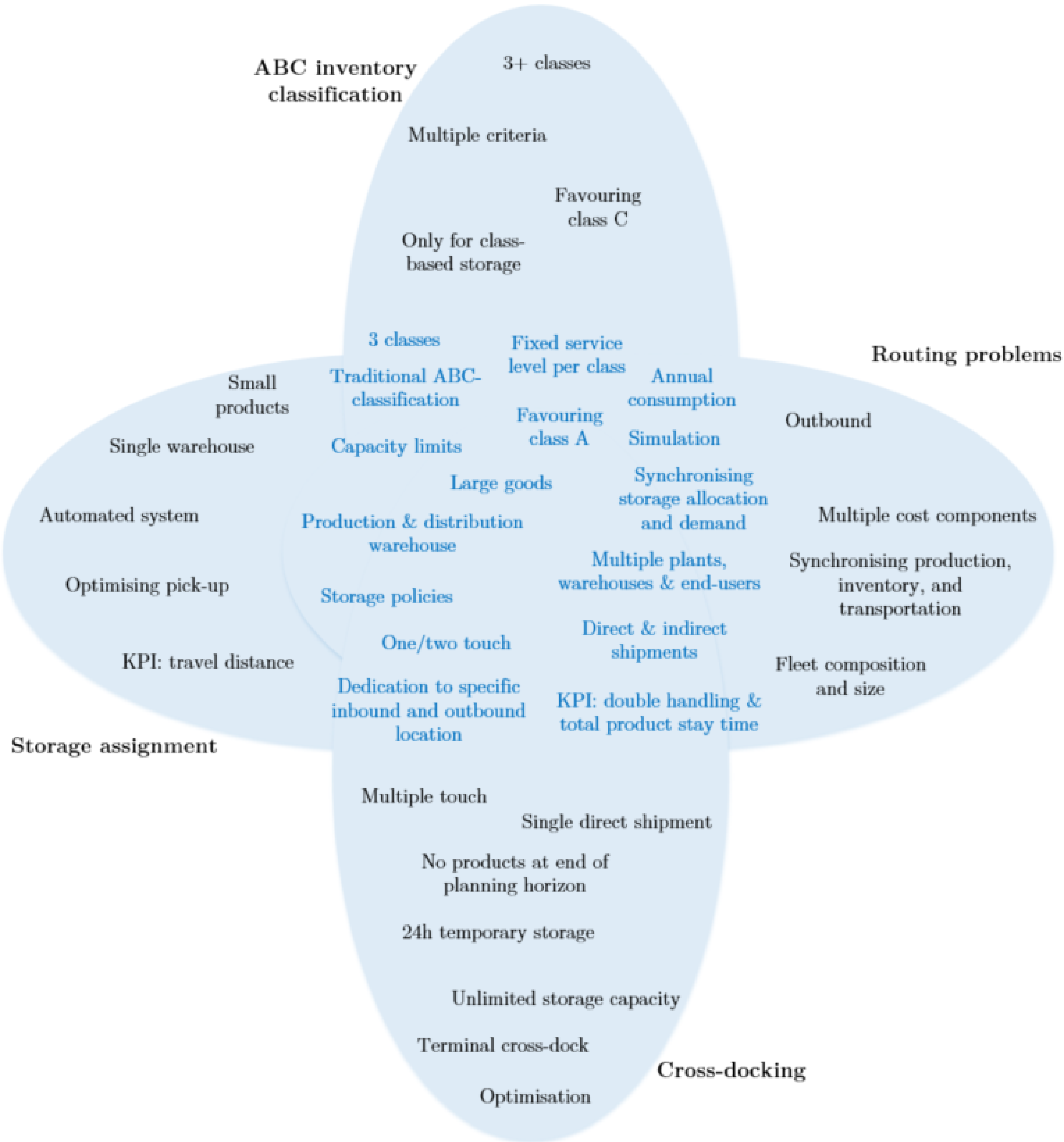

Figure 2.3: Literature framework

3
Problem description

The previous chapter discussed the literature review related to this research problem. The review suggests that papers on storage assignment decisions for large products are missing. The context of many different products and multiple warehouses makes it more difficult to capture the problem with existing studies. After showing the importance of having this kind of problem, this section describes the problem in detail. Section 3.1 defines the general problem, after which section 3.2 explains the practical problem. The chapter ends with a concluding section in 3.3.

3.1 General problem definition

The research problem considers a fully connected network with seven plants, nine warehouses, and two end-user locations. Out of the seven production facilities, two are the suppliers, three are the demand locations, and two are the service points located between the supplier and the demand. Therefore, there are two suppliers and five demand locations (two end-users and three factories). The set of warehouses have specific characteristics, such as the capacity, the type of product that can be stored, and the dedication to a supplier or demand location. There are capacity limits as the inventory is often approaching or exceeding the warehouse capacity. The product type that can be stored at a warehouse depends on whether the hall is closed or open and the support to put the product on. The suppliers each have an output warehouse for their goods, and the same holds for the demand locations with their input warehouses. Furthermore, the service installations also have an input hall and output hall. All of these warehouses are dedicated, although they can also function as an intermediate location for other goods. There are three exceptions: 1) one supplier warehouse does not have a capacity to store products, 2) one hall of the service installation does not store products that do not need a service, and 3) there is one large and independent warehouse without any dedication to a supplier or demand point.

There is also a set of large products with specific attributes. The first attribute is the production route that specifies the supplier (or origin) and demand (or destination) locations. The production is a pull system, which means that the destination is known a priori. The route incorporates if the good needs a service. The second attribute relates to the storage conditions, which are the dry storage and the rest time. Certain goods need to be stored in a closed warehouse if it should remain dry. The rest time holds for specific goods that restricts the product for leaving the system (further production or export) until the product passes the rest time. Some of the halls are not able to store the products that still need to rest. The third characteristic is the product priority. There are five groups of delivery time windows. The final attribute is the SKU type of the product, which consists of six classes. The various distinctive products, origins, and destinations leads to numerous possible production lines.

The complicated structure of the network, and the characteristics of the warehouses and products result in the need of warehousing. On the one hand, the suppliers are continuously producing, which in turn results in large amount of inventory, and on the other hand, the warehouses have capacity limitations. Products arrive daily to the system with expected demand on certain days. These products are then assigned to a warehouse dependent on their attributes, the remaining space, and the assignment rules. The assignment is either directly to the destination or an intermediate location, which results in double handling. Afterwards, when a demand request arrives to the system for a specific product, this product is retrieved from one of the warehouses, and both the demand request and product leave the system. Important to mention is that there is no FIFO (first in, first out) principle. Moreover, the demand pattern determines the production pattern, where the assumption is that the production is always higher than the demand. Thus, there is 100% stock availability and no stock-out option is possible.

The warehousing model aims to reduce the number of handling. Two other objectives are to reduce the average storage time and meet a higher due date. It takes the delivery windows of products into account, which means that urgent products with shorter windows should be prioritised on the objectives. The model takes the decision explicitly on which product to send to which warehouse considering their attributes. There are multiple direct assignments as there are multiple origins and destinations, and one intermediate assignment is possible to one of the warehouses. The number of handling can only be reduced on the non-service products, since the path of products in need of service is fixed within the model. The goal is achieved by synchronising the storage allocation and the demand. Even though these two are synchronised, there might be still double handling as there are capacity limits.

3.2 Practical problem definition

The case for this research is Tata Steel IJmuiden. Tata Steel IJmuiden is one of the locations of Tata Steel Europe (Tata, 2018). The steel is used for the packaging industry, construction, automotive, and manufacturing goods (Tata Steel, 2017b). This section presents practical information regarding the problem. First, the network is discussed in section 3.2.1. Section 3.2.2 describes the features of the plants and warehouses, and section 3.2.3 the features of the products. The final section describes the current storage assignment and provides some current measurements.

3.2.1 The network

Figure 3.1 presents the fully connected network for this case study with the suppliers, the demand, and the service locations (Interviews D.1 and D.6). The warehouses W1, W7, and W9 are located next to each other, which is shown with a dashed connection. The other lines indicate the dispersion of these warehouses over the site. The numbers on the connections are the number of handling (or unit of effort). In case of a dashed connection, the number of handling is two, and otherwise the unit of effort is four. This does not represent the transportation costs, but is a normalised measure to incorporate the extra handling with train movements. The number of handling can only be reduced for the non-service products. Overall, the minimum number of handling is two (no train) or four (train), and the maximum number of handling is eight (no service) or ten (service). This network is chosen after narrowing it down, since the steel production is a complex production process with many more facilities. Appendix A.1 provides a detailed overview of the production process and the site facilities, and appendix A.2 shows the flow to determine the minimum and maximum number of handling.

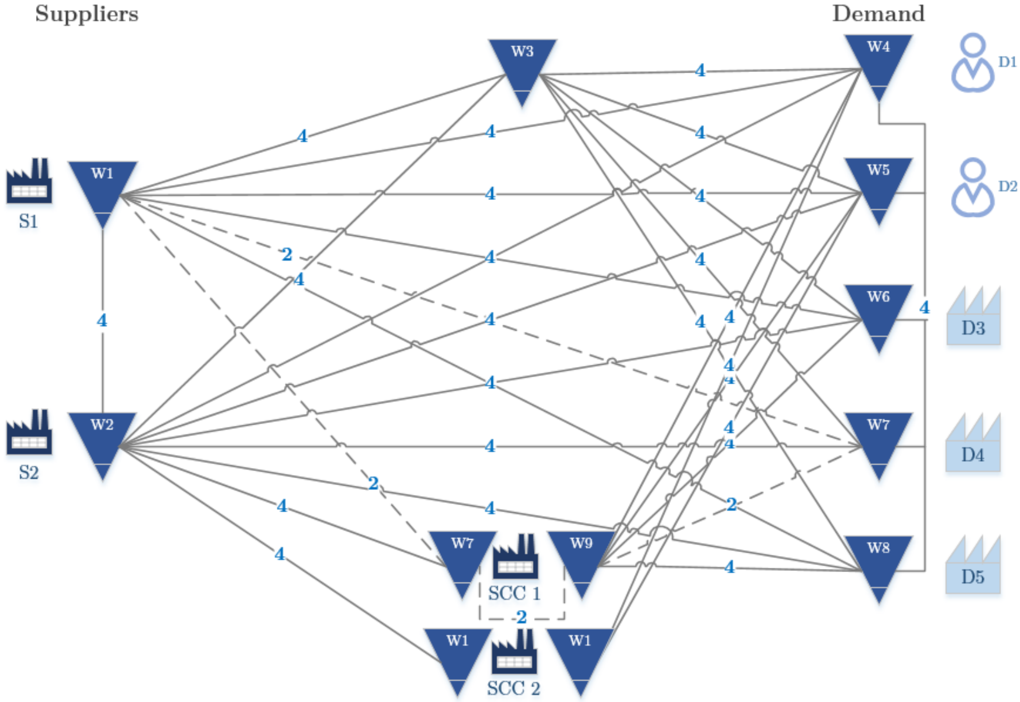

Figure 3.1: Network

3.2.2 Factory and warehouse characteristics

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3.2.3 Product features

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3.2.4 Current storage assignment

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3.3 Conclusion problem description

This chapter described the problem in general terms and in case-related concepts. There are three objectives to achieve within the problem: reducing the number of handling and the average storage time, and meeting the due date for a higher number of products. This multi-objective system should especially be improved for the high priority products. Figure 3.2 depicts an overview of the system characteristics that needs to be considered in the solution approach.

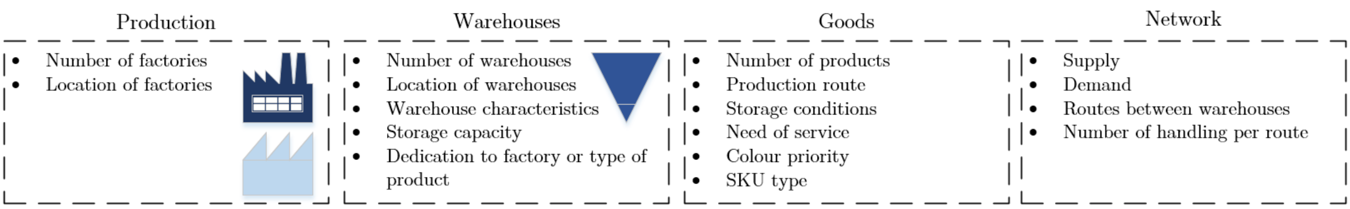

Figure 3.2: System characteristics

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4
Methodology

The simulation model attempts to reduce the double handling by synchronising the storage allocation and the demand. Furthermore, the model pursues a reduction in the average storage time and an improvement in the due date met, which results in a multi-objective solution approach. The three main components of the model are: 1) arrival, 2) assignment, and 3) pick-up (see figure 4.1). There are inbound and outbound locations. Products and demand requests arrive on a daily basis to the system. Products are assigned to one of the assignment locations. A demand arrival results in the computation of the pick-up. The product and demand request have to match in order to leave the system after a temporary storage of the product. The figure can also be presented in a pseudocode that represents a conceptual algorithm. The algorithm describes the general steps that every entity follows in the system. Let the sets be denoted with: products $p \in P$, storage locations $s \in S$, and demand requests $r \in R$. The summary of notations is presented in 4.1. The main components of the simulation model result in Algorithm 1. The various assignment policies that will follow are related to line 4.

This chapter provides a description of the methodology. It is structured according to the modules. Although, first an overview is given of the simulation model in section 4.1. Section 4.2 discusses the first component, which is the arrival. Section 4.3 presents the assignment module, and section 4.4 explains the pick-up module. The chapter ends with a conclusion in section 4.5.

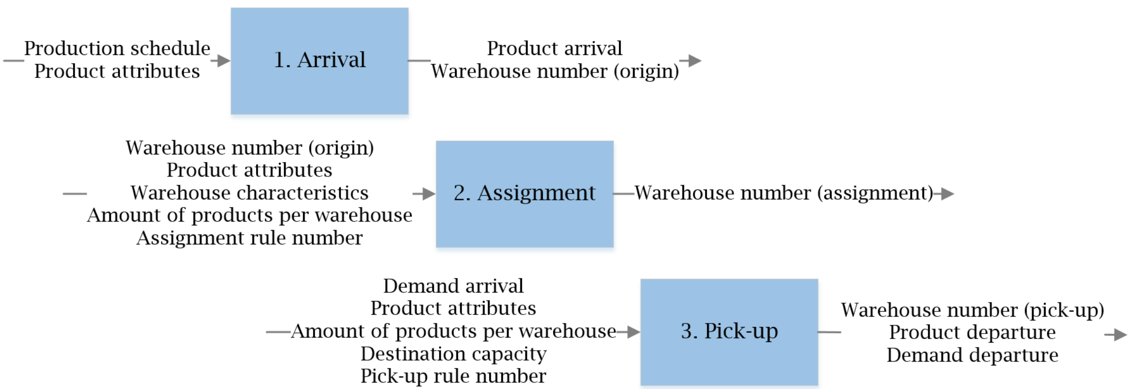

Figure 4.1: Modules

Table 4.1: Summary of notations

Sets		**Parameters**	
$p \in P$	Set of products	u	Uniform draw between 0 and 1
$o \in O$	Set of origins	I_{sp}	Inventory in storage location $s \in S$ for product $p \in P$
$d \in D$	Set of destinations	V_s	Capacity of storage location $s \in S$
$c \in C$	Set of colours	LB_s	Lower bound of storage location $s \in S$
$t \in T$	Set of SKU types	UB_s	Upper bound of storage location $s \in S$
$s \in S$	Set of storage locations	LB_{sd}	Lower bound of storage location $s \in S$ for destination $d \in D$
$r \in R$	Set of demand requests	UB_{sd}	Upper bound of storage location $s \in S$ for destination $d \in D$

Algorithm 1 Conceptual simulation algorithm

```
for all products p ∈ P do
    Assign attributes to product p ∈ P: origin, destination, SKU type, priority, SCC 1, SCC
  2, dry storage, rest time, arrival time, earliest due date, latest due date, delivery time window
    Move product p ∈ P to supplier storage location s ∈ S
    Determine assignment storage location s ∈ S
    Move product p ∈ P to assignment storage location s ∈ S
for all demand requests r ∈ R do
    Assign attributes to demand request r ∈ R: destination and SKU type
    Determine pick-up storage location s ∈ S
    Retrieve product p ∈ P from pick-up storage location s ∈ S
    Match product p ∈ P and demand request r ∈ R to leave the system
    Assign attributes to product p ∈ P: departure time, storage time, handling
```

4.1 Simulation modelling

The warehousing model is implemented using Discrete Event Simulation (DES). The object-oriented simulation tool in this research is Simulink within MATLAB. SimEvents is a package in Simulink that models DES. The choice for a simulation model is governed by the fact that the system under study is relatively complex. The system is dynamic and involves numerous amount of factors that are difficult to capture with optimisation tools. Moreover, simulation is traditionally applied as a modelling tool in warehousing (Macro and Salmi, 2002; Gagliardi et al., 2007; Liong and Loo, 2009). In addition, the company preferred the use of simulation. There is also no optimal solution for the problem they are facing. The purpose of this research is to evaluate the impact of different allocation rules on the performance measures. This section discusses the objectives, scope, implementation, and the logic of the simulation model.

4.1.1 Objectives

The main objective of the simulation model is to determine the effect of different storage policies on the performance measures. These Key Performance Indicators (KPI's) are the number of handling, the storage time, and meeting the due date. This main objective to be achieved with simulation can be divided in the following four-folded objectives:

1. Quantify the base performance with the current storage assignment policy
2. Create insight on the effect on the KPI's when implementing different assignment rules
3. Test the effect of favouring important products above less ones on the performance measures
4. Test the effect of a disturbance within the system on the performance measures

4.1.2 Scope

The model scope is shown in figure 4.2. The process starts with the steel product arrival from the suppliers, W1 and W2. Afterwards, the crane loads the item on the train or POP. The transportation movements are out of scope, and is thus indicated with a black box. Then the crane unloads the product from the transportation mode to a spot within one of the warehouses. When this warehouse is not the destination, after a while a re-allocation to the destination occurs with additional handling. The destination warehouses are W4, W5, W6, W7, and W8, which are indicated in italic in the figure. The last process is the departure of the good from the destination.

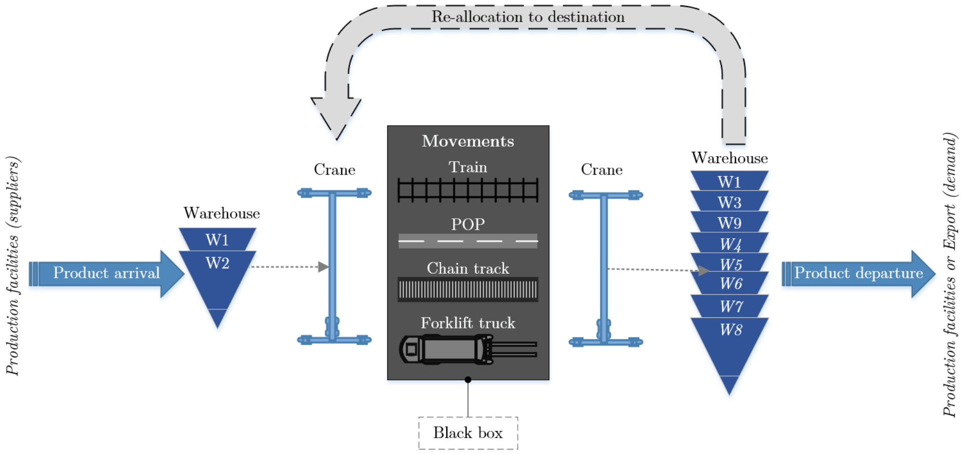

Figure 4.2: Model scope

4.1.3 Implementation

The model runs for 180 days. There are two types of simulation models: 1) terminating with a well-defined end time, and 2) non-terminating (Duinkerken, 2016). The model in this research is a non-terminating simulation with a warm-up period of ten days. The initial state of the system can influence the performance measures. During the initialisation phase, production is generated, while the demand will arrive after the warm-up period in order to partially fill the warehouses with goods. There are no replications considered. Replications cause stochasticity in every run for the attributes, while the idea is to keep the attribute values fixed so that solely the effect of different assignment rules can be measured.

To classify the products in order to reduce the number of different types, the ABC-classification and the Repeating profile are defined. The ABC classes are formed based on the annual production weight and the amount of SKUs. The repeating profile indicates the annual demand pattern, where Runner is most frequently ordered and Stranger the least. *Table has been removed.* Since three classes do not exist, there are six SKU types defined. The idea is to provide higher service levels for Class A in combination with a Runner or Repeater. Appendix B.1 presents the analysis of the SKU classification. The products and demand requests are implemented per type and destination. The combination of six SKU types and five destinations leads to 30 combinations of SKU per type and destination (see table 4.2).

Multiple input files are constructed for the production and demand schedules to test the robustness of the assignment policy with different inputs. The future production and consumption are relatively uncertain. To cope with the future uncertainty, the assignment rule sets will be analysed for all input files. The production of steel is a pull system and it depends on the customer orders. A new demand pattern is constructed with a corresponding feasible production pattern. The first two files are deterministic, the fluctuations are manually differentiated in Excel. The other three input files have stochastic components. The statistical distribution depends on the demand type, such as lumpy, cyclical, and stochastic. In literature, the main distribution to represent stochastic demand is the normal distribution (Willemain et al., 2004; Ramaekers and Janssens, 2008; Choy and Cheong, 2011). Therefore, the normal distribution is selected with $\mu = 580$ and $\sigma = 37$ for the daily demand. In addition, a stochastic value is added for the type and the destination with a uniform distribution. The intervals are different for each type and each destination.

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Table 4.2: Combination of SKU type and destination

Type \Destination	**D1** *W4*	**D2** *W5*	**D3** *W6*	**D4** *W7*	**D5** *W8*
A-Runner	T1D1	T1D2	T1D3	T1D4	T1D5
A-Repeater	T2D1	T2D2	T2D3	T2D4	T2D5
A-Stranger	T3D1	T3D2	T3D3	T3D4	T3D5
B-Repeater	T4D1	T4D2	T4D3	T4D4	T4D5
B-Stranger	T5D1	T5D2	T5D3	T5D4	T5D5
C-Stranger	T6D1	T6D2	T6D3	T6D4	T6D5

Figure 4.3 visualises the model specification.

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Regarding the due date, a KPI is added to test whether the due dates are met. Therefore, the colour represents the due date in the model with the respective delivery time windows (see table 4.3). In the report, the phrase of colour is still used for convenience. The earliest due date is four because of the rest time of the products. Even though the S2 semi-finished products do not have a rest time, for simplicity, these products also incorporate these delivery time windows. In comparison to the S1, the S2 products are much lower in amount.

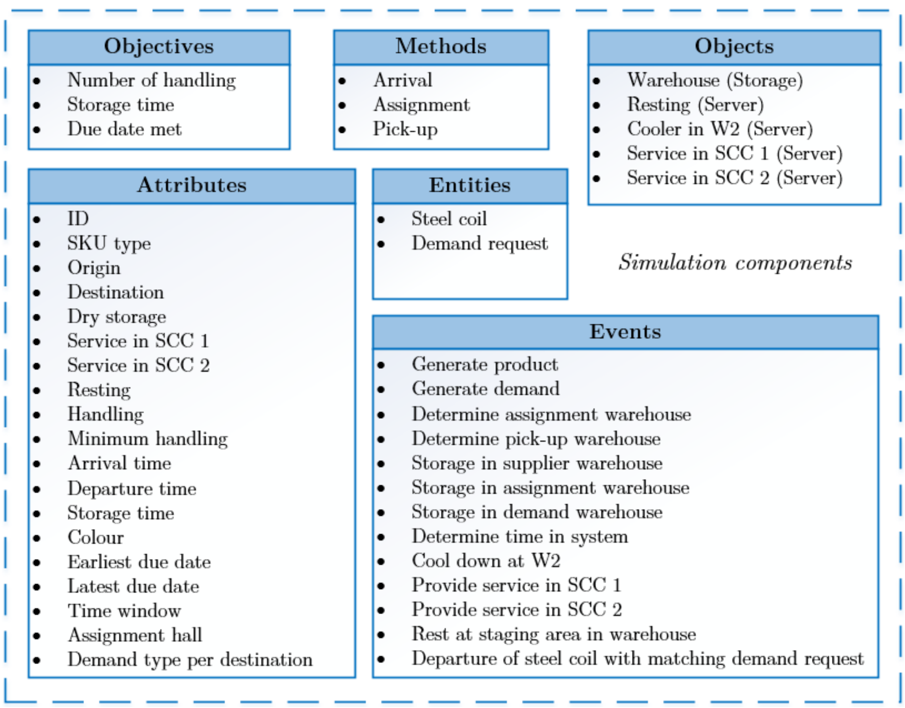

Figure 4.3: Model specification

Table 4.3: Due dates per colour

	Earliest due date	Latest due date	Delivery time window
Black	4	7	3
Red	4	10	6
Amber	4	14	10
Green	4	21	17
Blue	4	35	31

4.1.4 Logic

Figure 4.4 shows the logic of the simulation model.

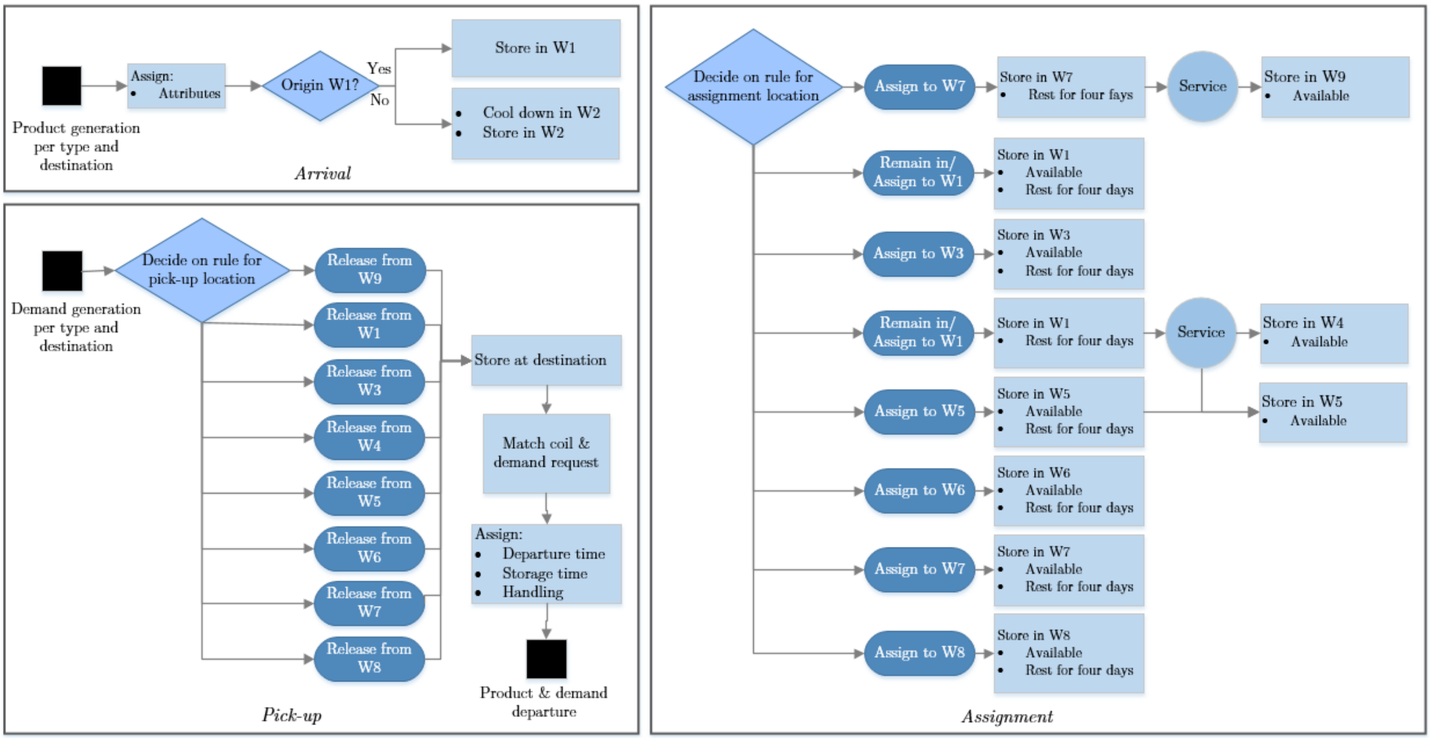

Figure 4.4: Model logic

4.2 Component 1: Arrival module

Figure 4.5: Arrival module

The first component of the model is the product arrival (see figure 4.5). The products arrive daily to the system dependent on the production schedule specified per type and destination. When the product is generated, it is assigned all the other attributes, such as the origin and colour. After the attribute values are determined, the product is moved to one of the supplier warehouses dependent on the attribute origin. If the supplier is S2 and it is not a finished good, the product is cooled down in W2.

4.3 Component 2: Assignment module

The second module is the assignment (see figure 4.6). The assignment locations consist of the warehouses mentioned in section 3.2.1. Moreover, a dummy warehouse is included in case the other warehouses are full. There are three possibilities in the model:

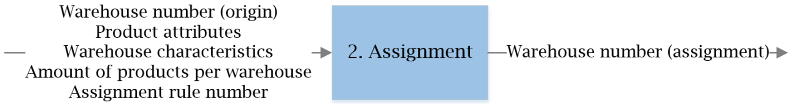

Figure 4.6: Assignment module

1. **Origin - Destination**: when the assignment is to the destination.
2. **Origin - Intermediate - Destination**: when the assignment is not to the destination, but another warehouse. It includes the assignment to SCC 2.
3. **Origin - Intermediate - Intermediate - Destination**: when the product needs a service in SCC 1, it passes two intermediate storage places.

This means that if the assignment is to the destination warehouse, products will depart from this location. If the assignment is to an intermediate warehouse, the products will be re-allocated to the destination warehouse, which results in extra handling. The movements from an intermediate to another intermediate hall, or from destination to intermediate is irrational and as a consequence not taken into account. Moreover, it is possible that within a warehouse the products switch places that result in additional handling, for example when products are being stacked and the lower product is needed. These crane movements are also not incorporated.

The assignment module starts at the supplier warehouse. There are many types of assignment policies (or heuristics) tested, each will be elaborated on later in this section. The assignment depends on the product attributes, the warehouse characteristics, the number of products per warehouse, and the assignment rules. Which attributes are incorporated, depends on the assignment policy. Although, the production route, need of a service, and the storage conditions are always considered as these are fixed. The storage conditions of the product are matched with the warehouse characteristics. The product is only assigned to the assignment location if the number of products in the corresponding hall is lower than the capacity. An assignment rule number is selected, and the assignment policy provides the warehouse number for the assignment location, which can be either the destination or an intermediate warehouse.

All the heuristics based on pseudocode will be next explained. First some models are tested that are derived from interviews (sections 4.3.1 and 4.3.2). These policies consider the same assignment rules as the base case (section 4.3.3), though with a slightly modification. The current state model does not incorporate the attributes colour and SKU type in the assignment. The other heuristics consider various assignment rules to test the performance of the system. Some of them are retrieved from literature, such as the random storage (section 4.3.4) or the closest open location storage (sections 4.3.5 and 4.3.6). The other heuristics are developed with a multi-criteria assignment, where the scores are obtained through a questionnaire (see appendix E). A multi-criteria assignment is required, as there are multiple attributes incorporated, for instance the colour and SKU type. When there are three or more attributes to decide on, a method is needed to derive the importance of these features. This results in the implementation of the Best-Worst method (BWM), which will be discussed in section 4.3.10.

4.3.1 Input SCC 1 (SCC 1)

The practical problem description showed that the installations of SCC 1 are located in W9. These warehouses cannot store the hot products and as a consequence, the resting of the products occurs in the W7 hall. W7 is also the destination for the demand location D4. This results in an often fully occupied W7. This is slightly adapted on the advice of a scheduler (Interview D.8): W3 will serve as input for SCC 1. It is the largest warehouse and the rest time is 2.5 days instead of 4 days in W7.

4.3.2 Warehouse capacity (Cap)

Two capacities are identified in the case study: the lower maximum capacity and the critical maximum capacity. In the current state model, the critical maximum capacity is considered. This scenario takes the lower maximum capacity into account (see the values in appendix B.2.1).

4.3.3 Base case (BC)

The current state assignment is constructed from several interviews (D.6 and D.8), in which the rules per destination were discussed. The main steps are depicted in algorithm 2. Let the set of destinations be denoted with $d \in D$, a random draw from a uniform distribution between 0 and 1 with u, the sum of all products $p \in P$ in storage location $s \in S$ with $\sum\limits_{p \in P} I_{sp}$, and the parameter of the capacity of storage location $s \in S$ with V_s. First of all, an order list of assignment locations is constructed per destination that is denoted with L_d. The products in need of a service are assigned to the corresponding service storage locations. Moreover, a random number is generated. The ranges for the storage locations are defined per destination. These ranges are constructed in accordance with the current state measurements in section 3.2.4, and the interviews D.6 & D.8. The storage location in which the random number can be classified, based on the lower bound LB_{sd} and upper bound UB_{sd}, is checked on available space and if the storage conditions of the product match the characteristics of the storage location. If these requirements are all satisfied, the product is assigned to this location. When one of the conditions is not satisfied, the order list per destination is retrieved. This list will in the same order be checked until the product is assigned to a storage location. Appendix B.2.2 shows the lower- and upper bounds for the storage locations per destination, and the order lists per destination.

Algorithm 2 Base case algorithm

Output: Assignment storage location

for all destinations $d \in D$ **do**
    $L_d \leftarrow$ Construct order of storage locations $s \in S$ based on interviews and current measures
    for all products $p \in P$ **do**
        if SCC $1 = 1$ **then**
            assign product $p \in P$ to SCC 1 storage location $s \in S$
        else if SCC $2 = 1$ **then**
            assign product $p \in P$ to SCC 2 storage location $s \in S$
        Compute u
        if $LB_{sd} < u \leq UB_{sd}$ $s \in S \wedge \sum\limits_{p \in P} I_{sp} < V_s$ $s \in S$ $\wedge$ satisfies storage conditions **then**
            assign product $p \in P$ to storage location $s \in S$
        for all storage locations $s \in S$ in the order of list L_d **do**
            if $\sum\limits_{p \in P} I_{sp} < V_s$ $s \in S$ $\wedge$ satisfies storage conditions **then**
                assign product $p \in P$ to storage location $s \in S$

4.3.4 Random assignment (R)

The literature review on storage assignment discussed several policies. One of these storage assignment policies is random assignment, where products are assigned to the possible warehouses with equal probability (De Koster et al., 2007). Algorithm 3 presents the random assignment. There are some slightly changes compared to the base case algorithm. The ranges for all the warehouses are approximately equal. These ranges are not exactly the same, as the storage conditions cause some differences that need to be accounted for. The ranges of lower bound LB_s and upper bound UB_s are the same for all the destinations, as well as the checking list L. These lower- and upper bounds, and the order list are described in appendix B.2.3.

Algorithm 3 Random algorithm

Output: Assignment storage location

$L \leftarrow$ Construct order of storage locations $s \in S$
for all products $p \in P$ **do**
  if SCC $1 = 1$ **then**
    assign product $p \in P$ to SCC 1 storage location $s \in S$
  else if SCC $2 = 1$ **then**
    assign product $p \in P$ to SCC 2 storage location $s \in S$
  Compute u
  if $LB_s < u \leq UB_s$ $s \in S \wedge \sum_{p \in P} I_{sp} < V_s$ $s \in S \wedge$ satisfies storage conditions **then**
    assign product $p \in P$ to storage location $s \in S$
  for all storage locations $s \in S$ in the order of list L **do**
    if $\sum_{p \in P} I_{sp} < V_s$ $s \in S \wedge$ satisfies storage conditions **then**
      assign product $p \in P$ to storage location $s \in S$

4.3.5 Closest open location from origin (CO)

Another storage assignment policy from literature is the closest open location. The first empty available location will be used to store the product. This results in full places around the depot and gradually more empty further away (De Koster et al., 2007). The policy is applied with the starting point from the suppliers. From the supplier, the closest warehouses will be checked in order. Let the set of origins be denoted with $o \in O$. The algorithm is shown in Algorithm 4. The order list of closest locations from the suppliers L_o is shown in appendix B.2.4.

Algorithm 4 Closest open location from origin algorithm

Output: Assignment storage location

for all origins $o \in O$ **do**
  $L_o \leftarrow$ Sort all storage locations $s \in S$ in increasing order based on Euclidean distance
  for all products $p \in P$ **do**
    if SCC $1 = 1$ **then**
      assign product $p \in P$ to SCC 1 storage location $s \in S$
    else if SCC $2 = 1$ **then**
      assign product $p \in P$ to SCC 2 storage location $s \in S$
    for all storage locations $s \in S$ in the order of list L_o **do**
      if $\sum_{p \in P} I_{sp} < V_s$ $s \in S \wedge$ satisfies storage conditions **then**
        assign product $p \in P$ to storage location $s \in S$

4.3.6 Closest open location from destination (CD)

The closest open location can also be defined from the destinations (see Algorithm 5). The list of closest locations from the destination is denoted with L_d. Appendix B.2.5 presents these lists.

Algorithm 5 Closest open location from destination algorithm

Output: Assignment storage location
```
for all destinations d ∈ D do
    L_d ← Sort all storage locations s ∈ S in increasing order based on Euclidean distance
    for all products p ∈ P do
        if SCC 1 = 1 then
            assign product p ∈ P to SCC 1 storage location s ∈ S
        else if SCC 2 = 1 then
            assign product p ∈ P to SCC 2 storage location s ∈ S
        for all storage locations s ∈ S in the order of list L_d do
            if Σ_{p∈P} I_sp < V_s s ∈ S ∧ satisfies storage conditions then
                assign product p ∈ P to storage location s ∈ S
```

4.3.7 Assignment on production route (PR)

The previous heuristics (Algorithms 2 till 5) showed that the destination or origin, storage conditions, and service in SCC are always taken into account in the assignment rules. There are two additional attributes that should be incorporated, which are the colour and the SKU type. These features are not applied in current practice. Furthermore, in the aforementioned algorithms the production route is in different approaches considered, while the storage conditions and need of service are applied in the same manner. This results in variations of three attributes in the next heuristics: the production route, colour, and SKU type. Since chapter 3 discussed the importance of including various attributes, a multi-criteria assignment is necessary. The process of selecting an alternative among a set of available alternatives with the involvement of numerous criteria in the selection, is referred to as multi-criteria decision-making (MCDM) (Rezaei, 2015). In this research, the alternatives are the assignment locations and the criteria are the product attributes. Through MCDM, an order list is retrieved per combination of attribute values. The scores are obtained through a questionnaire (see appendix E), which is filled in by decision-makers in the company. The production route is always considered in each heuristic. The heuristics formed by means of MCDM implement the following linear function:

$$f_s = \beta_1 A_{1s} + \beta_2 A_{2s} + \beta_3 A_{3s}$$

where f_s is the sum of scores for storage location $s \in S$, A_{1s} is the score on production route for storage location $s \in S$, A_{2s} is the score on colour for storage location $s \in S$, and A_{3s} is the score on SKU type for storage location $s \in S$. The betas $(\beta_1, \beta_2, \beta_3)$ are the respective weights of the attributes showing the importance. The following tests are implemented in the next sections: a test with only production route, a test with the production route and colour, a policy with production route and SKU type, and the combination of all the features.

The first rule set using the linear function is the assignment on the production route. This means that β_1 is 1, as only 1 attribute is considered, and β_2 and β_3 are 0. The resulting function is: $f_s = A_{1s}$. A list of storage locations is implemented per pair of origin and destination through the scores from the questionnaire in a decreasing order, which is denoted with L_{od}. Algorithm 6 shows the production route heuristic.

Algorithm 6 Production route algorithm

Output: Assignment storage location

for every pair of origin $o \in O$ and destination $d \in D$ **do**
  $L_{od} \leftarrow$ Compute function f_s and sort all storage locations $s \in S$ in decreasing order based on the value of function f_s
  for all products $p \in P$ **do**
    if SCC $1 = 1$ **then**
      assign product $p \in P$ to SCC 1 storage location $s \in S$
    else if SCC $2 = 1$ **then**
      assign product $p \in P$ to SCC 2 storage location $s \in S$
    for all storage locations $s \in S$ in the order of list L_{od} **do**
      if $\sum_{p \in P} I_{sp} < V_s$ $s \in S \wedge$ satisfies storage conditions **then**
        assign product $p \in P$ to storage location $s \in S$

4.3.8 Assignment on production route and colour (PRC)

A combination of the production route and colour is implemented with the following function: $f_s = 0.57A_{1s} + 0.43A_{2s}$. The SKU type is not taken into account for this scenario, thus β_3 is 0. Three respondents filled the weights in, and the model incorporates the mean. Per combination of production route and colour values, an order list of assignment storage locations is constructed that is denoted with L_{odc}. The first warehouse is checked on available capacity, and afterwards the next one on the list. If there is capacity in the warehouse and it satisfies the storage conditions, the product is assigned to this location. Let the set of colours be denoted with $c \in C$. The PRC algorithm is presented in algorithm 7.

Algorithm 7 Production route and colour algorithm

Output: Assignment storage location

for every pair of origin $o \in O$, destination $d \in D$ and colour $c \in C$ **do**
  $L_{odc} \leftarrow$ Compute function f_s and sort all storage locations $s \in S$ in decreasing order based on the value of function f_s
  for all products $p \in P$ **do**
    if SCC $1 = 1$ **then**
      assign product $p \in P$ to SCC 1 storage location $s \in S$
    else if SCC $2 = 1$ **then**
      assign product $p \in P$ to SCC 2 storage location $s \in S$
    for all storage locations $s \in S$ in the order of list L_{odc} **do**
      if $\sum_{p \in P} I_{sp} < V_s$ $s \in S \wedge$ satisfies storage conditions **then**
        assign product $p \in P$ to storage location $s \in S$

4.3.9 Assignment on production route and SKU type (PRST)

The production route and SKU type are examined with the function: $f_s = 0.7A_{1s} + 0.3A_{3s}$ (β_2 is 0). The same description holds for these tests as PRC, except that now the SKU type is used instead of the colour. A similar storage assignment policy is defined in the literature review, the class-based storage. Each class is assigned to a dedicated warehouse (De Koster et al., 2007). A list of storage locations per combination of origin, destination, and SKU type is implemented. Let the set of SKU types be denoted with $t \in T$. The PRST algorithm is presented in algorithm 8.

Algorithm 8 Production route and SKU type algorithm

Output: Assignment storage location

for every pair of origin $o \in O$, destination $d \in D$ and SKU type $t \in T$ **do**
  $L_{odt} \leftarrow$ Compute function f_s and sort all storage locations $s \in S$ in decreasing order based on the value of function f_s
  for all products $p \in P$ **do**
    if SCC $1 = 1$ **then**
      assign product $p \in P$ to SCC 1 storage location $s \in S$
    else if SCC $2 = 1$ **then**
      assign product $p \in P$ to SCC 2 storage location $s \in S$
    for all storage locations $s \in S$ in the order of list L_{odt} **do**
      if $\sum_{p \in P} I_{sp} < V_s \; s \in S \wedge$ satisfies storage conditions **then**
        assign product $p \in P$ to storage location $s \in S$

4.3.10 Assignment on production route, colour and SKU type (PRCSTa & PRCSTb)

All three of the attributes are combined in these algorithms. When there are three or more criteria, the importance of these criteria, or the weights, are derived from a MCDM method. There exist several methods for this purpose (Ishizaka and Nemery, 2013). The weights are derived using the BWM. In the BWM, the decision-maker identifies the best and worst important criteria. The decision-maker then determines the preference of the best criterion over all the other criteria, and the preference of all the criteria over the worst criterion. Afterwards, a model is run to determine the optimal weights of the criteria. This method is chosen, as it requires less comparison data compared to some other methods. It is also easy understandable and applicable to any case (Rezaei, 2015). The linear BWM provides a unique solution that is desirable in this research. The following linear programming problem is implemented to obtain the weights (Rezaei, 2016):

$$\min \xi^L$$

s.t.

$$|w_B \text{ - } a_{Bj} w_j| \leq \xi^L, \text{ for all } j$$

$$|w_j \text{ - } a_{jW} w_W| \leq \xi^L, \text{ for all } j$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{for all } j$$

where ξ^L is an indicator of the consistency of the comparisons, (w_1^*, w_2^*, ..., w_n^*) the optimal weights of n criteria, a_{Bj} the preference of the best criterion B over criterion j, and a_{jW} the preference of criterion j over the worst criterion W. The consistency indicator is a measure to show the reliability of the outcome of the BWM. The lower the consistency indicator, the more consistent the comparisons, thus the more reliable the results. A value lower than 0.25 has a very high consistency level (Rezaei, 2016).

The results of the BWM are shown in figure 4.7. Respondent 1 finds the colour more important than the production route, and respondents 2 and 3 agree on the higher importance of production route compared to the colour. All the respondents find the SKU type equally less important than the other two attributes. The average of these weights are considered. The resulting function for PRCSTa is: $f_s = 0.52A_{1s} + 0.42A_{2s} + 0.06A_{3s}$. Since there is consensus on the less importance of the SKU type, and different opinions on the production route and colour, PRCSTb considers the higher importance of colour compared to the production route. The function for PRCSTb is:

$f_s = 0.42A_{1s} + 0.52A_{2s} + 0.06A_{3s}$.

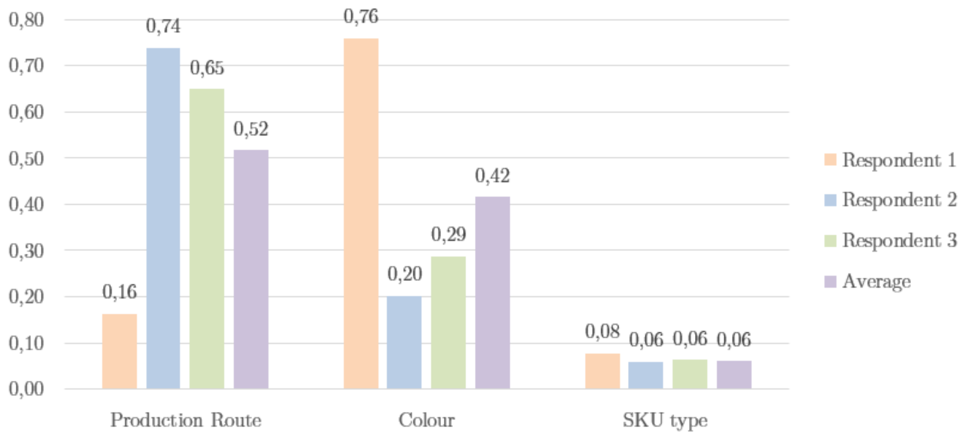

Figure 4.7: Weights of the criteria

The consistency indicators of each of the respondents, as well as the average over the three respondents, are depicted in table 4.4. The outcome indicates that the results are very reliable. Algorithm 9 presents the final algorithm. The algorithm is the same for both PRCST models except that the implemented lists are different. The list for all attributes is denoted with L_{odct}.

Table 4.4: Consistency indicators

	Respondent 1	Respondent 2	Respondent 3	*Average*
Consistency indicator	0.22	0.27	0.21	*0.23*

Algorithm 9 Production route, colour and SKU type algorithm

Output: Assignment storage location

for every pair of origin $o \in O$, destination $d \in D$, colour $c \in C$ and SKU type $t \in T$ **do**
  $L_{odct} \leftarrow$ Compute function f_s and sort all storage locations $s \in S$ in decreasing order based on the value of function f_s
  for all products $p \in P$ **do**
    if SCC 1 $= 1$ **then**
      assign product $p \in P$ to SCC 1 storage location $s \in S$
    else if SCC 2 $= 1$ **then**
      assign product $p \in P$ to SCC 2 storage location $s \in S$
    for all storage locations $s \in S$ in the order of list L_{odct} **do**
      if $\sum_{p \in P} I_{sp} < V_s$ $s \in S \wedge$ satisfies storage conditions **then**
        assign product $p \in P$ to storage location $s \in S$

4.4 Component 3: Pick-up module

The final module is the pick-up (see figure 4.8). The programming of the pick-up is in the company with a points system. The programme computes the solution daily with the most points. Some of the features that play a role are the colour, the storage location, and the product dimensions. Whether the product is picked-up depends on this points system and the factories further in the production chain. There is no room to improve these decisions. According to several interviewees (D.8 & D.9), if modification of the

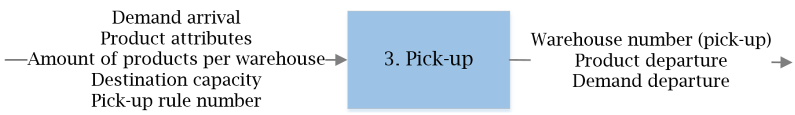

Figure 4.8: Pick-up module

pick-up is included, the model is too optimistic and far from reality. The pick-up module is fixed in order to exclusively determine the effect of different storage policies.

The process of picking starts with the arrival of a demand per type and destination. When the demand arrives to the system, the pick-up function is computed. The product attributes influencing the pick-up are the SKU type, the destination, and the assignment location. The demand and product are matched on the SKU type and the destination. A list of assignment locations is specified per demand point. In this order, the assignment locations are checked for a match (see table 4.5). When the assignment location is another warehouse than the destination hall, a product can only be released from the assignment location if there is still capacity at the destination. A pick-up rule number is selected and the product is released. At the pick-up location, the product and the demand are matched so that both of them are able to leave the system.

Table 4.5: Pick-up order per destination

	D1	**D2**	**D3**	**D4**	**D5**
1.	W4	W5	W6	W7	W8
2.	W1	W1	W1	W1	W1
3.	W9	W9	W9	W9	W9
4.	W5	W3	W7	W3	W7
5.	W3	W4	W3	W5	W3
6.	W7	W7	W5	W8	W5
7.	W6	W6	W4	W6	W6
8.	W8	W8	W8	W4	W4

4.5 Conclusion methodology

A simulation model is built to represent a simplification of the system under study. It consists of three components: the arrival, assignment, and pick-up. After arrival of the product, it is send to one of the supplier warehouses. Then, the assignment module is computed using one of the algorithms to determine the assignment storage location. An arrival of the demand request results in the computation of the pick-up, where one of the products from the assignment locations is released to the destination. The product and demand request are matched on SKU type and destination in order to leave the system. Various assignment policies are implemented. Some of them are constructed based on interviews, others are existing policies from literature, and the main assignment policies are implemented using MCDM. There are multiple attributes, hence, a multi-criteria assignment is necessary. The production route, need of service, and storage conditions are always considered, although the approach for production route can differ. The implementation of these attributes with the colour and SKU type results in the application of BWM to derive the importance of each of these attributes. The scores on the attributes are obtained through a questionnaire. The sum of these scores is then computed dependent on the considered attributes in the algorithm, and afterwards a list of assignment locations is constructed per combination of attribute values. These lists are implemented in the simulation model.

5 Results

This chapter describes the results of the current situation, the assignment policies, and the disruption. Various heuristics are evaluated on the performance measures with especially a focus on the important products. The main message from the results is that incorporating the production route, colour, and possibly the SKU type results in a higher overall performance of the system on the objectives, but also on the critical and prioritised categories (black, red, and eventually in combination with A-Runner and A-Repeater). Thus, considering the delivery windows of the products for the storage assignment show better outcomes than the current practice, which excludes the due dates of the products in the assignment. Figure 5.1 presents a flow diagram with the main messages from the various subsections that will be discussed in this chapter. The final section, section 5.5, presents the conclusion of the results. The points related to the main message are examined in the main text, and detailed outcomes are presented in appendix C.

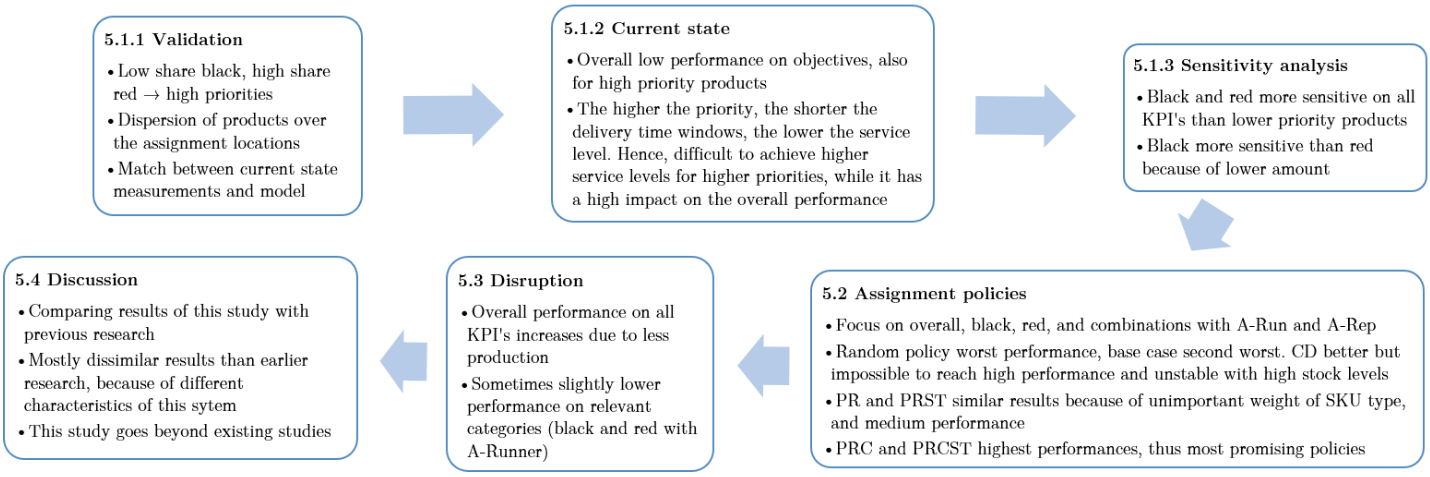

Figure 5.1: Main messages of the results

Before discussing the various subsections, the data will be described that is used in the model implementation. This study contains qualitative and quantitative data. The qualitative data are:

- **Internal documents**
- **Interviews**: the transcripts can be found in appendix D
- **Questionnaire**: three respondents filled in the survey that is shown in appendix E

The quantitative data, which are either real or simulated, are:

- **Order book**: the file is retrieved for entire 2017. It contains data on ±15.000 SKUs with information on the orders per week per SKU type and per supplying facility.
- **Production and demand patterns**: besides one production pattern, all the other production patterns and all the demand patterns are simulated data.
- **Snapshots of inventory files**: it consists of snapshots of the inventory at 25th of May, 2018 and 12th of July, 2018 with characteristics of the inventory.
- **Inventory over time**: one of the interviewee performed an analysis on the storage time where the inventory over four weeks, 21st of May, 2018 until 17th of June, 2018, is considered.
- **Warehouse capacities**: this file contains the capacities of all the storage locations.

Important to mention is that the quantitative data collected do not represent the historic data on the same product. There is a mismatch on product level. Several files are retrieved and combined. This forms a limitation on the data of this research. There are also no data available on the KPI's. Details of the implementation of the data are described in appendix C.1.

5.1 Value of the current situation

This section describes the outcomes of the current situation. The current state is developed using the base case algorithm (see algorithm 2) and the first input file of the production and demand patterns. Section 5.1.1 presents the output of the validation process. This process consists of comparing the current state measurements in section 3.2.4 with the results of the model. Afterwards, the current state results on the performance indicators are discussed in section 5.1.2. Finally, section 5.1.3 gives the results on the sensitivity analysis, performed on the service in SCC 1 & SCC 2, and the colour. Detailed outcomes of the current situation are shown in appendix C.2.

5.1.1 Validation

Verification and validation of the model are necessary. The verification process is presented in appendix C.2.1. According to Law and Kelton (2000), validation is defined as *determining whether the conceptual simulation model (as opposed to the computer program) is an accurate representation of the system under study.* There exist no 100% proof for validation (Duinkerken, 2016). The base case assignment rules are constructed from several interviews (D.6 & D.8), and are aligned with the current state measurements in section 3.2.4. These measures show the composition of the colours per destination, and the dispersion of the colours over the storage locations per destination. It should be noted that this is a snapshot of the inventory at a certain day, hence, it does not incorporate the locations over time. The validation process consists of comparing the current state measurements (section 3.2.4) with the output of the base case model run. The outcomes suggest that there are slightly differences, since the base case rules also follow the results from the interviews. However, these small variations are acceptable. The results will be presented in the remaining of this section. The average storage time in the current state and model is also tested, which are quite similar. The detailed output of the average storage time per destination is shown in appendix C.2.2.

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In conclusion, it is confirmed that the model is able to represent the system under study with the specified input. The small differences with the current state and the simplification will create a gap between the model and the current practice. Nevertheless, these are acceptable within the scope and purpose of this research. Furthermore, it is important to take the red goods into consideration next to the black ones, especially because of the large amount within the system, the high priority, and the dispersion of these high priority goods over the storage locations.

5.1.2 Current state results

This section presents the results of the base case model run. As mentioned earlier in section 4.3.3, the current state rules are constructed from interviews and the current state measurements. The corresponding algorithm shows that the assignment locations per destination contain a range of the random draw. When the random draw is within the range of a specific assignment location, and this location has remaining capacity, the product is assigned to this warehouse. Note that it is not a random assignment. For example, when the assignment of D3 products is 95% of the time to the destination, this also forms a rule in the model. The results show the output of the performance indicators per colour. The performance measures are the number of handling, the storage time, and the due date met. This section shows that there is room for improvement in the current performance, especially on the high priority products (black and red), as these categories are performing poor. More outcomes of the model are described in appendix C.2.3.

KPI 1: Handling
The service products are excluded for the analysis on the handling, since the minimum and extra handling for these goods are the same, and thus the handling on service products cannot be improved. *Numbers have been excluded.* Next to reducing the number of extra handling, the preferred situation is to especially prevent extra handling for black and red labelled products instead of green or blue ones. Notice that particularly the red products have much extra handling, probably because of the large amount in the system.

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KPI 2: Storage time
The second KPI is the storage time. For the storage time and the due date met, the output of the products generated in the warm-up period of ten days is not considered, as these can influence the KPI's. The initialisation phase does not affect the number of handling. *Numbers have been excluded.* Black and red products also occur in the higher ranges of storage time. The idea is to reduce the storage time especially for these goods with shorter delivery time windows.

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KPI 3: Due date
The final performance measure consists of if the due date is met. *Numbers have been excluded.* The higher the priority, the smaller the delivery time window, and the lower the percentage of meeting the due date. This suggests that the service level is always higher for green or blue than for black or red. *Numbers have been excluded.* These two attributes are related: a higher storage time results in a lower due date met. This also makes sense since the pick-up does not consider the delivery time windows of products. The simplification of the pick-up affects the storage time and the due date, which results in lower performance on these KPI's.

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5.1.3 Sensitivity analysis

According to Sargent (2009), sensitivity analysis consists of *changing the values of input of a model to determine the effect upon the model's behaviour or output. (...) Those parameters that* *are sensitive, i.e., cause significant changes in the model's behaviour or output, should be made sufficiently accurate prior to using the model.* Interesting attributes for the tests are the service and the colour. In reality, these values are relatively dynamic. Furthermore, both attributes have a significant impact on the KPI's. If there are for example more products with a service treatment, more goods have to be assigned to the SCC, and therefore limiting the "room" for assignment decisions. Two tests on each attribute are performed. Service test 1 has -5% service in all the installations and test 2 +5%. The first test of colour has -2% of black and red labelled goods, while +2% of green and blue goods. The second test has +4/5% of black and red goods, and -4/5% of green and blue goods. The effect of slightly increases or decreases on the performance measures is checked with these tests. The outcomes of the service tests are presented in appendix C.2.4, and the results on the colours are shown below.

Numbers have been excluded. Black products in test 1 operate with a higher percentage with the extra number of handling in comparison to test 2. Regarding red goods, the difference between both tests is less. This means that black goods are more sensitive than red goods as the number of blacks is relatively limited in comparison to the red products.

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The overall average storage time is the same in both sensitivity tests, while on colour level there are to a certain extent some differences. When there are more black and red goods, the average storage days of black decreases and red increases. On the other hand, when there are more green and blue goods in the system, the average storage days of green or blue decreases. The base case has a better performance on black and red products, although the performance on the other colours is less.

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Numbers have been excluded. This means that when there are less black and red goods, a higher percentage of the due date is met. However, when there are more red and black products, also a higher percentage of the due date is met compared to the base case. If there are more black or red products (test 2) than the number of goods that do not meet the due date increases. In addition, slightly modifications in the number of green and blue has no impact on the due date.

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In conclusion, according to the current state results, there is room for improvement on the KPI's. Especially favouring the high priority products (black and red) is important in the assignment policies. These products are crucial as they have a high priority, but also because of the lower performance of these priorities in comparison to the others, and the huge amount of red products in the system. The lower performance occurs due to the smaller delivery time windows compared to the lower priority products. Although, less improvements can be achieved on the storage time and due date if the pick-up rules cannot be optimised. The rule sets are constructed with interviews and some data. This showed in the validation and results somehow a reasonable mismatch between the current state and the model. The sensitivity analysis on the colour also described that the model is sensitive to particularly the high priority products. This means that considering the colour has potential to improve the performance. Important to mention is that the data is a snapshot taken at a particular time; this is not an accurate representation. Therefore, it is important to test various assignment rule sets, which will be described in the next section.

5.2 Value of the assignment policies

The previous section showed that the current state can be improved on especially the high priority products with a short delivery time window, which are the black and red goods. Note that these categories of due dates are not equal in numbers. The composition differs per destination, but it can be generally stated that the share of black products is very low and red products quite high. There is a lot of extra handling for all the products. The due date met is particularly low for the black and red goods. Therefore, achieving improvements on the important products is relevant. This section describes the results from the assignment policies. Table 5.1 presents an overview of all the heuristics, as explained in section 4.3. All the assignment policies except SCC 1 and Cap run for five different input files of production and demand. This section shows a summary of the results. The following outcomes are discussed: the bounds on the handling, the best and average cases, the point estimates, and the monetary value of the handling. The last three results are only presented on the overall value of the system, and on the important categories (black and red with A-Runner and A-Repeater). The extensive results are shown in appendix C.3. The outcomes for SCC 1 are excluded in the main text, as this policy does not consider a different algorithm.

A dummy warehouse is included in the model in case there is no place in any of the warehouses. Since the warehouses have limited capacities, some scenarios result in the use of the dummy warehouse. The assignment rules of these scenarios result in a situation that goods cannot be stored in one of the warehouses. There are two options: 1) from a certain time step, almost all the products are assigned to the dummy warehouse, or 2) at some time steps a couple of products are assigned to the dummy warehouse after which the system recovers. The first case is a problem, however, the second case is acceptable if there are not a lot of items assigned to the dummy warehouse. The first case applies on scenarios Cap, CO 1-5, and CD2. These scenarios have to be excluded from the analysis, as it cannot store goods from a certain time step. The second case has more scenarios: BC3, R3, PR2-4, PRC2 & 3, PRST3, and PRCST1a. These scenarios only assign some items to the dummy warehouse and are therefore included in the analysis.

Table 5.1: Overview of heuristics

	Description
SCC 1	• Resting of service products for SCC 1 in W3
Cap	• Lower maximum capacity
BC	• Current state rules
R	• Random
CO	• Closest open location from origin
CD	• Closest open location from destination
PR	• List of assignment locations per pair of origin and destination
PRC	• Combination of the criteria production route and colour • List of assignment locations per pair of origin, destination, and colour • Weights are PR: 0.57, C: 0.43
PRST	• Combination of the criteria production route and SKU type • List of assignment locations per pair of origin, destination, and SKU type • Weights are PR: 0.7, ST: 0.3
PRCSTa	• Combination of the criteria production route, colour and SKU type • List of assignment locations per pair of origin, destination, colour, and SKU type • Implementation of BWM, PR: 0.52, C: 0.42, ST: 0.06
PRCSTb	• Combination of the criteria production route, colour and SKU type • List of assignment locations per pair of origin, destination, colour, and SKU type • Implementation of BWM, PR: 0.42, C: 0.52, ST: 0.06

Bounds on number of handling

The main performance measure is the number of handling. Each model run has a different throughput of goods. This means that the number of handling or extra handling are not reliable measures to compare the runs. To provide a comparable measure, for each scenario the minimum, maximum, and extra possible handling (maximum - minimum) is determined. The number of extra handling is measured as a percentage of the extra possible handling for that run, see the formula below. Moreover, the service products are excluded as these do not have any extra handling.

$$\%ExtraHandling = \frac{(Handling - Minimum)}{(Maximum - Minimum)}100\% = \frac{Extra}{ExtraPossible}100\%$$

Figure *has been removed* shows the minimum (blue), extra (green), and maximum (grey) for each model run. When comparing the formula and the figure, the indicator is measured as green over the sum of green and grey. The random models have the highest share of extra handling, and the current state model the second highest. Though the CD has almost the same results for every input file, the second input file had to be excluded. As the figure depicts, the second input file has the worst performance in each rule set. The reason is that this file has the highest inventory levels; four destination warehouses are most of the time full. Besides this input file, PRC and PRCST are performing the best. Appendix C.3 presents the absolute values of the handling and extra handling, which shows a similar outcome in colouring as the values in percentages.

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Best-average cases for all models and KPI's

The average cases depict the relatively poor performances of the random and current state models on all the KPI's: the other policies incorporate more green cells in comparison to these two. The performance of CD is well, however, the second input file had to be excluded, as it resulted in an unstable system. This input file is incorporated in the other models, which deteriorates the average performance. The PR - PRCST models have a high share of green cells or positive impacts. *Numbers have been removed.*

When considering the best cases, also in the best case are the random and current state policies performing low. The best case represents the highest performance per KPI over the five input files. Thus, it is possible that the best case for KPI 1 is for example the first input file, while for KPI 2 the highest performance is achieved with the second input file. The idea is to show the highest performance that can be accomplished considering the five input files. The CD and PR assignments result in the least best cases, the number of green cells is approximately none. Moreover, the PRST has slightly more higher performances achieved, although, it is still less in comparison to the PRC, PRCSTa, and PRCSTb. These three assignment policies have the highest share of green cells. The performance is high on the important categories such as the black and red products, but also on the overall value where the other colours and SKU types are taken into account. The differences between these three models are to a low extent. However, when the "best" performance of a model has to be picked, it will be PRCSTa, as it has the highest share of green cells. On the second place is the PRC, and the third place the PRCSTb. Appendix C.3 presents the detailed outcomes of the model including for example the worst cases, the values of the other categories, and the values per SKU type.

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Point estimates for all models and all KPI's

The table depicts some dispersion of coloured cells. Similar to the previous table, the performance of the random assignment is the lowest and the base case model the second lowest. The other assignment policies incorporate more green cells. This table is particularly presented to describe the relationships between the performance indicators. The outcomes show that in case of a lower average storage time, a higher percentage of the due date is met. Meeting a higher due date means that the time of the products stored in the system is less. The higher the inventory levels, which is related to the second input file, the more extra handling, but the better the performance on the storage time and the due date. In the models PR - PRCSTb, the outcome of the second file has a low average storage time and a high percentage of the due date met. This can be reasoned as follows. When there are more products in the system, the top 3 of the assignment and pick-up warehouses (destination, supplier, and service in SCC 1) are almost always full. This results in products being more assigned and picked-up from these locations instead of the other intermediate warehouses, which are lower on the pick-up list. There is less need of picking from the warehouses that are not preferred. However, this output is not true for the current state and the random polices as these incorporate random components.

On the other side, the least extra handling in the criteria models, which is related to the third, fourth, and fifth input files, does not result in the best performance on the storage time and due date. This is because of two reasons. First of all, the performance on the green and blue goods in these cases are less compared to the other files, as the lower priority products are more send to intermediate warehouses. When products are send to intermediate locations, it takes more time to pick them up due to the lower position on the pick-up order list. This suggests that lower positions are only checked when all the locations on higher positions do not have a matching product, and this in turn affects the storage time and due date. Although, the differences are not that high since the green and blue products have a wide delivery window. What is more, the stock levels in these files are lower and as a consequence it takes more time to pick-up. The simulation model works with discrete times, and it releases multiple products at a discrete time step. If there are less products in the system, there are less products released at a certain time step, which results in more time needed to pick the products in order to fulfil the demand. The first input file has medium stock levels compared to the other files, and the output shows that the performance is also located in between. Therefore, the inventory levels have a high impact on the performance of the system. Another observation from the point estimates is that the performance of black or red products in combination with A-Runner results in low performance on especially the third and fourth input files. The reason for this outcome is that the share of black and A-Runner or red and A-Runner on the total products is very low, *Numbers have been removed.* Overall, it can be concluded that particularly the models using the criteria production route and colour, and possibly the SKU type incorporate the highest achievements in the performance measures. Appendix C.3 presents the detailed results of the point estimates for the other colours and all the SKU types.

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Monetary values of handling
The results are visualised for the same categories as in the previous tables. It shows the average costs of handling in the base case, and the average savings or losses in the other models compared to the current state value. The same holds for the best performance. Also for this table, the average is the average value over the five runs and the best case is the highest performance over the five runs per policy. *Numbers have been removed.*

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In conclusion, the random policy has the lowest performance on all the KPI's. The base case model has a slightly better performance, though it is still worse compared to the other policies. The CD policy has a stable performance. Furthermore, the performance is high on storage time and due date, but it results in an unstable assignment process in case of high stock levels. The production and demand patterns have a high impact on the performance of the system. For instance, higher inventory levels result in the best improvements achieved on the storage time and due date. The outcomes also suggest that there are relationships between the objectives: a lower average storage time and a higher due date met go hand in hand. The best performances on the overall system as well as on the important classes (black and red with A-Runner and A-Repeater) are achieved in the PRC and PRCST policies. Therefore, these form the most promising assignment policies within this context. These policies assign the high priority colours to the destination, while the blue and green are allocated to intermediate locations except if the destination often does not have capacity limitations. A second option for black and red products in case the destination is full, is to temporary stay at the supplier until there is place at the destination. Moreover, important classes in combination with high priorities should always be allocated to the destination.

5.3 Value of the disruption

Section 3.2.4 discussed the occurrence of disturbances in the current storage assignment. One of the crucial disruptions is the failure of S1, which is the critical factory on the site. Keeping this in mind, it is interesting to test the robustness of the system when a disturbance occurs in the production. One model is tested with disruptions in the production of a specific input file. PRCST2a is selected for this purpose, as the performance of this model and the corresponding input file is relatively high. However, the performance is poor on the number of handling because of the higher inventory levels. This was also shown with other rule sets and the same input file. The closest open location from destination even had to be excluded. PRCSTa is the model with the combination of all the criteria, using the weights for production route (0.52), colour (0.42), and SKU type (0.06). Since some of the input files already incorporate stochastic demand, only the production has been modified in the second input file to test the impact on the performance measures. Over the entire run length of 180 days, 14 days have disturbances in the production process. A uniform distribution in the interval 0 - 180 has been used to extract 14 draws for the days, these days are: 5, 15, 35, 48, 50, 57, 58, 85, 115, 116, 157, 162, 171, and 175. In these days, sometimes the production facilities are completely down (production is 0) or part of the day (production is lower). In some cases, the production is partly added to the next day.

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Performance on handling - PRCST2a versus disturbance

The effect on the KPI's are next examined. In the results of the disruptions, all the colours and SKU types are presented, although, only the important classes of the combinations are depicted. *Numbers have been removed.* All categories have a decrease as less goods are generated that in turn results in more space for the generated items at the destination. Particularly the reduction of important goods (black, red, A-Runner, A-Repeater, and the combinations) occurs, which is desirable. *Numbers have been removed.*

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Performance on storage time - PRCST2a versus disturbance

The average storage days on all the products is decreased with more than one day. Nevertheless, not all categories in this figure have a reduction. The less relevant SKU types, which are B-Repeater, B-Stranger, and C-Stranger, have a worse performance compared to PRCST2a. The disturbances have a high impact on the performance of B-Repeaters. *Numbers have been removed.*

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Performance on due date - PRCST2a versus disturbance

Numbers have been removed. Similar to the impact on the storage time, not all the categories have a higher performance on the due date met. The relevant groups with a reduction are the A-Runners, and black and red with A-Runner. *Numbers have been removed.*

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In conclusion, while the production is lower with disturbances, the completed demand is reduced with a lower magnitude. In addition, having disruptions in the PRCST2a model results in a much better performance on the handling in absolute and monetary values. The overall performance of the system on the storage time and due date is improved. On attribute level, some attribute values result in a worse performance on these KPI's. However, sometimes these classes are relatively unimportant such as the B-Stranger or C-Stranger. *Numbers have been removed.* Also important categories, for instance black or red with A-Runner, have to a certain extent a lower performance. Although the share of these categories in the system is low, these are crucial combinations of attribute values. The overall performance of the system is improved.

5.4 Discussion

Two types of random policies are implemented. The first one is the current state model that incorporates partly a random component. The division is mainly to the destination, though products are also randomly assigned to other warehouses with a lower probability. The second set is the randomised model that is completely random. The results on these model runs indicate that the random model has the worst performance, and the base model second-worst. In the light of previous research, Ong and Joseph (2014) claim that random storage maximises the utilisation of storage space. Although random assignment generates unnecessary travel distances (Pan et al., 2012). This is supported with the results: the inventory levels are higher in the warehouses and more handling (thus higher travel distances) is required in the random runs. However, earlier research focuses on warehousing within a single warehouse. This study incorporates multiple warehouses dispersed over an area. In this situation, a randomised allocation is not desirable, as the pick-up and drop-off points and destinations are spread out over the site and as a consequence the inventory levels in the halls are irrelevant high. The study by Chan and Chan (2011) on storage assignment policies shows that random only has a little bit worse performance. Nonetheless, the authors also suggest that the performance of random storage is dependent on the characteristics of the warehouse. Their results are in contrast with this research, as the random model has the worst performance. The network in this system ensures in the deterioration of the random algorithm.

Two other policies tested are the closest open location from origin (CO) or from destination (CD). The closest open location is to a lower extent analysed in the current literature. De Koster et al. (2007) argue that the random storage and closest open location storage have a similar performance. The results in this research have contradicting outcomes. CO leads to an unstable system with all the input files, thus this storage assignment policy does not fit to the characteristics of the system. CD does result in a high performance on the storage time and due date met, while the number of handling has a medium performance. This is true because the destinations are fully utilised, but when there is no place, the closest location is checked that creates more handling. Nevertheless, in case the inventory levels are higher (input file 2), which also applies on the current practice of the company, this storage policy results in an unstable system as well. It should be noted that CD does deviate from the concept of this storage policy in literature. The first empty location is checked when products arrive from the supplier side and not from the demand. The PR model is similar to the CD except that now an order list of assignment locations are checked dependent on the production route. The output is as expected: compared to the CD, the handling in PR is lower and the other two KPI's have comparable outcomes.

Another implemented assignment policy is the class-based storage. Previous research has applied class-based storage (Petersen et al., 2004; Fontana and Nepomuceno, 2017). The class-based models are PRST, PRCSTa, and PRCSTb. The general outcome is that the class-based policies have a better performance over random policies, which is supported in earlier research (Jaikumar and Solomon, 1990). Research of Mirabelli et al. (2015) with ABC analysis, class-based storage, and the objective of handling costs have shown that all the class-based cases have a better performance than the current situation. The findings of this study have similar outcomes. Thus, the class-based assignment is a promising policy. Their research incorporated sub-classes in the ABC-classification, likewise within this study with the repeating profile. Other storage assignment studies with sub-classes in the ABC-classification are still lacking. The literature analysis also mentioned the discussion in earlier research on the service level for the different ABC classes. In this study, class A products are favoured instead of class C. Favouring class A results in more improvements due to more production of this category. Moreover, traditionally a warehouse is divided in three areas corresponding to the classes (Li et al., 2016), although here the areas are covered over multiple warehouses. This research goes beyond the existing literature, as it focuses on certain sub-classes with specific product attribute (e.g. colour). For instance the production route and colour model has the highest performance with the PRCST assignment policy.

5.5 Conclusion results

This chapter examined the current state results, the values of the heuristics, the impact of disruptions in the system, and the comparison between the outcomes of this study and of previous research. The results showed that the overall performance of the current situation on all the KPI's (handling, storage time, and due date) is lacking. There is particularly room for improvement on the performance of the high priority products, which are the black and red products due to the lower service levels of these colours compared to the others. Higher priorities have shorter delivery time windows that makes them difficult to improve. It is interesting to, next to the overall performance of the system, especially aim to improve the performance of these products, because of three reasons: 1) the low performance on these highly relevant categories, 2) the high amount of red products in the system, and 3) the sensitivity of the system's performance on these groups.

Section 5.2 presented the main output of the evaluation of several heuristics. Most of the heuristics are run for five various input files of production and demand. The results indicated that the random policy has the lowest performance on all the KPI's, and the current state model the second lowest. The CD algorithm has stable results under the different files, but does not reach very high performances compared to some other heuristics. Furthermore, in case of high stock levels, the CD policy leads to an unstable assignment process. The PR and PRST have similar outcomes due to the low importance of SKU type in comparison to the production route. The performance of PRST is slightly higher than PR, but still not achieving the highest improvements. The performance of PRC and the PRCST models is the best on the overall system, and also on the important categories (black and red, and in combination with A-Runner and A-Repeater). Therefore, assigning according to the due dates, and eventually the SKU type have promising outcomes in this case study. The main rule is to allocate these high priority products directly to the destination, and lower priorities to intermediate warehouses unless there are mostly no capacity limits at the destination. If the destination is full, a temporary storage at the supplier for high priority goods is an alternative. Furthermore, important classes (A-Runner and A-Repeater) with high priority should always be assigned to the destination.

Many disruptions occur in current practice. The performance of the PRCST2a model is tested where disturbances in the production are taken into account. The output is presented as differences between the PRCST2a run and the model with disturbances. The values show that lower inventories result in a reduction in completed demand, although, with a lower magnitude. The overall performance of the system is improved. On attribute level, some categories have a lower performance. However, these are either classes with less importance or with low shares on the total amount of products. It can be concluded that the best heuristic, PRCST2a, even has a very high performance with disruptions in the production process. The discussion shows that mostly the outcomes here are different compared to previous research due to the uncommon characteristics of the system, or that earlier studies did not test the algorithms related to this research.

6 Conclusion

6.1 Managerial implications

The findings of this research have important managerial implications. Different heuristics have been implemented for the various (semi-)finished goods among multiple plants and warehouses, also incorporating several production and demand patterns. This is a scientific novelty with high practical relevance. From the perspective of a sales manager, effective warehousing can increase the customer satisfaction by reduction in the order fulfilment time. Regarding the warehouse manager, improvements in warehousing reduces the warehousing costs (e.g. labour costs, equipment costs) with less handling required. If products-oriented rules are implemented for the storage assignment, the risk is lower that goods are put somewhere and not retrieved for a long period of time. Goods with high storage time could be prevented. When multiple factories and plants are involved, transportation plays a role. From the perspective of a transportation manager, correct planning of product allocations will in turn lower the transportation movements and the respective costs. Moreover, the supply chain managers get better insights on which products to plan in what amount along the chain. In addition, successful implementation of storage assignment decisions indirectly influences procurement decisions. Better warehousing will probably require less material as the production could be better aligned with the inventory.

Warehouse and supply chain planner managers have to decide on the location of the SKUs, where to collect the products from to fulfil the demand, but also how much space to assign to each class. Furthermore, replenishment strategies need to be decided on with a focus on a higher reliability of the inventory. These decisions are quite complex with a crucial effect on the performance of the system, which is highly affected by the product characteristics (Chan and Chan, 2011). The random storage is easier to implement than the other models, because it does not require knowledge on the product features. In the current state, information is needed on the destination. Though, class-based storage and other policies considering the product features result in much better performance. The implementation of the MCDM ensures that the opinions of decision-makers are easily taken into account. Thus, the combination of the engineering method simulation and the perspectives of the managers with MCDM is an useful approach.

6.2 Conclusion

Several sub-questions are identified to address the main research question sequentially. The sub-questions will be first addressed, and then the answer to the main research question will be provided. As presented in chapter 1, there are six sub-questions. The first four questions will be answered in this section. Sub-questions 5 and 6 are discussed in the next section, as these are regarding the recommendations of this study.

Sub-question 1: *What are the characteristics of the system?*
The steel production is a complicated process with the involvement of many factories and warehouses with various production lines of large products. There are two supplier factories, five demand locations (two end-users and three plants), and two factories to offer a service in between. Each factory has a dedicated warehouse, which forms the origin or destination location. These halls can also function as intermediate warehouses for other products. Furthermore, there is one additional independent warehouse. The storage locations differ in features, such as the capacity and the type of product that could be stored. The large products also have specific features, which are the production route, need of service, the storage conditions, colour, and SKU type. The production is a pull system, hence, each product is assigned the destination a priori. The storage conditions of the products should be matched with the characteristics of the halls. The colour of the products need to be considered, as this defines the urgency or due date.

Sub-question 2: *How can the current state of assignment be measured?*

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Sub-question 3: *How to categorise the (semi-)finished products into classes?*
The products need to be categorised, as it is difficult to form separate rules for thousands of different goods. For this purpose, the ABC classification in combination with the repeating profile is applied. The ABC classification is based on the annual consumption in tons. The repeating profile indicates the demand pattern. Combining these two leads to six classes. By assigning SKUs to these classes, rules per class can be provided dependent on the specified service levels. The idea is to favour class A items with a Runner or Repeater demand pattern.

Sub-question 4: *Which set(s) of assignment policies should be applied on warehousing?*
Several assignment policies are tested: BC, R, CO, CD, PR, PRC, PRST, PRCSTa, and PRCSTb. The last two models differ in the weights used for production route and colour; the weights are switched between model A and model B. The findings indicate that the random model has the least performance on extra handling, storage time, and due date. The current state has slightly better results. Thus, the use of models with randomised aspects leads to worse performance. CO results in a situation of an unstable system for all input files, which means that this policy cannot be applied. CD has a high performance on the storage time and due date met, but has lower performance on handling in comparison to the criteria models. The results are stable among the runs, although this policy will probably not work with high stock levels, as the second input file provided an unstable assignment process.

The remaining sets incorporate the criteria production route, colour and/or SKU type. When the SKU type is included, it can be seen as an modification of the class-based storage policy. In general, all of these policies have better outcomes than the current state. The PR model does not take the colour into account, and is therefore not reaching high performances on the prioritised products. PRST has slightly better results compared to PR, as it also incorporates the SKU type. However, the importance of SKU type (0.3) is lower than Production Route (0.7), and the outcomes of PRST are therefore not much improved. Following this line of reasoning, PRC, PRCSTa and PRCSTb have comparable results. The outcome of the BWM shows the relatively unimportant SKU type compared to the other two features. When the high priority products need to be favoured above the less relevant, the aforementioned three models provide a good solution. The black and red products have better results on all performance measures in case of PRC or PRCST than PR or PRST. Another interesting finding to point out is the implementation of the various runs under different production and demand patterns. The second input file has high inventory levels. This excessive stock results in more extra handling, however, the storage time is lower and a higher percentage of due date is met. When the inventory levels are high, the PRCST appears to have the best outcomes for the storage time and due date met. When disturbances occur in the production process, the PRCST reaches even a higher performance.

Main research question: *How should the various (semi-)finished goods among multiple locations (plants or end-users) in the production chain be allocated to the warehouses such that the number of handling are taken into account?*

This research takes multiple warehouses, plants and end-users as an example to improve the performance of storage assignment by performing 48 experiments on different sets of assignment policies under various production and demand. Both semi-finished and finished products are incorporated. The case study is Tata Steel IJmuiden. The performance of storage assignment is measured in terms of the number of handling being the main indicator, the storage time, and meeting the due date. The fixed attributes for all the sets are the production route, the storage conditions, and the requirement of a service treatment. The other attributes that are tested and varied between the multi-criteria sets are the colour priority and the SKU type. By simulation with SimEvents and implementation of MCDM for the criteria, the results show that the different sets of assignment rules have various outcomes on the three performance indicators.

Although the performance is dependent on the system characteristics, there are some interesting learning points. At first it is important to define the relevant due dates categories and SKU types. In this case, the urgent products with a due date in a short period are defined as black and red labelled goods. The important SKU types are the A-Runner and A-Repeater. The crucial assignment rule is to allocate all the goods with a due date in a short time to the destination unless the service or storage condition does not make it possible. Class A has slightly a higher priority than for example class C. Particularly the combination of a high priority and important class should always be directly assigned to the destination. However, when a C product leaves the supplying plant with a high urgency, the priority could be higher for this specific product if the A product has a long time window to be delivered. The capacity of the destination and the amount of inventory with the corresponding destination determines whether all the stock can directly be assigned. For instance when there is a destination with almost always having place, all the goods should be allocated directly. A distinction can be further made that if the destination is full, a high priority product remains for a while at the supplier until there is a spot free at the destination, instead that the product is for a short period of time assigned to an intermediate location. This means that the high priority products should always be allocated to the second-best location over the low priority ones. Thus, the composition of the product features and the list of assignment locations differ in each of the cases. Goods that are not required in a short period, which have a wide delivery window, should be assigned to an intermediate warehouse except when there is (almost) always capacity at the destination. If this particular product is a frequently ordered product, it should be earlier allocated to the destination than a rarely requested good.

6.3 Scientific and practical contributions

6.3.1 Scientific contributions

The huge scientific contribution is that this research considers an integrated approach of both the literature fields and the methodologies. The four streams of literature are: storage assignment, ABC classification, routing problems, and cross-docking. Several concepts are retrieved and put together from these disciplines (see figure 2.3). Some of these concepts are:

- **Storage assignment**: warehousing, storage assignment, picking, large products, handling, assignment policies
- **ABC classification**: assignment with traditional ABC-method, higher service level class A
- **Routing problems**: synchronising several aspects, involved network of multiple plants, warehouses, and end-users
- **Cross-docking**: synchronising several aspects, reduction of double handling, direct and indirect shipments

The integrated approach of the methods consists of simulation with the implementation of several heuristics, ABC classification, and MCDM with application of the BWM. A simulation model is built to represent a simplification of the system under study. Simulation is a useful method to easily implement several heuristics and evaluate these policies on the performance indicators. These rules are constructed per combination of attributes. For this purpose, the ABC classification is performed to provide different service levels for the products. The application of MCDM ensures that the preferences of relevant decision-makers are taken into account in forming the rule sets. Therefore, the combination of the various methods is a promising way for this topic.

The results in this study also contributed to the scientific field. The system characteristics have a significant influence on the performance of the assignment policies, such as the network and the dedication of the warehouses. Other important factors with an effect on the outcomes are the inventory levels, the production and demand with their attributes, the specification and order of pick-up locations, and the definition of high priority products and important classes. Moreover, the KPI's are related: the lower the average storage time, the higher the due date met. However, less handling does not result in better performance on the other two indicators due to the specification of the pick-up. The outcomes showed that some rule sets cannot be applied in this type of system with respective features, which was also highly influenced by the inventory levels. Randomness in policies result in much worse performance in this particular system. Moreover, the degree of randomness is of influence, which is concluded on the performance of the random model versus the current state. Nonetheless, previous research stated the wide applicability of this policy due do the easiness and only slightly lower performance. The highest performances are achieved considering the due dates and SKU types of the products. The improvements are accomplished on the overall system, but also on the high priority products and relevant classes. Neglecting the SKU type also results in a high performance, however, the positive outcomes are a bit less. Therefore, considering the product features as the due dates and SKU type next to the fixed attributes, is a promising policy. Despite the disturbances in the production, the overall performance of the system with this policy increases, which shows that the policy is robust.

6.3.2 Practical contributions

The main contribution for Tata Steel IJmuiden lies in the fact that the current state performance is lacking compared to other tested assignment policies. The outcomes of this study show that huge improvements can be achieved in the current practice of storage assignment. When incorporating the product features, which are the priority and SKU type next to the fixed production route, need of a service treatment, and the storage conditions, and favouring high priority colours and important classes of SKU types, result in higher performances of the overall system, and also on these particularly relevant products. Replacing the partly randomness in the current assignment with products-oriented rules have positive outcomes. Improvements could be accomplished on all the KPI's. In addition, the monetary values of handling discussed the high savings that can be achieved once a reliable estimate of the average costs of a handling can be determined. A better alignment of storage allocation and demand is feasible in this manufacturing environment.

This research is a first step in designing and testing these assignment policies, and since the results are positive, next steps should be taken in the future. Tata Steel should further refine the analysis and the model before any implementation. Section 6.4.1 describes the rules in order to achieve a higher performance. It also presents some other recommendations that should be followed, such as the implementation of demand forecasting outcomes as input for the simulation, the need of current measures on the performance, and the analysis of the locations of the inventory over time with their attributes. Moreover, the model needs to consider the product dimensions, the availability of resources, the possibility of re-assignments, and the occurrences of disruptions (see section 6.4.2). These kind of storage assignment decisions are also relevant for other steel industries, manufacturers or distribution centres where warehousing and inventory play a role.

6.4 Recommendations

This study is built on several assumptions for simplification that may result in less reliable results. Nonetheless, some important insights can still be inferred as learning points for the company. The recommendations for Tata Steel IJmuiden will be discussed in the first section. The second section describes the limitations of this research and the opportunities to conduct future research.

6.4.1 Recommendations for Tata Steel IJmuiden

This section discusses the recommendations for Tata Steel IJmuiden, which can be captured with the following two sub-questions of this study:

Sub-question 5: *How to translate the outcomes of the study to simple rules?*
The rules are dependent on the supplier (S1, S2), the demand (D1, D2, D3, D4, D5), the colour (black, red, amber, green, blue) and possibly the SKU type (A-Runner, A-Repeater, A-Stranger, B-Repeater, B-Stranger, C-Stranger). An overview of the main rules are:

- Black and red items should be directly assigned to the destination.
- No or limited use of other warehouses that are intermediate for the particular product (as it has another destination), but the warehouse is a destination for other products. In this way, the destinations are not occupied with goods that should not be stored here. When the destination is full, intermediate halls with no dedication to a destination is an alternative.
- Distinctions can be made regarding the SKU types. A commonly ordered product with a lower priority could be allocated to the destination dependent on the amount of WIP for this destination and the capacity of the destination location.
- A high priority product (black and red) for an important class (A-Runner and A-Repeater) should always be assigned to the destination.
- Finished goods with the destination W4 cannot be directly assigned, as these items are always hot and this warehouse cannot store hot goods. Black and red products with origin S1 should always remain in W1 until the items are cooled down. When W1 is full, then the W3 or W5 should be considered. Regarding amber, green or blue products, these should be allocated to W3, unless the finished goods should remain dry. Then, the W5 forms the assignment location for these items. The same holds for the supplying facility W2, except that black and red products should be assigned to W5. It does not make sense to assign it to W1 if the supplying facility is W2, since the S1 warehouses already have restrictions in

capacity. If the W5 is full, the W3 is an alternative. In case of lower priority products, these should be assigned to W3 unless the goods need to remain dry.

- Black, red, and possible even amber goods with the origin S1 and the destination W5 should be assigned to the destination. If the destination is full, black or red products should remain in W1 till there is a spot free in W5. Amber products could be allocated to W3 directly if they are allowed to get wet. Green or blue products should be at first assigned to W3. The same holds for the supplier S2. However, in this case the W1 should not be used unless W5 and W3 are full. The main idea is to not occupy the S1 warehouses for the finished goods with a low priority.
- Destination D3 (W6 hall) has most of the time capacity. Therefore, all the products could be assigned to the destination. If W6 is fully occupied, the high priority products with the origin S1 could remain in W1, and the low priority products should go to W3. In case of supplier S2, all products should be assigned to the W3 when W6 is full.
- Black and red products from both origins and destination D4 should be allocated to W7. Amber products should remain at first in W1. When W7 is full, black and red goods have to stay in W1, as this warehouse is next to the destination. Only when W1 and W7 are full, the high priority products should be allocated to W3. Green and blue products should always be allocated to W3 if W1 and W7 are often almost full.
- The destination hall for D5 (W8) has limited capacity in comparison to the amount of inventory for this destination. Black and red products from both suppliers should be directly assigned to W8. The second-best option in case W8 is full, is to remain in W1 for the products coming from S1. Otherwise the W3 is an option. Amber products should not be assigned to the destination if the number of red products for D5 is a lot. The low priority products should go to W3. If W3 is full, W5 is the alternative.

Sub-question 6: *What recommendations can be made regarding the actions?*

- Many departments in Tata Steel IJmuiden are involved and of interest. In the production and storage assignment process, information is crucial and divided among the departments. Therefore, a clear understanding should be created for the involved departments on the working of the process before any improvement could occur. Furthermore, it appears that the different departments have other points of interest for the improvements. These should be discussed in order to have consensus on the desired objective.
- It seems that multiple times products are re-assigned between two stages in a production chain. Sometimes the current assignment location of a product with a specific destination does not make sense. The numbers on these occurrences should be analysed and the reasons. These decisions on warehousing create re-assignments and therefore unnecessary handling.
- It appears that the warehouses contain products with a high storage time; sometimes for even more than a year. The products with high storage time should be removed from the warehouses, as these occupy space and deteriorate in quality.
- The results of this study show that the production and demand patterns highly affect the performance of the storage assignment process. It is recommended to use demand forecasting tools or the existing outcomes of it as input for the storage assignment decisions.
- A snapshot of the current assignment location with the colour and destination is studied. The locations with the colours and the corresponding destinations should be analysed over time to create more insights on the current performance and the possible improvement directions.
- The boundary on importance of SKU type classes need to be defined. Whether A-Stranger or B-Repeater are important classes to account for, will affect the storage assignment decisions.

- The colours of the goods should be transparent for the planners and operators. It appears that these are not considered or even visible for them due to the outdated ICT systems.

6.4.2 Limitations and recommendations for future research

There are some limitations in this research, which are discussed in this section. Each limitation is described with potential future research avenues.

- **Data availability**: there is a mismatch of the data on product level. The data is also from other periods. There is limited to no data available on the KPI's. In future research, a file should be constructed from multiple data sets with data on all the relevant attributes of the same product. Also historic data of these goods on the performance indicators should be retrieved. Another possibility is to consider the assignment locations of the products from past data. Test if after implementation of different rules compared to the historic data, better performance would be achieved with the new rules.
- **Demand pattern**: different input files are created to test the effect on the KPI's. The ideal output would be that the same policy with all the demand patterns would have the best performance. However, this is not the case. Also existing literature indicate that demand patterns of items have a great effect on the performance (Petersen, 1999), and studies should account for stochastic demand that is often the case in practice (De Koster et al., 2007). Therefore, it is important to retrieve and test real demand patterns from data. Furthermore, more input files to account for the stochastic demand should be examined.
- **Questionnaire MCDM**: due to the time restrictions of this study, only three respondents filled in the questionnaire. The results on the weights also showed that the view on the importance of production route or colour is different. It is important in future research to collect data from more decision-makers on the BWM and scores to get a more reliable result.
- **Product dimensions**: The dimensions of the good and other features are important in the steel industry, such as the weight, length, width, thickness, and steel grade. This is also a crucial factor in the pick-up. These dimensions should be included in the model for both the goods and the demand requests. The demand will search for a match on the dimensions.
- **Modification / Optimisation of pick-up**: the pick-up had to be fixed in this research. It now matches the destination and SKU type of the product and the demand request. The pick-up checks the assignment locations based on an order list. The pick-up affects the outcomes on the KPI's. These are determined by the assignment as well as the pick-up. In the pick-up can be specified to pick for example an important colour first or the oldest product. A combination of optimal assignment and pick-up rules will result in better results, as these influence each other and should be considered simultaneously (Petersen, 1999; Ong and Joseph, 2014). Different sets of assignment and pick-up rules should be constructed, and the combination of each of these sets should be modelled.
- **Availability of trains and cranes**: the objective of this research is to reduce the number of handling. Neither the transportation time, capacity, and distances or the handling time and capacity are taken into account. Due to no prior studies similar to this research and the time limitations of this study, the scope is narrowed down to only reduce the number of handling, thus, neglecting the availability of resources. The choice for the number of handling is justified by the fact that for large products, the handling costs are higher than the transportation by train, as handling also causes damages. However, this forms a limitation of the research, as the model considers a "continuous" flow: when a good is requested or produced, it can be directly moved without considering the capacities of the resources or the time. In reality, there is the requirement of available capacities of resources and the times to accomplish the movements. Particularly in routing problems, the equipment's are

relevant (Andersson et al., 2010). When the number of handling is reduced, the capacities of the resources are less restricted. Additionally, less handling results in a reduction in the transportation distances. Although, the occupancy rates of the cranes are reduced and indirectly the transportation, it is possible that certain days not all the products can be handled because of limited capacities and high demand. The model minimises the number of handling over time, but it does not incorporate minimising over the daily limited capacity. Hence, the model will work if the daily movements are lower than the available capacities, though, when there is peak demand on a specific day it will become more difficult to handle them all on the same day. If the number of handling are reduced, the service levels of the high priority products could also be improved due to higher availability of the resources for the important goods. Therefore, the resources will affect the outcomes on the performance measures. In follow-up research, the trains and cranes should be implemented with resources. The resources represent the trains where the capacities, time schedules, and tracks should be specified. A requirement should be added with the possibility of a product movement to the next storage hall only with an available resource. Also the cranes have daily capacities with the constraint that goods can be handled when there is an available crane.

- **Re-assignments**: when goods are produced, they stay in the assignment location until there is a demand request to pick the good up. Nonetheless, in reality there are re-assignments to other warehouses. This is particularly interesting for Tata Steel with the colour adaptations over time, but also because of the dynamic environment in warehousing, which is mostly neglected in academic research (Gu et al., 2007). Some reasons are for instance making room for products with higher priorities in the corresponding warehouses. If for example a black product is coming into the system and there is no place at the destination due to stored blue products in this hall, the black product is assigned to an intermediate warehouse in the model. Future research should incorporate re-locations over time by adding a new module, the relocation. Rules should be decided on to consider the possibility of relocation.
- **Disturbances**: quite often disturbances occur in reality. As stated in the problem description, these are for example defect cranes or failures in the production facilities. The stochastic demand incorporates for some days lower demand requests. Moreover, a disruption is tested with failures in the supplying facilities. However, still some disturbances need to be examined, such as failures in the demand facilities and defect cranes. When the cranes are defect, less or no products can be handled to or from a warehouse. These disturbances affect the storage assignment and should be studied. The failures in the facilities can be modelled by implementing input files with disruptions in production and/or demand requests. Cranes could be modelled with resources with specific capacities per period. In the time aspect, defects could be specified where there is no capacity for a certain time period.

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Appendix A Problem description

A.1 Steel production and facilities

Figure A.1 shows the production process of steel in IJmuiden (in Dutch). Steel is manufactured from the raw materials iron ore (*ijzererts*), coke (*kool*) and lime (Tata Steel, 2017a). The blast furnaces (*hoogoven*) create hot liquid iron from coke, sinter, and pellets. Since the liquid iron contains a lot of carbon, the carbon is as much as possible removed from the liquid iron by adding oxygen in the steel factory (*staalfabriek*). Then the steel can follow two different production techniques. The first one contains the direct sheet plant (*gietwalsinstallatie*) where the processes of casting and rolling are integrated into a single process. The second route is where liquid steel from the steel factory is cast into slabs. Initially, the slabs are 22.5 centimetres thick and in the hot strip mill (*warmbandwalserij*) the slabs are heated up to 1250 °C to roll to a thickness of 1.5 to 25 millimetres. At several points in this production process, the steel can be either sold or processed further. In the next process, pickling line (*beitsbaan*), acid is added to remove the rust from the steel coil. The cold strip mills (*koudbandwalserij*) roll the hot-rolled coils into even thinner material. The next processing steps are customer-specific, and will not be discussed.

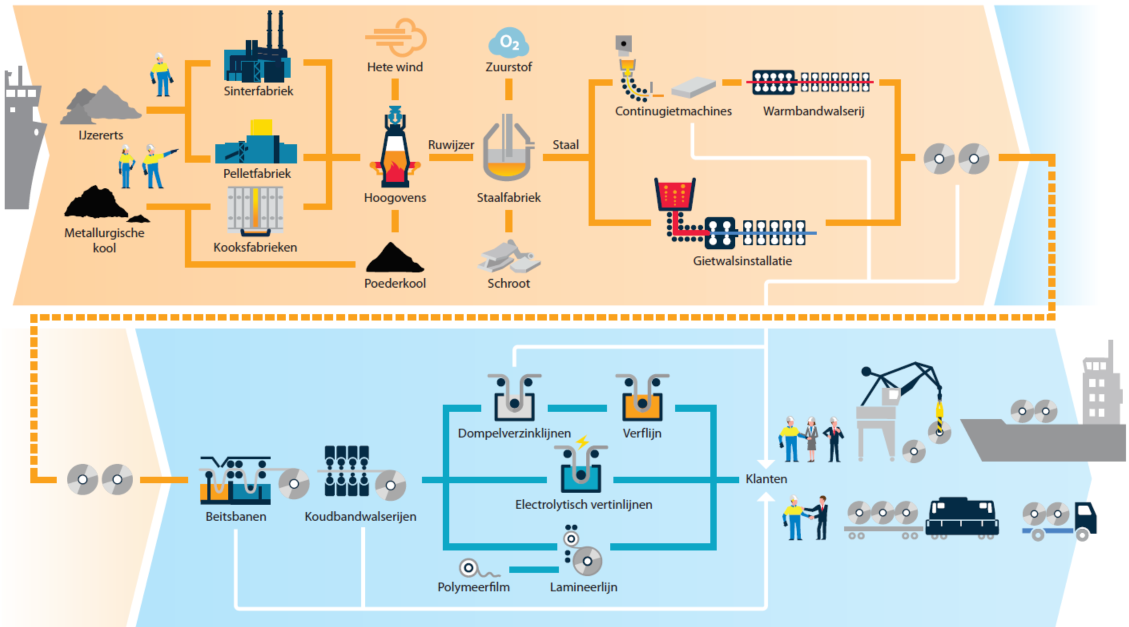

Figure A.1: Steel: From ore to finished product in IJmuiden (Internal data)

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A.2 Number of handling

Figure A.2 depicts a flowchart to represent the minimum and maximum number of handling. The attributes influencing the amount are the origin, service, the resting, and the destination. It shows that there is only room for improvement when the good does not need a service treatment.

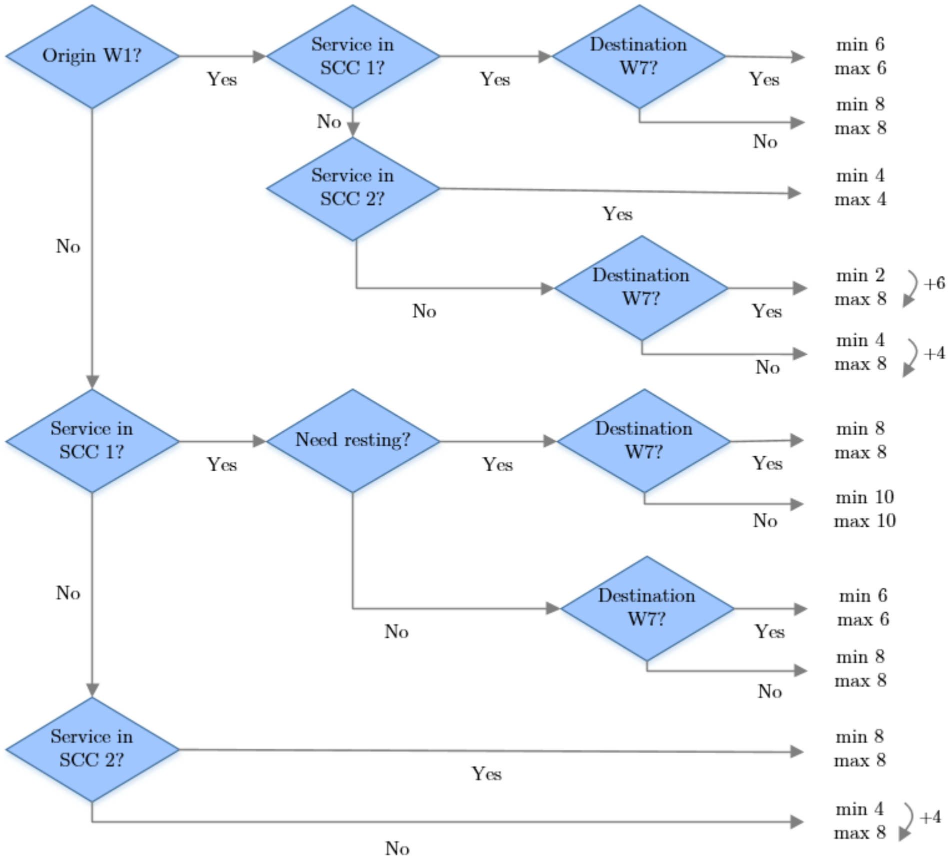

Figure A.2: Description of number of handling

A.3 Process description

< Removed due to confidentiality >

A.4 Company departments analysis

< Removed due to confidentiality >

Appendix B Methodology

B.1 SKU classification

The SKU classification is performed with the ABC analysis and the repeating profile. The ABC inventory classification is based on the annual consumption in tons. The Pareto consists of the distribution of the weight of production and number of SKUs. Figure B.1 shows the graph of the annual weight and the annual amount of SKUs. Approximately 25% of the products account for 81% of the annual production weight (class A), 38% of the SKUs for 15% of the tons (class B), and 37% of the number of products for 4% of the annual production weight (class C). Therefore, the ABC classification of the items is consistent with the Pareto principle or 80/20 rule (Chu et al., 2008; Tinelli et al., 2011). The groups of repetition are the Runner, Repeater and Stranger. The categorisation is based on some simple formulas shown below.

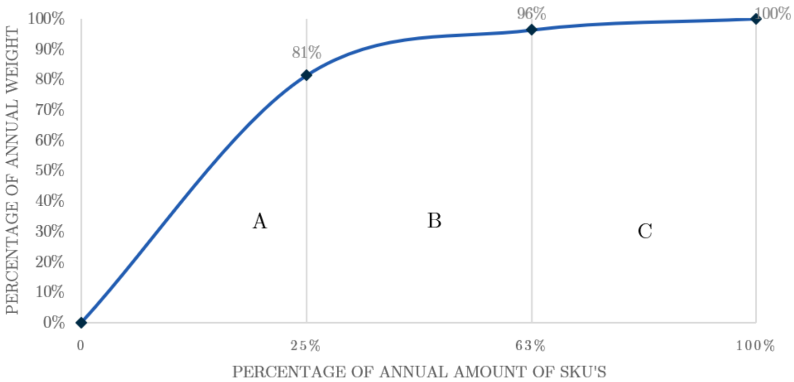

Figure B.1: ABC classification graph of weight and SKUs

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B.2 Assignment algorithms

B.2.1 Warehouse capacity (Cap)

The table below depicts the two capacities, as identified within the company. The lower maximum capacity is applied for this model run.

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B.2.2 Base case (BC)

The lower bounds (LB) and upper bounds (UB) for the storage locations per destination are depicted in table *has been removed.* Table B.1 shows the order list per destination.

< Removed due to confidentiality >

Table B.1: Order list - base case

D1	**List**	*D2*	**List**	*D3*	**List**	*D4*	**List**	*D5*	**List**
1.	W5	**1.**	W5	**1.**	W6	**1.**	W7	**1.**	W8
2.	W1	**2.**	W3	**2.**	W1	**2.**	W1	**2.**	W3
3.	W7	**3.**	W1	**3.**	W7	**3.**	W3	**3.**	W7
4.	W6	**4.**	W7	**4.**	W3	**4.**	W5	**4.**	W1
5.	W8	**5.**	W6	**5.**	W5	**5.**	W8	**5.**	W5
6.		**6.**	W8	**6.**	W8	**6.**	W6	**6.**	W6

B.2.3 Random (R)

Table *has been removed* describes the lower- and upper bounds, and the order list.

< Removed due to confidentiality >

B.2.4 Closest open location from origin (CO)

Table B.2 shows the order list of closest open locations from origin.

Table B.2: Order list of closest open location from origin

	S1 (W1)	**S2 (W2)**
1.	W1	W5
2.	W7	W4
3.	W8	W3
4.	W3	W6
5.	W6	W1
6.	W5	W7
7.	W4	W8

B.2.5 Closest open location from destination (CD)

Table B.3 presents the order of closest locations from the destinations.

Table B.3: Order list of closest open location from destination

	D1 (W4)	**D2 (W5)**	**D3 (W6)**	**D4 (W7)**	**D5 (W8)**
1.	W4	W5	W6	W7	W8
2.	W6	W3	W3	W1	W7
3.	W3	W4	W4	W8	W1
4.	W5	W6	W5	W3	W3
5.	W1	W1	W1	W6	W6
6.	W7	W7	W7	W5	W5
7.	W8	W8	W8	W4	W4

Appendix C Results

C.1 Model input and output

Table C.1 shows the fixed input data implemented in the model. The first production schedule is retrieved from the order book file, while all the other input files are simulated data. It contains the orders per SKU type and per supplier. The distinction per destination is lacking, which is taken from the inventory file over time. However, the distribution of export products to intercontinental and regional is simulated (55% and 45%).

Table C.1: Fixed input data

Input	**Unit**
Product arrivals per SKU type and destination	Number/Day
Demand requests per SKU type and destination	Number/Day
Warehouse capacity	Number

Table has been removed. The origin per SKU type follows an Arbitrary Discrete distribution (Disc). For the colour per destination and dry storage, an average is taken from two snapshots of inventory files with the following filters: S1 and S2 products, stored on the site IJmuiden, stored in one of the warehouses within the scope, and per destination (D1 - D5). The due date is based on the respective colour. The service in SCC 1 per destination is extracted from four weeks of inventory. There is no data available on the service in SCC 2, a probability of 20% on non-service products in SCC 1 is chosen. Since dry storage and the service both have two classes, a Bernoulli distribution (Bern) is applied. In queuing theory, the common distribution for service time is the Exponential distribution (Shortle et al., 2018). For both the service and the cooling, determined from interviews, the Exponential distribution (Exp) is used.

< *Removed due to confidentiality* >

This model has two categories of output measures. The first and most key ones are the KPI's or objectives. The second class are some other indicators. Table C.2 presents the output variables.

Table C.2: Output measures

	Output	**Unit**
Performance measures		
	Extra handling	Percentage
	Storage time	Days
	Due date met	Percentage
Other measures		
	Products arrivals per SKU type and destination	Number
	Products per warehouse per colour	Number
	Maximum occupation rate per warehouse	Percentage
	Total demand	Number
	Completed demand	Number

C.2 Current situation

C.2.1 Verification

When building the model and after the implementation, it is important to verify the model. Verification assures that the computerised model is correct against the conceptual model and specifications (Sargent, 2009). There are various verification tools within Simulink and SimEvents. The following tools are applied:

- **Model correctness**: building in steps and checking the results directly after implementing each part. When an error occurred, it was solved before continuing the model building. First the products were generated, then the start at the origin, afterwards the assignment, demand generation, and the pick-up from the assignment location. Finally, the process of matching the product with the demand, and the departure from the system were implemented.
- **Simulation Data inspector**: this is a tool in Simulink to inspect the input. It visualises and compares multiple kinds of data. The Simulation Data Inspector is used to inspect the product generation, the demand generation, and their attribute values.
- **Run time visualisation**: statistics in graphs and tables are continuously checked to see whether the output is as expected. Some examples are the number of products departed from a block and the number of products in a block.
- **SimEvents Debugger**: it is a block in the SimEvents package. It enables the debugging of the model by inspecting entities and their attribute values, and set breakpoints on blocks and events. It also presents the event calendar.
- **Sequence viewer**: it is a block in SimEvents showing the sequence of events and the movement of entities between blocks.

Verification tests should also be executed, such as the implementation of slightly different parameters or checking the consistency (Duinkerken, 2016). The input data and the number of variables in the model is limited. The fixed parameters in the model are the demand and production pattern, and the warehouse capacity. These fixed input will be modified in some policies. Regarding the random input, the most important attributes will be slightly differentiated in the sensitivity analysis. Therefore, the verification tests are covered and not separately performed. According to the verification tools, it can be concluded that the model functions according to the conceptualisation and the likelihood of errors occurring has been reduced.

C.2.2 Validation of storage time

< Removed due to confidentiality >

C.2.3 Results of current state

The results discusses the total production and demand, the occupation rate per warehouse, and the performance measures (handling, storage time, and due date met).

Total production and demand
Figure *has been removed* depicts a graph with the total production, the total demand, and the completed demand over time. The total production (blue) is higher than the total demand (red) to ensure that there is always inventory. This is in line with the assumption of 100% stock availability. The completed demand (purple) is slightly lower than the total demand, as the picking and matching of the goods occurs after the demand generation. As the figure shows, the production starts at the first day, while the demand starts after ten days.

< Removed due to confidentiality >

Maximum occupation rate per warehouse

< Removed due to confidentiality >

KPI 1: Handling
The handling is divided in the minimum handling required and the extra handling. D5 has the

least performance, and D3 the best performance. D1 goods cannot be improved due to the inability of W4 to store hot goods. There is always an intermediate hall needed for these products.

< Removed due to confidentiality >

KPI 2: Storage time

< Removed due to confidentiality >

KPI 3: Due date

The ranges indicate the number of days the items are delivered late. The general pattern is the higher the range, the lower number of too late delivered goods. Green labelled products perform better than black goods even though the percentage of green items is much higher than black goods. The reason for this outcome is that black items have a shorter time window (3 days) in comparison to blue products (17 days).

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C.2.4 Sensitivity analysis on service

< Removed due to confidentiality >

C.3 Results of assignment policies

KPI 1: Handling

The results are presented per KPI. First the outcomes on the handling are shown, then storage time, and finally the due date met. The tables include the best-worst and average cases on overall, per colour, per SKU type, and the important categories. In addition, it shows the point estimates. The first KPI also incorporates the monetary savings or losses of handling. As the results are extensively discussed in the main part of the report, no description is added here.

< Removed due to confidentiality >

KPI 2: Storage time

Next the detailed outcomes of the average storage days are shown below.

< Removed due to confidentiality >

KPI 3: Due date

Finally, the detailed results of the due date met are presented below.

< Removed due to confidentiality >

Appendix D Interviews

D.1 Manager Logistics Projects - 17 April 2018

< Removed due to confidentiality >

D.2 Improvement Consultant - 24 May 2018

< Removed due to confidentiality >

D.3 Production Manager SCC - 30 May 2018

This is a combination of an interview and a tour in W1, W7, and W9, SCC and D4.

< Removed due to confidentiality >

D.4 Chef Stevedoring & Warehousing - 31 May 2018

This interview is based on a tour in the following warehouses: W2, W3, W4, W5, W6, and W8. To simplify the questions per hall, the sub-questions per warehouse are removed. Each hall is discussed with its characteristics as mentioned by the interviewee.

< Removed due to confidentiality >

D.5 On Site Logistics Planner - 1 June 2018

< Removed due to confidentiality >

D.6 Planner & Scheduler S1/S2 - 8 June 2018

< Removed due to confidentiality >

D.7 On Site Logistics Controller - 12 June 2018

< Removed due to confidentiality >

D.8 Planner & Scheduler S1/S2 - 8 October 2018

In this interview, the assignment rules in current practice per destination were discussed.

< Removed due to confidentiality >

D.9 Manager Planning & Scheduling D3 - D5 - 8 October 2018

< Removed due to confidentiality >

Appendix E Questionnaire scenarios

This questionnaire is part of the graduation project on the storage assignment to the warehouses between the S1-S2 and D1-D5. The purpose of this research is to test the performance of the current practice and test the effect of new sets of assignment rules on the performance measures. This questionnaire takes the opinions of employees into account in constructing the new sets of assignment rules. The scope of this project is between the aforementioned production stages. Both semi-finished and finished products are taken into account. The number of storage locations is limited; all others are out of scope. These warehouses are W1, W3, W4, W5, W6, W7, and W8. The three criteria of interest are:

1. **Production route**: the production route defines the origin, S1 (W1) or S2 (W2) and the destination, D1 (W4), D2 (W5), D3 (W6), D4 (W7), D5 (W8). The warehouses in brackets are the corresponding output warehouse of the origin or the input warehouse for the destination. The finished goods (export) are divided into two destinations, as finished goods can leave from W4 as well as from W5.
2. **Colour**: the colour is categorised into black, red, amber, green, blue.
3. **SKU type**: the SKU type defines the combination of the ABC-classification and the repeating profile (Runner, Repeater, Stranger). Following the data, there are six combinations: A-Run, A-Rep, A-Str, B-Rep, B-Str, and C-Str.

Part 1: Criteria

1A. Combination of two criteria

Consider the goal (selecting the best assignment location) and only two attributes: the production route and the colour. Now give a weight to each attribute indicating the importance of taken the attribute into account in the storage assignment: a higher weight means a higher importance. Make sure that the sum of both weights is equal to 1 (fill in ONLY shaded cells throughout the whole questionnaire).

Production Route	Colour	
		$\sum = 1$

Consider the goal (selecting the best assignment location) and only two attributes: the production route and the SKU type. Now give a weight to each attribute indicating the importance of taken the attribute into account in the storage assignment: a higher weight means a higher importance. Make sure that the sum of both weights is equal to 1.

Production Route	SKU type (ABC & RRS)	
		$\sum = 1$

1B. Combination of the three criteria

Considering the goal (selecting the best assignment location), select the MOST IMPORTANT criterion from the three criteria (first line), and insert it in the most left-hand side cell of the second row.

Now use a number between 1 and 9 to show the preference of your MOST IMPORTANT criterion over the other criteria, where 1 shows the same importance and 9 the extreme importance of the most important criterion over the other criterion (If the most important criterion is for example the production route, you can fill in the value 1 in the blue cell of production route).

The MOST IMPORTANT criterion	Production Route	Colour	SKU type (ABC & RRS)

Considering the goal (selecting the best assignment location), select the LEAST IMPORTANT criterion from the three criteria (first column), and insert it in the top cell of the second column.

Now use a number between 1 and 9 to show the preference of all the criteria (first column) over the LEAST IMPORTANT criterion (If the least important criterion is for example the production route, you can fill in the value 1 in the blue cell of production route).

The LEAST IMPORTANT criterion	
Production Route	
Colour	
SKU type (ABC & RRS)	

Part 2: Scores

Production Route

Consider the goal (selecting the best assignment location) and indicate per **production route** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

	W1	W3	W4	W5	W6	W7	W8
S1 – D1							
W1 – W4							
S2 – D1							
W2 – W4							
S1 – D2							
W1 – W5							
S2 – D2							
W2 – W5							
S1 – D3							
W1 – W6							
S2 – D3							
W2 – W6							
S1 – D4							
W1 – W7							
S2 – D4							
W2 – W7							
S1 – D5							
W1 – W8							
S2 – D5							
W2 - W8							

D1 - Destination is W4

Notice: scores are given per destination. Give scores for finished goods with W4 as destination.

Consider the goal (selecting the best assignment location) and indicate per **colour** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

D1 (W4)	W1	W3	W4	W5	W6	W7	W8
Black							
Red							
Amber							
Green							
Blue							

Consider the goal (selecting the best assignment location) and indicate per **SKU type** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where

1 indicates the least preference and 10 the highest preference.

D1 (W4)	**W1**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**
A-Runner							
A-Repeater							
A-Stranger							
B-Repeater							
B-Stranger							
C-Stranger							

D2 - Destination is W5

Notice: scores are given per destination. Give scores for finished goods with W5 as destination.

Consider the goal (selecting the best assignment location) and indicate per **colour** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

D2 (W5)	**W1**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**
Black							
Red							
Amber							
Green							
Blue							

Consider the goal (selecting the best assignment location) and indicate per **SKU type** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

D2 (W5)	**W1**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**
A-Runner							
A-Repeater							
A-Stranger							
B-Repeater							
B-Stranger							
C-Stranger							

D3 - Destination is W6

Notice: scores are given per destination. Give scores for semi-finished goods with W6 as destination.

Consider the goal (selecting the best assignment location) and indicate per **colour** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

D3 (W6)	**W1**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**
Black							
Red							
Amber							
Green							
Blue							

Consider the goal (selecting the best assignment location) and indicate per **SKU type** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

D3 (W6)	W1	W3	W4	W5	W6	W7	W8
A-Runner							
A-Repeater							
A-Stranger							
B-Repeater							
B-Stranger							
C-Stranger							

D4 - Destination is W7

Notice: scores are given per destination. Give scores for semi-finished goods with W7 as destination.

Consider the goal (selecting the best assignment location) and indicate per **colour** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

D4 (W7)	W1	W3	W4	W5	W6	W7	W8
Black							
Red							
Amber							
Green							
Blue							

Consider the goal (selecting the best assignment location) and indicate per **SKU type** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

D4 (W7)	W1	W3	W4	W5	W6	W7	W8
A-Runner							
A-Repeater							
A-Stranger							
B-Repeater							
B-Stranger							
C-Stranger							

D5 - Destination is W8

Notice: scores are given per destination. Give scores for semi-finished goods with W8 as destination.

Consider the goal (selecting the best assignment location) and indicate per **colour** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

D5 (W8)	W1	W3	W4	W5	W6	W7	W8
Black							
Red							
Amber							
Green							
Blue							

Consider the goal (selecting the best assignment location) and indicate per **SKU type** the preference to locate it in the respective assignment location. Give a score between 1 and 10 where 1 indicates the least preference and 10 the highest preference.

D5 (W8)	**W1**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**
A-Runner							
A-Repeater							
A-Stranger							
B-Repeater							
B-Stranger							
C-Stranger							

Thanks a lot!